An Experimental Facility for the Study of Capillary Instability of Liquid Jets

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AN EXPERIMENTAL FACILITY FOR THE STUDY OF
CAPILLARY INSTABILITY OF LIQUID JETS

A Thesis

Submitted to the Graduate Faculty of the Louisana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Master of Science in The Department of Chemical Engineering

by
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B.S., Chengkung University, 1972 M.S., University of Kentucky, 1977 May 1980
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ABSTRACT

An overview of the instability of laminar Newtonian liquid jets in air is given, and the experimental procedures used by previous investigators are described. It is shown that empirical data are still needed for design purposes. For a systematic improvement of existing mathematical models through experimental data, a facility is designed, constructed, and tested for measuring the breakup length of jets and the size distribution of the drops. It consists of a flow system, an electro-optical detector and a signal conditioner. The performance of the electro-optical detector is shown to be good. The output signal from the electronics is a pulse train that corresponds to the train of drops passing through the detector. Anomalous "doublet" and "triplet" pulses in the pulse train are studied. For small nozzle, the anomalous pulses are attributed to large drops and/or small satellite drops passing through the detector simultaneously. For large nozzle, the anomalous pulses may come either from two partially overlapping drops or from a single drop with one or more waists.
I. Introduction

The instability and disintegration of liquid jets are important phenomena in a variety of physical processes. In many industrial operations, the production of liquid drops provides a large surface area for heat and mass transfer. Processes such as high-speed ink-jet printing, fuel injection, and spinning of synthetic fibers involve the phenomena of jet instability. Jet surface oscillations and drop size distributions have been observed in such diverse applications as the measurement of the surface tension of freshly formed surface and the detection of obstruction to flow in the lower urinary tract.

Considerable efforts have been extended to develop mathematical models to predict the breakup length of liquid jets and the size distribution of the resulting drops. Except for simple cases, however, empirical data are still needed for design purposes. For a systematic improvement of these existing mathematical models, an experimental investigation of the breakup processes is an appropriate first step. The effect of mechanisms not included in the theoretical models can be studied, and the results can be used to modify the models to account for these effects.

The purpose of this work is to design, construct and test an experimental facility for measuring the jet breakup length and the drop size distribution for liquid jets in air. The facility will
include a flow system to form the jets, a detection system to measure the jet length and drop size distribution, and an electronic system to condition the signal from the detector for automated data collection and processing.

This thesis begins with an overview of previous work on laminar jets in air. Different experimental techniques used in the past are then described. The new experimental facility is afterwards described in detail and its performance evaluated.
II. Overview of the Instability of Laminar Newtonian Liquid Jets in Air

A. Observations

Experimental observations of liquid jets in air result in a relationship between jet length and jet velocity as shown in Fig. 1. At very low jet velocities, drops form, grow, and are released individually at the nozzle tip. As the velocity is increased beyond a point called the jetting velocity, a short continuous stream of liquid exists between the nozzle tip and the point of drop formation. The formation and growth of axisymmetric disturbances near the breakup point can be observed from high-speed photographs. But to the eye the jet appears as a smooth column of liquid with occasional lumps.

As the jet velocity increases (the varicose region), the jet length also increases until it reaches a maximum length at the critical jet velocity. Below the critical velocity, the drop size is fairly uniform. At velocities beyond the critical velocity, the jet takes on a sinuous shape and the jet length decreases. The drop size varies irregularly as the amplitude of the sinuous disturbances increases. Eventually, the jet length will decrease to a point where the jet seems to burst. Further increases in the jet velocity have an irregular effect on breakup length.

The effect of nozzle turbulence depends on whether transition from laminar to turbulent flow occurs in the varicose region or in
Fig. 1. Typical breakup for a laminar Newtonian liquid jet in air.
the sinuous region. In the varicose region (below the critical velocity), nozzle turbulence results in a decrease in jet length. If transition occurs well into the sinuous region, the jet length will usually increase.

It has been observed that the surface of liquid jets expands and contracts to form swells and necks then grows to wave peaks connected by thin ligaments. Such ligaments will separate from the fluid mass to form relatively small satellite droplets interspersed among the main drops.

![Diagram](image)

Fig. 2.

Satellite formation leading to a (a) backward merging satellite, (b) forward merging satellite, (c) no merging (infinite satellite).
In the process of satellite formation, the ligament between drops may separate downstream first, upstream first, or simultaneously at both ends. As shown in Fig. 2a, if the ligament separates on the downstream of the drop first, the cohesive force tends to move the ligament back toward the following drop. The satellite drop formed from the ligament will be located near, and often coalesce with, the following drop. In Fig. 2b, the breakup process is reversed, the ligament separating from the trailing drop first. This will result in a forward-merging situation. In the third case (Fig. 2c), the ligament separates from the main drops at both ends simultaneously, and the satellite remains midway between the main drops. This situation is called an infinite satellite.

