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DESIGN, DEVELOPMENT, AND FIELD TEST OF A DROPLET MEASURING DEVICE

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DESIGN, DEVELOPMENT, AND FIELD TEST OF A DROPLET MEASURING DEVICE

by

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ABSTRACT

The design, development and field testing of a concept to measure liquid droplets in the size range from 1μm to 600μm is described in the report. The measurement probe is a platinum wire 5μm in diameter. With the probe electrically heated to a predetermined temperature, changes in the probe resistance are related to the size of the impinging droplets in the gas flow. The electrical signals from the probe are processed and used to classify the droplets into six different size ranges or bins.

Two prototypes consisting of the probe and electronic processing unit were constructed and tested in the field. Actual droplet distributions and concentrations were successfully measured.

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The field testing of the instrumentation was performed at the facilities of the Nassau County Sewage Treatment Plant, Wantagh, New York. Mr. Frank Flood, Superintendent of Operation and Maintenance in the Nassau County Department of Public Works, made the necessary arrangements at these facilities, and his support is gratefully acknowledged. The cooperation of all individuals at the treatment plant was outstanding and contributed greatly to the success of the field testing.

SECTION I

CONCLUSIONS AND RECOMMENDATIONS

In this study, the concept of measuring droplet size and concentration with a hot-wire sensor was investigated and implemented. From the results of the study, the following conclusions are made:

- The concept of measuring droplets with a hot-wire sensor is feasible over the size range from 1μm to 600μm. The measurement technique has been demonstrated in the laboratory and under field conditions.
- A prototype design, consisting of the probe and electronic processing unit, was implemented and used under field conditions. Actual droplet distributions and concentration were successfully measured and reported.
- The prototype system is well suited to field work since it is lightweight and easy to operate. The probe itself is delicate and must be handled carefully. However, the probes, once installed, lasted for many hours of measurement under the field environment.
- Techniques were developed to discriminate the signals generated by the droplets from the noise due to turbulence. These techniques proved very successful for the field environment encountered in this project.

Two prototype units were delivered to the Environmental Protection Agency. These units are suitable for making surveys of droplet distributions in scrubbers and mist eliminators provided the following operating conditions are not exceeded:

size:	1μm to 600μm
flow velocity:	3 m/sec
concentration:	500 droplets/cm^3
temperature:	0°C to 100°C

The prototype instruments are the first generation in the development of the concept, and further improvements can extend the operating range and usefulness of the device. Some recommendations for further research and development are:

- The units should be used to perform a series of measurements for numerous environmental conditions encountered in different scrubbers and mist eliminators. The data should be carefully recorded and analyzed to establish well defined performance characteristics for the device.

- The effects of turbulence and varying temperature conditions need more study in the laboratory. Work, thus far, was limited in this area. As the device is subject to new operating conditions, data would become available to help interpret measurements and to improve calibration procedures.

- The range of the device should be extended to higher flow velocity and smaller droplet sizes. Under a proper research program it appears that measuring submicron droplets should be possible.

- The device is now powered using a 110 volt 60 c/s supply. The usefulness of the device can be improved by making the unit battery powered.

- The output from the electronic signal processor is now a manual operation. For monitoring droplet distribution over extended periods of time in the field, the system should be automated to provide hard copy printouts.

SECTION II

INTRODUCTION

The measurement of small liquid droplets in the gas stream of scrubbers and mist eliminators is a need in pollution control technology. The capability to make such measurements will lead to improved performance of such devices and to a better understanding of the processes involved. The work described in this report covers the design, development and field testing of equipment to satisfy this measurement need. Specifically, the objective of the project is to produce a device capable of measuring droplet size and concentration as it exists in the gas stream in and around scrubbing systems.

Under this project, KLD Associates, Inc. developed a droplet measuring device which uses a hot wire for the sensor. As a droplet attaches to the wire, the local cooling of the wire causes an electrical pulse which is then analyzed for the droplet size. The instrument sorts the sizes with respect to six ranges or bins, and the number of droplets in each bin is accumulated to provide a droplet distribution. The probe can be placed directly in the gas stream and is connected to the electronics system via a coaxial cable. The system is designated the DC-1 Droplet Counter.

In this report, the work performed in the development of the droplet measuring device is presented. The initial effort involved a literature review to determine the desired operating characteristics for the measuring device. These specifications, which appear in Section III, provided the basis for the design and laboratory work presented in Section V. Extensive laboratory work was required to better understand the droplet-wire attachment mechanism over a wide range of droplet sizes. A special optical test apparatus was developed to calibrate the device, and, of course, a variety of droplet generating devices were used to provide drops of different sizes, concentrations and velocities.