B. Theory and Mechanisms

Savart (1833) examined and described the breakup behavior of a cylindrical liquid jet. By measuring the frequency of these drops, he formulated two laws. First, for a given fluid and a given orifice, he concluded the frequency and jet length of drops are approximately proportional to the square root of the liquid head. Second, for a given head, the frequency of these drops are inversely proportional to the diameter of the orifice. Savart also noticed the contractions and expansions of the jet surface close to the breakup point.

Plateau (1873) was the first to show that jet instability owed to the effects of surface tension. He found that if the wavelength of the original disturbance is greater than the circumference of the
jet, the jet is unstable. He reasoned that a cylindrical column of liquid has a high surface energy. Thus, it tends to break into several spherical drops whose total surface energy is lower than the surface energy of the original cylindrical column.

Lord Rayleigh (1878) showed that Plateau's conclusion that a jet would break into segments of length equal to the jet circumference was incorrect. He analyzed the jet stability problem by applying small perturbation theory. Neglecting the effects of the ambient atmosphere and all second order products of velocities and their derivatives, he found that only axisymmetric disturbances are unstable. His theoretical results showed that all axisymmetric disturbances with wavelengths greater than the jet circumference will grow, but that one particular wavelength will grow with a maximum rate and eventually destroy the jet. His linearized equation of motion showed good agreement with experimental data on low velocity water jets in air.

Weber (1931) extended Rayleigh's analysis to include the effect of the viscosity of the jet fluid and the effect of air drag on the moving jet surface. He solved the Navier-Stokes and continuity equations for a jet moving with uniform velocity in a zero body force field, and showed that the viscosity of the jet fluid has a stabilizing influence. Weber found that the aerodynamic forces at the jet surface would enhance the growth rate of a disturbance, and that the jet length would reach a maximum at a critical jet velocity. For low velocity jets, his theory agrees with experimental measurements over a wide range of fluid properties. However, Weber's theory overestimated
the aerodynamic effect for high velocity jets.

Grant (1966) conducted a series of experiments with nozzles of length to diameter ratios of about 100 and with liquids with a wide range of fluid properties. In order to correlate his experimental results, he made an empirical modification to Weber's theory. The modified theory agreed well with experiments in predicting the maximum jet length and critical velocity at atmospheric pressure, but failed for data at reduced ambient pressures. Fenn (1969) followed Grant's efforts with a series of experiments carried out over a range of subatmospheric pressures. For a fluid of high viscosity, his results showed that the maximum jet length and critical velocity increased as the ambient pressure decreased. For a fluid of low viscosity, he found the effect of ambient density on jet breakup length to be negligible. He concluded that Weber's treatment of aerodynamic effects on jet instability was qualitatively wrong.

Sterling and Sleicher (1975) studied the aerodynamic interaction between a capillary jet and the surrounding medium. They found that in all cases Weber's theory overestimated the aerodynamic effect. Experiments were carried out on jets formed by short nozzles to eliminate the possible effect of the relaxation of a fully developed laminar velocity profile. A semi-empirical modification to the theory to account for the ambient fluid viscosity was considered, and the result agreed well with experimental data taken at atmospheric as well as subatmospheric pressures. In addition, they found that jets formed from long nozzles were less stable than jets formed from orifices.
The difference between jets formed by short nozzles and jets formed by long nozzles was attributed by Sterling and Sleicher to the relaxation of the velocity profile in jets formed by nozzles in which there is fully developed laminar pipe flow. A laminar liquid jet ejected from a long nozzle leaves the nozzle tip with a fully developed parabolic velocity profile. If the surrounding medium is nearly inviscid, e.g. air, the shear stress on the jet surface is brought suddenly to near zero. This gives rise to an increase of surface velocity as the jet moves away from the nozzle exit, i.e. the velocity profile relaxes to a uniform profile downstream.

Before 1960, the linear theories stood as the preliminary foundation of jet instability studies. These theories predicted that surface tension and inertia will break a continuous jet into drops, and that one drop would be formed per wavelength of the most unstable disturbance. It was always assumed that the amplitude of the disturbance was small relative to the jet diameter. The form of disturbance was assumed to be sinusoidal and to remain sinusoidal during the growth of instability. However, the initially sinusoidal perturbation is observed to have become non-sinusoidal close to the jet breakup point; this indicates a nonlinear behavior. Satellite drops are formed also between the main drops, a result not predicted by the linear theories.

Crane, Birch and McCormack (1964) performed a series of experiments using a loudspeaker driven by an audio oscillator to introduce sinusoidal external disturbances. They found that an
induced vibration in the appropriate frequency range and at small vibration acceleration could trigger the capillary instability. However, if the vibration acceleration was large, inertial effects predominated over the capillary effects. A second order analysis was developed to explain the nonsinusoidal behavior of the surface deformation. Yuen (1967) also used the perturbation approach to construct a third-order nonlinear theory relating to wave growth rates and surface shapes. He predicted that the growth rate of the neck is faster than the growth rate of the crest. Also, he found that the cutoff wavenumber, the wavenumber which separates the region of stability from instability, is dependent upon the amplitude of disturbance.

Lafrance (1975) used a random noise generator as an external perturbation to study the breakup of laminar liquid jets and carried out a perturbation analysis up to third order. He concluded that the formation of satellite drops is attributed to the nonlinear behavior, and that the maximum growth rate of disturbances is very close to that predicated by linear theory.

The theory developed by Rayleigh, Weber, and Yuen to describe the jet breakup is based on a temporal instability, i.e. the wavenumber of the disturbance is a known real value and the temporal growth factor is an unknown complex quantity. They assumed an infinite jet in which the oscillations grow in amplitude everywhere along its length. The third-order theories predict the existence of satellites, but the ligament separation is predicted to occur at both ends.
simultaneously. The latter prediction fails to agree with experimental observations. Keller, Rubinow and Tu (1973) pointed out that jet nozzle problem must be analyzed in terms of spatial instability rather than temporal instability. Spatial instability specifies the temporal growth factor to be real and the spatial wavenumber to be complex.

The jet is taken to be semi-infinite. The surface amplitude for the growing disturbance is negligibly small near the nozzle and it grows as it proceeds in the axial direction. From a spatial analysis, it is possible to predict the backward-merging satellites, as was observed in the experiments carried out by Taub (1976).

The higher order perturbation analyses illustrated the non-sinusoidal behavior of the jet and the existence of satellite drops, phenomena not covered by linear theory. However, the various theories on the formation of drops and satellites predicted uniform sizes. In contrast, experiments show that there is a distribution of drop sizes for both the major and the satellite drops. In order to obtain valid results, experimental methods of obtaining drop size distribution are important. Also, data do not exist for drop sizes from jets in the regime where velocity profile relaxation occurs.

C. Experimental Techniques

The primitive investigations were carried out by visual observation. The variation in the shape of jets and drops from orifices of different shape have been described by earlier authors. The frequency of the drops was measured from the sound produced as the drops impinged on a flat surface. In order to measure the drop
size, Merrington and Richardson (1947) mixed a dye into fluid and allowed the drops to fall on a sheet of thin blotting paper. A single drop of the same liquid was dropped from a pipette onto the paper from the same distance. The relationship between average stain diameter and drop size was claimed to be linear for most fluids except water, which tended to splash when landing at high speed.

To determine the breakup length of high-speed water jets, Vereshchagin, et. al., (1959), and later Phinney (1970), used a method based on the electric conductivity of the continuous part of the jet. His jet emerged from a grounded metal nozzle and impinged on a wire mesh, to which a voltage source was attached. The mesh was placed at various distances from the nozzle. In the continuous region of the jet, the circuit was closed from mesh to the nozzle and a current was carried through the jet. The constants of the circuit were so chosen that a thyratron in the electrical circuit would generate a pulse signal every 0.02 sec. A gate circuit was used to let the pulses pass when the jet was broken and not to pass when the jet was continuous. Thus, the number of pulse per unit time was a measure of the percent time the jet was broken at any given length.

Schneider, et. al., (1966), used a charging electrode to produce charged droplets that were directed into a container. The current between the container and ground was measured with a micro- microammeter. It was assumed that a charge was trapped on the surface of the jet and that the net charge on each drop was equal to the net
charge on a jet segment whose volume was equal to the drop volume. Drop sizes and spacings between drops could be measured directly from the ammeter.

Photography has been the most widely used method to investigate jet phenomena. The jet is directed between the source of light and the camera. The best effect is obtained when the light is diffused by a piece of ground glass. This provides a background of uniform intensity. A stroboscope or high-speed flash is used to obtain exposures of short duration. From the photographs, drop sizes and breakup length can be determined by direct measurements if breakup is regular. When the breakup length tends to vary, a series of photographs can be used to determine an average value. Although photographic methods provide actual measurement on drop size and jet breakup length, a large quantity of pictures must be taken to obtain statistically significant averages.

An electro-optical method has been described by Ritter, Zinner and Sterling (1976). The instrument consists of a light source, a collimating lens, optical slits, and a photodetector. The optical components are adjusted to form a light sheet of uniform intensity. Each time a drop of liquid passes through the light sheet, a shadow is cast on the photodiode detector and an electrical pulse is generated. The amplitude of the pulse is directly proportional to the crossing diameter of the drop. Drop sizes can be obtained directly from the output of the electronic circuit. This method has the advantage that a large number of size measurements can be obtained in a short time.
The character of the jet breakup and the resulting drop size distributions are strongly dependent upon the initial perturbation. Thus, care must be exercised to isolate the jet from extraneous sources of vibration. In general, two types of disturbance have been used by different investigators. Some investigators used a forced axisymmetric sinusoidal perturbation of the jet with mechanical sources of vibration such as tuning forks and loudspeakers. The application of a periodic vibration usually produces more uniform drops and, because of the large initial amplitude, will usually shorten the continuous length of the jet. Other investigators let the jet be disturbed by the natural random vibrations transmitted from the surroundings. If the amplitude of these vibrations is small and independent of frequency, the Fourier component with the largest growth rate constant will predominate, and the jet will break into segments whose length is equal to the wave length of this component.
III. Experimental Apparatus

A. Flow System

A schematic diagram of the flow system is shown in Fig. 3. It is similar to the system used previously by Sterling and Sleicher. It consists of a pressured fluid reservoir, a calming section, nozzles, and a collector.