A most important phase of the project was the field testing (Section VI) of the device in the demisters on the power generation system for the Nassau County Sewage Treatment Plant. These tests immediately demonstrated that most droplets were less than 10μm in diameter. The device was then modified to measure droplets with diameters in the range of 1μm to 600μm. In addition, the effect of flow turbulence was noted and the device altered to discriminate between turbulent noise and the actual droplet signatures. The final design of the DC-1 incorporates these modifications and other secondary features to make it more suitable for field operation.

SECTION III

DESIRED CHARACTERISTICS OF THE DROPLET MEASURING DEVICE

The initial effort under the research program was to determine the specifications and operating conditions in scrubbers and mist eliminators where the droplet measuring device would be used. These specifications refer to

- Range of droplet size
- Concentration of droplets
- Velocity of the gas
- Temperature of the gas.

Such parameters are the basic information necessary for the design and testing of the droplet measuring device for the intended applications by the EPA.

The range of these parameters was initially determined by a literature review on water droplets, scrubbers and mist eliminators. A partial listing of the more relevant documents is presented in References 1 through 18. In addition, manufacturers and users of scrubbers, demisters and gas cleaning equipment were contacted for information on the operating parameters of their equipment. These industrial contacts included visits to local sites and telephone discussions with representatives who were outside the New York City metropolitan region. The gathered information was then analyzed and the specifications established for the droplet measuring device. In the following four sections, the results from this phase of the study are presented. Also presented are some comments on the specifications in view of the field measurements. As the field work progressed, the characteristics of the droplet measuring device had to be modified, since the specification for the range of droplet size was not adequate. By extending the range of the device to smaller droplets, a better representation of the distribution in the demister was possible.

RANGE OF DROPLET SIZE

The range of droplet size was defined using (1) empirical data from the literature, (2) specifications from manufacturers, and (3) the investigation of various criteria setting limits to the attainable droplet size. The relevant criteria are:

Thermodynamic minimum size
Aerodynamic maximum size
Evaporation minimum size.

The thermodynamic minimum size criteria postulates that the amount of mechanical work required for droplet formation is inversely proportional to the droplet size. Data on commercially available nozzles shows that the efficiency in converting flow energy into droplet breakage is of the order of 1% for sizes in the 10-micron range; the efficiency increases for larger droplets. Based on these results, the minimum droplet size can be predicted for a given pressure drop across the nozzle. The aerodynamic maximum droplet size is estimated from the balance between surface tension tending to keep the drop together and the aerodynamic forces. The largest droplet size corresponds to free fall in still air with diameters reaching 8 mm to 9 mm. Practical conditions encountered in scrubbers, with higher velocities and substantial turbulence, reduces the maximum possible droplet diameter down to one or two millimeters. The evaporation of droplet produces a reduction in diameter in such a way that the distribution becomes time dependent. The life of small droplets depends on the gas temperature and humidity, being, in general, rather short of the order of one second.

Using data on direct droplet measurement, as provided by manufacturers and investigators, the drop size distribution for cone nozzles, rotating disk and Venturi scrubber was analyzed. The result of this study shows that most of the droplets would be within the range of 10μm to 600μm. This range was used for the initial development of the device. However, the field measurements with the device indicated that most of the droplets in the scrubber (in the region of its demister) were less than 10μm. As a result of field work, the instrument was modified to operate over the range of 1μm to about 600μm.

CONCENTRATION OF DROPLETS

Values of droplet concentrations have been measured by several investigators and computed for a variety of situations. The maximum concentration was found to vary over several orders of magnitude. The following conclusions may be reached from the available data:

- Higher concentrations are achieved with small droplet diameters; the limit is set by either evaporation or coagulation due to Brownian motion.
- Monodispersions achieve larger concentration than polydispersion.
- Turbulence of the flow reduces substantially the concentration, as compared to a quiescent suspension.
- Computed maximum concentrations are orders of magnitude larger than measured values.

For the design of the instrument, the maximum droplet concentration measured in fog was adopted, with an actual value of 500 drops/cm^3. Such extreme conditions were observed in still air with droplets in the 10-micron diameter range. This value of concentration is higher than the data encountered in scrubbers where polydispersions and a strong turbulence are present.

FLOW VELOCITY

This parameter varies within wide limits and two basic types of scrubbers were considered; the spray scrubbers and the Venturi scrubber. The first type is characterized by a low velocity of the flow with substantial time for the fluid-contaminant interaction.