Reservoir

A 70-gallon vessel, rated at 250 psig, is used as the fluid reservoir. A 7-inch flange has been welded at both the top and bottom of the tank, and a stainless steel plate has been bolted to the flange. An O-ring gasket provides a tight seal. The fluid reservoir is pressurized by compressed dry nitrogen. An adjustable air relief valve set at 100 psig is installed in the pressure line. Fluid passes from the reservoir through a 4-foot length of 0.75-inch flexible high-pressure rubber hose (type 4133D, Goodyear Tire & Rubber Co.) to reach the calming section.

Calming Section

The calming section consists of a 1.5-inch copper water tube (type L) enclosed in a 29.5-inch length of 2-inch I.D. stainless steel tubing. The copper tube is constructed in sections, as shown in Fig. 4, so that a flow straightener and calming screens can be installed as part of the calming section. Brass rings are used to
Fig. 3. Experimental apparatus.
Fig. 4. Calming section.
support the screens and join the sections of copper tubing. O-rings around the circumference of the brass rings provide a tight fit between the support rings and the stainless steel enclosure.

The flow straightener is made from a bundle of 0.25-inch diameter, 2-inch long drinking straws. Its purpose is to remove the large turbulent eddies formed at the entrance to the calming section. A 150-mesh screen is placed at the downstream end of the flow straightener. A second 325-mesh screen is placed about 5 inches from the exit of the calming section. The purpose of the screens is to further reduce the eddy size so that viscous dissipation of the turbulence is enhanced. The acceleration of the fluid as it passes from the calming section to the nozzle further reduces the turbulence.

Inertia Pad

The calming section is firmly attached to a 350-lb concrete inertia pad. Two inflated rubber inner tubes are sandwiched between the inertia pad and a plywood sheet. The plywood sheet rests on three columns of concrete blocks. The purpose of this arrangement is to reduce the transmission of vibrations from the floor of the laboratory to the calming section.

Nozzles

Hypodermic needles made by Hamilton Company were used as nozzles. The I.D.s were 0.25, 0.51, 1.07 and 2.16 mm. The length to diameter ratio is greater than 100 to ensure a fully developed parabolic velocity profile at nozzle exit. The nozzles, however, can
be cut to any specific length. Emery cloth is used to grind the tip to a flat face. Jeweler's broaches are then used to remove burrs on the inner walls of the nozzle exit, and the ends are then examined with a magnifier for smoothness and circularity. All nozzles are fitted into a Teflon luer lock that is threaded to a stainless steel cap screwed onto the end of the calming section. Because of the long lengths of the needles, up to 24 inches, it is necessary to support the nozzle tip to avoid curvature and vibration of the nozzle.

Collector

A 1' x 1' x 5'6" fluid collector is made of a 24 gauge galvanized sheet. It is used to receive and store the test fluid for recycle. Water, however, is drained directly from the collector. A cover made of the same material is installed on top of the collector. The jet impinges on this cover and the fluid drains into the collector. The angle (45° to the horizon) of the cover helps to prevent acoustical feedback to the nozzle.

B. Detector (Spectrometer)

The spectrometer consists of a light source, a collimator, two optical slits and a photodetector. It is a modification of an instrument described earlier by Ritter, Zinner and Sterling. A Lambda regulated power supply (series LK351) is used to power a GE G-9 miniature lamp in a collimator (N-3C gunsight, Edmund Scientific Co.). The collimator is mounted on an aluminum frame as shown in Fig. 5. Two sets of slits, which are fixed to firm but adjustable mounts are
Fig. 5. Photograph for detector frame.
used to define the light field. A thickness gauge is used to adjust the gap of the slits to 0.5 mm. The first set of slits is installed 3.5 inches away from the collimator. The second slit is mounted 6.5 inches away from the first slit. The width of the light field is limited by the 2.25-inch diameter lens of the collimator. Light passing through the second slit falls on a silicone photodiode (model PIN L/4, United Detector Technology) with an active area of 4 x 0.1 inches².

C. Electronics

Amplifier

The signal from the diode is too small to be processed by a signal analyzer. A five stage preamplifier, as shown in Fig. 6, is used to process this signal. This amplifier was built from a design by T. J. Ouwerkeck (1976). A Lambda regulated power supply (model LZD-32) provides ± 15 volts DC current for the amplifier and the photodiod. The first stage of the amplifier converts the small current, created by the DC light incident on the photodetector, to voltage. The DC output of this stage is about 6.5 volts. Drops passing through the light field generate negative going pulses (see Fig. 7a). If the incident light is blocked completely, the Zener diode will maintain a constant 5.6 volts at the output of first stage amplifier. Both the first stage and photodetector are built into the detector frame. In stage two, a negative DC voltage is added to reduce the DC offset from stage one, and the difference is amplified (Fig. 7b). The DC voltage offset can be adjusted by a variable
Fig. 6. Electric circuit for preamplifier.
Fig. 7. Signals at various points in preamplifier.
resistor (R1) according to the intensity of incident light (which changes when a new light bulb is installed). The output of stage two is a two-volt baseline with negative going pulses. A BNC connector is provided here as a check point to monitor the 2 volts with a voltmeter. Stage three consists of two parallel 741 amplifiers of different function. The first one is connected to a diode which eliminates all the pulse signals leaving a positive DC voltage equivalent to the output baseline from stage two—approximately two volts (Fig. 7c). The second 741 serves as a voltage inverter (Fig. 7d). At the end of stage three, the outputs from these two 741 are combined so that the output signal (Fig. 7e) is a positive going pulse. A variable resistor (R3) is installed to keep this baseline at zero volts.

The fourth stage consists of a 741 amplifier with a variable feedback resistor. In this stage, the signal is inverted and filtered (Fig. 7f). The variable resistor (R2) is used to adjust the gain of the amplifier.

Fig. 8. Motor-driven chopper
For preliminary adjustment of the circuit, a motor-driven chopper (see Fig. 8) is placed in the light field. The chopper blade has a width of 0.6 cm and a thickness of 0.1 cm. The chopper blocks the maximum amount of impinging light when the wider side (0.6 cm) faces the light field. After the chopper rotates 90°, the narrower side (0.1 cm) will face the light source and block only a minimal amount of light. Another 90° rotation will bring back the wider face. A rotation of the blade generates a rectified sinusoidal signal at the output of the final stage amplifier. The gain of the final amplifier (R2) is adjusted to give a signal with an amplitude of 0.5 volts. For fine tuning the gain, 0.25 inches (0.635 cm) steel balls are dropped through the light sheet, and the gain is adjusted to give a pulse with an amplitude of 0.635 volts, i.e. the pulse height in volts is set equal to the crossing diameter of the steel ball in centimeters.

Signal Conditioner

For analog/digital (A/D) conversion of the pulse heights, it is necessary to condition the signal and provide synchronization. A schematic diagram of the signal conditioner is shown in Fig. 9. The complete circuit diagram is given in the Appendix A. The pulse signal may enter the signal conditioner either directly from the preamplifier or from an FM recorder. Since recorded signals have a higher noise level than the direct signals, a filter is used to reduce tape noise and provide a clean signal for the differentiator which follows. A 0.5-1.5x variable gain amplifier is installed to
Fig. 9. Schematic diagram for signal conditioner.
assure that the voltage of the recorded pulses is at the calibration level. For direct input from the preamplifier, the amplifier and filter are usually set off.

In order to detect the peaks, the pulses (see Fig. 10a) are electronically differentiated and inverted by a 741 operational amplifier. The differentiator output (Fig. 10b) is then fed into an amplifier. It inverts the signal and drives the output to +12.5 volts when the input signal is negative and stays at -12.5 volts when the input signal is zero or positive (Fig. 10c). The transistor that follows generates a -5 volt output when the input is positive and a zero volt output when the input is negative (Fig. 10d). The output of the transistor is fed into a one-shot multivibrator (74121). When the input jumps from -5 to 0 volts, a +3.5 volt rectangular pulse (3 \mu sec width) is generated (Fig. 10e). This pulse is generated when a peak is detected by the differentiator no matter how small the peak is.

On a parallel path, the pulse signal is fed into a comparator. It outputs a +5 volt signal whenever the input pulse is greater than a pre-set threshold level (Fig. 10f). The output of the comparator initializes a "clock", i.e. a JK edge-triggered flip-flop (7470), that is triggered by the pulse from the one-shot multivibrator. The output of the "clock" is +2.5 volts from the time of the pulse peak to the time the pulse signal goes below the pre-set threshold level (Fig. 10g). The output of the "clock" is fed into a second 74121 which generates a TTL level signal (3.3 volts x 0.2 m sec, Fig. 10h)
Fig. 10. Signals at various points in signal conditioner.
which can be used to initiate an A/D converter.

The purpose of the third parallel path is to stretch the pulse signals. The drop pulse is inverted by a 741 amplifier (Fig. 10j) and then fed to a field effect transistor (FET). The FET, which serves as a sample and hold device, is controlled by a trigger signal. The trigger signal is the output of the "clock" and is amplified and inverted before it reaches the FET (Fig. 10i). The leading edge of the trigger signal is in phase with the peak of the drop pulse.

When the trigger signal is at zero volts, the pulse passes through the FET unchanged. When the trigger signal drops to -4.0 volts, the FET blocks the transmission of the pulse signal and its output is held at a constant amplitude equal to its input voltage at the time of the leading edge of the trigger signals. When the trigger signal returns to zero, the pulse signal is again passed through the FET. The Signetics 536 amplifier then inverts the signal. The result is a stretched pulse (Fig. 10k). The amplitude of the stretched portion is equal to the peak amplitude of the drop pulse. Since an A/D conversion of the drop pulse will occur at some small but finite time after the TTL trigger pulse (Fig. 10h), it is necessary to stretch the peak amplitude for accurate conversion.