Venturi scrubbers operate at high velocity; the gas flow is totally or partially responsible for the generation of small droplets. Flow conditions are changed downstream to generate settling conditions.

A survey of typical installations shows that gas velocities between .6 and 2 m/sec (2 and 6 ft/sec) are encountered in spray scrubbers and 40 to 100 m/sec on the venturi throat. The droplet measuring device with a standard probe is designed to operate with a flow velocity up to 3 m/sec (~10 ft/sec). At higher velocities, the flow may become very turbulent and errors in the measured data can result. To make measurements at high velocity, a special probe needs to be developed.

TEMPERATURE OF THE GAS

The temperature of the gas can vary over a wide range in scrubbers. For certain facilities, a portion of the injected water is used to cool the gas and the proper scrubber action takes place downstream where the gas temperature has been substantially reduced. On the lower side, freezing of the water sets a minimum limit to the flow temperature. Hence, a temperature range between 20°C and 100°C is representative of conditions to be encountered in typical scrubbers and mist eliminators. This range was used in the development of the probe for droplet measurements. All the field studies were made at temperatures within this range.

SECTION IV

PRINCIPLE OF OPERATION AND DESCRIPTION OF THE DC-1

The operation of the hot wire droplet sensor DC-1 is based upon the localized heat transfer and cooling which is caused by the droplet impinging on a small hot wire or surface.

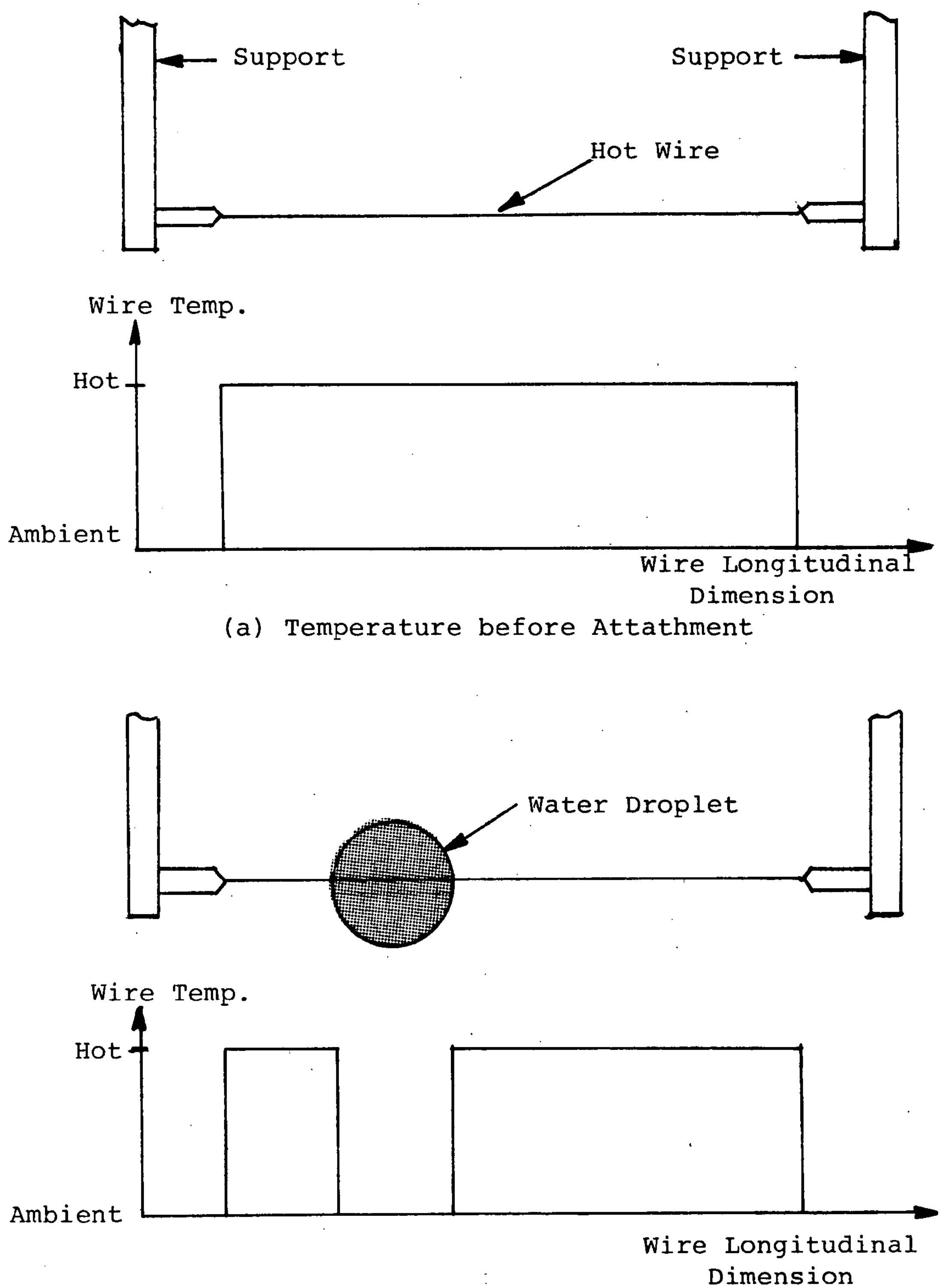
The concept is schematically shown in Figure 1, where the hot wire sensor and its longitudinal temperature distribution is shown (a) before and (b) after a water droplet (cross-hatched circle) attaches. The electrical resistance of the wire is a function of the wire temperature, which in situation (a) is high and substantially uniform along the wire. In situation (b) the portion of the wire covered by the droplet is cooled to approximately the droplet temperature. A constant electrical current flows along the wire creating a measurable voltage drop at the wire support. The high voltage encountered before droplet attachment (a) is reduced for (b) in direct proportion to the cooled length of wire; i.e. the droplet diameter. The electrical energy delivered to the wire evaporates the water, leaving the sensor clean and ready for further interaction.