The last stage is a level shifter that drops the baseline of the signal to -1.0 volt. This is done to increase the dynamic range of an A/D conversion since a common input range for A/D converters is ±1.0 volt. Oscilloscopic tracings for trigger signal, stretched signal and original pulse signal are shown in Fig. 11.
Oscilloscope tracings of (a) trigger signal, (b) stretch pulse, (c) drop pulse.

D. Ancillary equipment

The detector frame including light source, slits, photo-detector, and first stage amplifier is fastened to two clamp holders. As shown on the right part of Fig. 12, the detector frame can be adjusted to different angles. The detector and the clamp holders are mounted on two aluminum supporting rods. This enables the adjustment of the height of the detector. The two aluminum bars are installed on a 50-lb rack which has four casters mounted underneath. The rack can be moved back and forth on the casters which ride on two angle irons. This arrangement is to assure that the drops will pass through
Fig. 12. Mounting arrangement for positioning transducer.
the light field at right angles.

A dual beam storage oscilloscope (model 5113, Tektronix) displays the time-varying output. A digital multimeter (model 8000A, John Fluke Mfg. Co.) is used to monitor and calibrate the electronic devices. A standard 19 inch wide instrument rack is the home of a clock, the preamplifier, the signal processor, an oscilloscope, a multimeter, and the DC power supplies.
IV. Evaluation of the Experimental Facility

A. Flow System

Reservoir

The flow system was tested under a pressure of 100 psig. The Teflon lure lock was blocked by a lure cap, and the calming section and the flexible rubber tube were filled with water. Compressed nitrogen was introduced into the system twice, once with the reservoir filled and once with the reservoir half-filled. Each time the pressure was brought to 100 psig for at least 20 min. No water or air leakage was found. Once the pressure of the system exceeded 100 psig, the spring-controlled relief valve opened automatically.

Under experimental conditions, the operational pressure will seldom exceed 50 psig. For the smallest nozzle (I.D. 0.025 cm), a 40 psig nitrogen pressure can produce a jet stream with Reynolds number equal to 2500 which is beyond the laminar region. For large nozzles, the Reynolds number of the jet can easily reach 4500 even without help from the compressed nitrogen.

Calming Section

When the Reynolds number is below 4800, the liquid jet is smooth and clear and no ruffled surface is observed. This indicates that the flow pattern of the jet is laminar. When the flow is turbulent, the irregular eddies inside the jet make the jet surface
ruffled, the liquid jet becomes opaque. When a very short nozzle is attached to the needle fitting, and the flow rate is increased to a Reynolds number of 3000, there is no ruffled surface observed on the cylindrical jet column. It indicates that the needle fitting does not generate turbulent eddies and is installed adequately.

Inertia Pad

It was pointed out that vibrations and disturbances at the jet nozzle can affect the breakup behavior of a liquid jet. The building vibrations which are transmitted to the supporting structure can be reduced or attenuated by proper isolation. A vibration analyzer (model IRD, Mechanalysis, Inc.) was used to evaluate the vibration damping of the combination of inner tubes, plywood and the inertia pad. The peak-to-peak displacements at frequencies ranging from about 1 Hz to 8000 Hz were measured for both the inertia pad and the cement block that is attached to the floor. The results are shown in Fig. 13 for frequencies up to about 1000 Hz. The displacements above 1000 Hz were too small to be measured accurately. Although the isolation system is effective in damping the building vibrations above a frequency of 20 Hz, the resonant response at 28 Hz may bias the breakup behavior for jets formed by the largest nozzle \((d = 0.216 \text{ cm})\) at velocities close to 20 cm/s. This effect should be considered in future experiments.
Fig. 13. Spectral distribution of the vibration of the laboratory floor and the inertia pad.
B. Transducer-electronics

Frequency Response

The amplifier distortion is the departure of the output from an accurate representation of the input signal. Distortion can be classified into two types: amplitude and phase. Our electronic device is tested by its response to both a sine wave (frequency response) and a step change (transient response).

To test the frequency response, the gain (or attenuation) of a sinusoidal input is measured over a wide band of frequencies. The sinusoidal input can be generated in two ways. First, the motor-driven chopper can be introduced into the light field. This gives a rectified sinusoidal input and its rotational speed, thus the frequency of the sinusoid, can be adjusted by varying the voltage to the motor. However, the frequency range of the chopper is only from 5 to 55 hertz. The second method is to inject a sinusoid from a signal generator (model 113, Wavetek Co.) into the system; the frequency range of the signal generator is from 0.01 to 10,000 hertz. The sine wave is injected into the electric circuit after the first stage preamplifier. The peak output voltage for the respective constant amplitude input sources is recorded at different frequencies.

A semi-log plot of db vs. frequency is shown in Fig. 14 where

\[ db = 20 \log \frac{E}{E_{\text{max}}} \]

\( E = \) the voltage of output signal, and \( E_{\text{max}} = \) the maximum voltage of the output signal. The results from the motor-driven chopper coincide
Fig. 14. Frequency response of preamplifier.
with those from the signal generator in the frequency range from 5 to 55 hertz. No distortion of the pulse shape was observed, and the phase shift between the input and output signals was small (less than 30 μsec).

The other method to describe the character of an amplifier system is to measure the transient response. Instead of using sine waves of different frequencies, one uses an input voltage step as shown in the upper part of Fig. 15. The output signal is not ideally rectangular, but in most cases, is smoothed out and distorted. The pulse is also delayed in passing through the amplifier system. The time delay was determined to be 20 μsec from time zero to the time that the 50% point is reached. The rise time measured between the 10% and 90% points on the curve is found to be 44 μsec. The time delay is small compared to the rise time of a typical pulse signal, but is sufficiently large to reduce the amplifier response to small amplitude, high frequency noise.

![Diagram](image)

*Fig. 15. Transient response (a) step change input, (b) preamplifier output.*
Thus, the baseline of the output signal is fairly flat (0.5 mV peak-peak noise). The absence of an overshoot in the response to the step change indicates that this amplifier system is non-oscillatory, an important characteristic for our signal processing. An oscillatory response would cause major problems with the differentiator in the signal conditioner. The results of this transient test indicate that the electronic stability of the amplifier system is good.

Light Field Uniformity

The uniformity of the light field was tested by dropping ball bearings at different positions across the light sheet. Two rulers were mounted parallel with the two slits. The 1/4-inch ball bearings were dropped through a funnel mounted on a piece of wood positioned on these two rulers. Data, shown in Fig. 16, were collected at 1/8-inch intervals along the width of the light field. The variation of the light field is ± 3%.

![Fig. 16. Uniformity of light field.](image)
Linearity with Sizes

Different sizes of ball bearings, ranging from 1/16 to 3/8-inches, were dropped through the center of the light field to obtain the relationship between ball sizes and signal outputs. The results, shown in Fig. 17, represent a linear relationship between the ball sizes and the output voltage.

V. Evaluation of Pulse Shapes

Procedures

The liquid drops vibrate and rotate while proceeding in air. Owing to surface tension, the drop size is the most important factor for the departure of the drops from sphericity. The viscosity of fluid tends to damp the oscillations of the drops. An examination of the output signal on the oscilloscope reveals the existence of pulses of different shapes, e.g. "doublets" or "triplets". Such pulses may come either from partially overlapping drops or from distorted drops. These phenomena have been observed in earlier use of the drop spectrometer. However, little study has been done to resolve the cause of these "doublet" pulse signals. In order to interpret the drop size distribution and to estimate the volume of each drop, it is necessary to understand this behavior. For this purpose, it is informative to take photographs of drops as they pass through the light sheet and to record simultaneously the electronic signals they generate on oscilloscope.

A Nikon camera equipped with 55 mm micro-lens was used to
Fig. 17. Linearity of pulse height with crossing diameter of steel balls.
take close-up pictures of drops. Exposures were made at f/5.6 and 1/125 sec. Photographs of the drops were taken on Kodak Tri-x film (ASA 400). The jet was illuminated by means of a stroboscope (model 1531-AB, General Radio Co.) with a 0.8 µsec duration at one-third peak intensity. The illuminating flash was diffused to provide a nearly uniform background. This has to be carefully arranged so that the intense flash will not saturate the photodiode.

A circuit, shown in Fig. 18, is used to synchronize the strobe with the camera shutter.

![Circuit Diagram]

**Fig. 18.** Circuit for synchronization of strobe light and oscilloscope with camera shutter.

All films were developed in Microdol-X liquid developer and fixed by Kodafix solution (both from Eastman Kodak Co.). A Polaroid CU-5 land camera with a 3 inch lens is used to photograph the stored tracings on the oscilloscope. Exposures set at f/5.6 and 1/2 sec are satisfactory for Polaroid land film (type 667, ASA 3000).
The I.D. of the first nozzle under study was 1.07 mm. The upper part of Fig. 19a shows a representative photograph of water drops emerging from right to left. The oscilloscope pulse tracings, which correspond to the photographic drops above, are shown in the lower part. The light field is located at the left edge of the picture. The shapes of the drops change from the time the photograph is taken to the time they pass through the light field. A ruler installed on the top of the jet provides a reference for estimating the size of the drops and their velocity. The distance between any two drops can be measured from the photograph. This can be most easily done if the photograph is projected onto a wall. The time interval between the two drops can be obtained from the corresponding pulse tracings on the oscilloscopic photo. The first peak from the left, a bi-modal peak, can be easily identified from the stroboscopic photograph as two separate liquid drops. The two following small satellites are also observed on the oscilloscope.

The "triplet" pulse shown in Fig. 19b is attributed to the combination of two main drops and one satellite travelling between them. The second peak in Fig. 19c turns out to be a main drop and a satellite, but the bi-modal shape of the pulse is not clearly defined. Shown in Fig. 19d, two main drops and one satellite display a doublet on the oscilloscopic tracing. In Fig. 19e, the first pair of drops shows a tri-modal pulse owing to a waist in the first drop and a closely following second drop. The second pair with two small satellites following clearly changed their orientation before they
Fig. 19. Photograph of drops and oscillographic tracings.
passed through the light field; the result is a big spike.

The large nozzle with 2.16 mm I.D. produces larger drops than the previous one. The peanut-shaped first drop in Fig. 19f shows only modest deformation in signal output. The second drop clearly demonstrates its waist on the oscilloscope output as a small notch on top of the pulse. Both Fig. 19g and 19h show two highly distorted drops after breakup. In Fig. 19i, the second and third drops result in a spiky pulse. This indicates that they either pass through the light sheet simultaneously or merge together.

In this study, we have observed that for drops generated by large nozzle a "doublet" pulse nearly always owes to a waist in the drop. For drops generated by small nozzles, the "doublet" pulse nearly always owes to two drops passing through the light field simultaneously. The absence of a waist in small drops owes to the effect of surface tension.

In the general case, it doesn't seem possible to tell from the signal whether the "doublet" pulse owes to a single pulse of the waist or to two drops passing through the light field simultaneously. From our observations, we can estimate roughly that from 1% to 5% of the pulses will be a "doublet" or "triplet" with the larger value occurring at higher jet velocities. Thus, a distortion of the drop size distribution because of the existence of the "doublet" or "triplet" should not be great. Further work is necessary to determine this quantitatively.
For small nozzles, it is appropriate to collect the drop size data at 4 cm downstream of the breakup point. At this distance, there is little drop shape deformation, and it is easy to center the drop trajectory in the light field. For the large nozzle, a suitable distance for data collection is at least 6 cm from the breakup point; as the jet velocity is increased, this distance should be increased.
VI. Discussion and Conclusions

The flow system, calming section, detector, amplifiers, and signal conditioner have been built and tested. They are stable and reliable. Only minimum maintenance is required for these instruments, e.g. the preamplifiers must be recalibrated whenever a new light bulb is installed. The uniformity of the light field is shown to be good, and the amplitude of the pulse signal from the electronic component is linearly related to the crossing diameter of drops traversing the light field.

Over 400 pictures have been taken to investigate the "doublet" pulses discussed previously. For the small nozzle, these "doublet" pulses and other distorted tracings are attributed to the main drops and/or the small satellites traversing the light sheet simultaneously. Owing to the effect of surface tension, the small drops seldom show large distortions. For the large nozzle, the "doublet" pulses may come either from two partially overlapping drops or from a drop with one or more waists. The irregularity in pulse shape arises largely from the effect of residual deformation and oscillation after breakup.

The main advantage of drop spectrometry over the photographic method is the ease of data analysis. Drop sizes can be read out directly from the oscilloscopic tracings. The distribution of the pulse heights can be obtained with a multichannel pulse height analyzer, or the pulse heights and time intervals between pulses can be measured and analyzed by a mini-computer with an A/D converter and real time clock. However, limitations have to be considered. Close to the
breakup point, the drops vibrate and rotate, and their shapes depart from spheres. Downstream, the aerodynamic drag will distort the large, high-velocity drops. Thus, the measured drop sizes will deviate from their true values. However, the effect of these deviations can be reduced by averaging a very large number of drops (19,000 drops). The total volume of the drops can be calculated from the drop size distribution. Since the volume is related to the third power of the drop diameter, a comparison of the calculated and measured volume will provide a sensitive test of the accuracy of the drop size distribution. This comparison should be an early goal of future studies.

The experimental procedure has to be carried out with room lights off. Otherwise, the light emitted from the fluorescent lamps will be picked up by the photodiode. The result is a 60 Hz sinusoidal baseline that messes up the pulse signals. If a miniature lamp with stronger intensity was used as a light source, the effect of the ambient fluorescent light would be reduced.

Our original idea was to record the signal from the spectrometer on an FM recorder, and to program the EAI 680 computer as an A/D converter for the Sigma 5 computer. This idea was abandoned because of the death of the Sigma 5. Furthermore, the present FM recorder is totally inadequate for accurate reproduction of the spectrometer signal. We also attempted to obtain the use of a multi-channel analyzer, but were unable to do so. The study of alternative methods for automated data collection and analysis is currently under way.
Apart from the data collection and analysis system, only two items are needed to complete this facility: 1) a reliable FM recorder is needed for data storage, and 2) a small pump is needed to deliver collected fluid back into the reservoir.

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Appendix A. Electric circuit for signal conditioner.
VITA

The author was born in Taipei, Taiwan, Republic of China, March 29, 1950. He received his elementary and secondary education there and graduated from the Taipei Chen Kuo Boy's High School in 1968. He enrolled at National Cheng Kung University in Taiwan in the fall of 1968 and received the B.S. degree in chemistry in June, 1972. From October 1972 until August 1974, the author served in the Chinese Army. In July, 1975, the author was married to the former Chinwei Helen Chang. In the fall of 1975, the author entered the University of Kentucky and obtained his M.S. degree in chemistry. In 1977, he was admitted to Louisiana State University, and since that time he has been working toward the M.S. degree in chemical engineering. Following completion of his M.S. degree, the author will work for Shell Oil Company as a process engineer.
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