The above description of the operating principle is an idealization and in actual practice many aspects influence the electrical signal. For example, heat conduction in the radial and longitudinal directions can have an important effect on the electrical signal. These effects were extensively investigated analytically and experimentally. The analytical studies (described in section V) guided our research in the selection of materials which are used in the probe.

DESCRIPTION OF THE DC-1

The instrument consists of a box containing the circuitry for analyzing the electrical pulses and a hot-wire probe to be located in the region where the water droplets are present. A single coaxial cable with lengths up to fifty feet is used to connect the probe to the electronic circuit.

The probe was designed around a five micron platinum wire for measuring droplets in the range from 1μm to 600μm. The electronic circuit for analyzing the pulses from the probe



(a) Temperature before Attathment

(b) Temperature after Attachment

Figure 1: Principle of Operation of the Sensor (Idealized)

is designed to classify the droplets into six subranges or bins. The droplet size range in each bin can be modified by changing a plug-in ladder network. For both the probe and electronic circuit, particular attention was devoted to:

- Simplicity of the construction
- Small size of the instrument
- Operation by a non-skilled operator
- Clear display of the measured parameters.

Electronic Subsystem

The front end and conditioner (FECA) of the instrument (Figure 2) is a bridge able to operate in three modes:

- temperature
- velocity
- droplet count.

For the temperature mode, the probe is fed with a low current so as not to introduce appreciable electrical heating; the wire assumes the temperature of the surrounding medium and the instrument may be used as a sensitive thermometer. In the velocity mode, the probe current is substantial and the probe wire is heated well above the surrounding medium. Due to air movements relative to the probe, a signal is generated in proportion to the fluid velocity. In the count mode, a value of reference resistance 1.5 larger than the corresponding cold probe resistance is set. A feedback power amplifier supplies sufficient current to normally balance the bridge. However, fast fluctuation of the sensor temperature due to droplet interaction is not compensated by this power amplifier and the corresponding electrical signal appears at the bridge output. This output signal is used in the remaining portion of the electronic circuit to determine droplet size.

The signal from the FECA goes into an amplifier and afterwards splits in two directions:

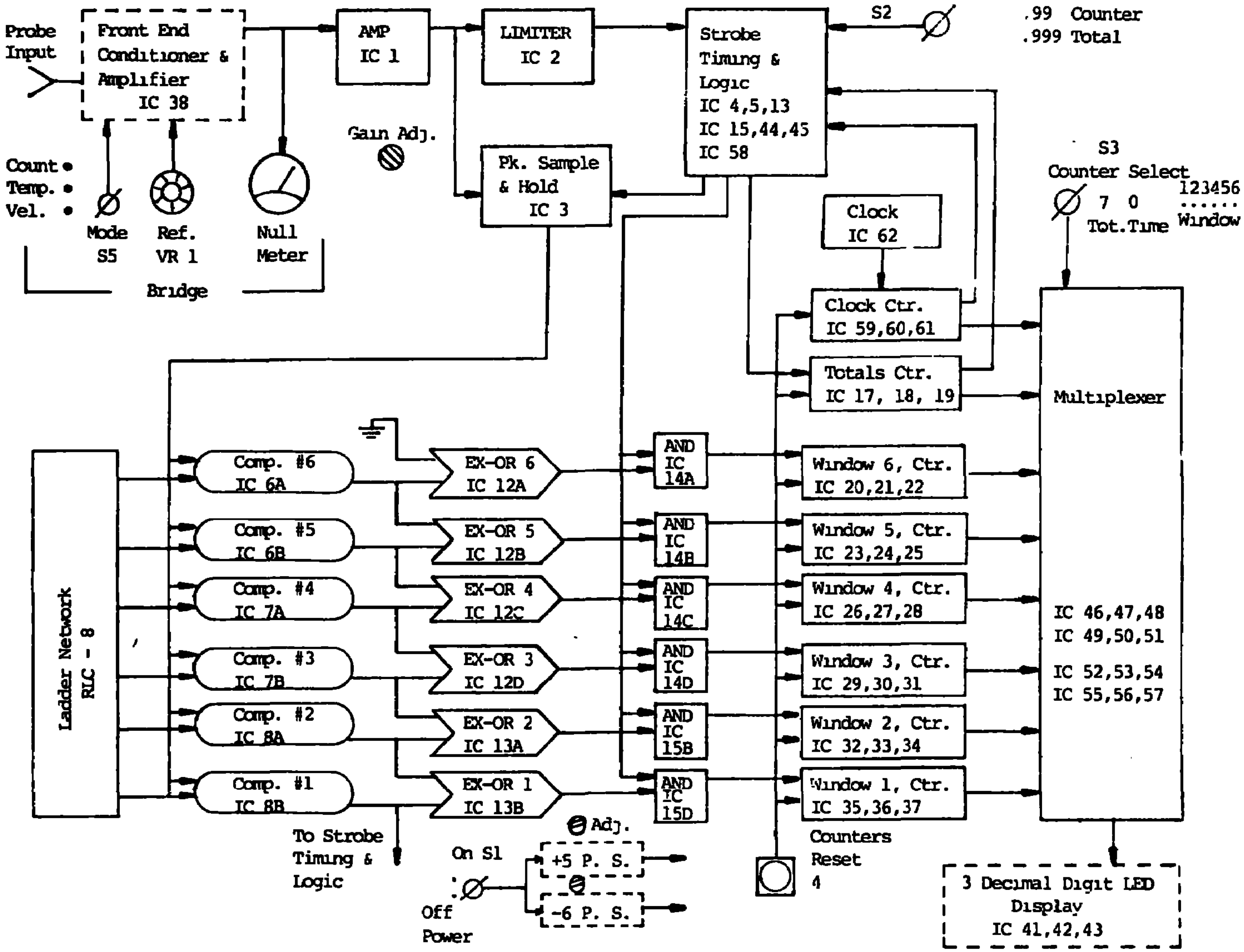


Figure 2: Model DC-1 Droplet Counter Block Diagram

- to a LIMITER, and
- to PEAK SAMPLE AND HOLD circuit .

The LIMITER triggers the sampling when the electrical signal has a fast front and exceeds the background noise level. The droplet signal amplitude is determined at the PEAK SAMPLE AND HOLD (PSH) circuit which provides a square pulse with an amplitude directly proportional to the signal peak and with a duration of two milliseconds.

The signal from the PSH goes to six COMPARATORS. Each comparator has a fixed D.C. reference established by a RESISTANCE LADDER NETWORK, which determines the droplet diameter intervals for each one of the six channels. Several ladder networks are available and can be easily changed since the network is a plug-in circuit. When the peak detector signal is greater than the reference signal at one comparator but less than the reference level at the adjacent comparator, the pertinent logic provides a signal output at this particular channel only. This output signal increments a counter which is stored in a channel counter. The TOTALS counter is activated whenever any one of the channels is activated. Thus the sum of all the channels counters equals the total count.

The counting process is started by the operator by pressing a reset button which also activates a CLOCK with a .1 second resolution. The counting process stops when either 99 or 999 droplets are counted in the TOTALS counter, or when 99.9 seconds has been reached, whichever occurs first. The results of this counting function are stored until the reset button is pressed again.

At any time during the counting cycle, or at its completion, the content of the counters may be displayed, one at a time. This selection is performed with a thumb wheel switch which controls the multiplexer interfacing between the selected counter and the three decimal digit display.

All the instrument controls and display are mounted in the front panel. The finished instrument is shown in Figure 3.

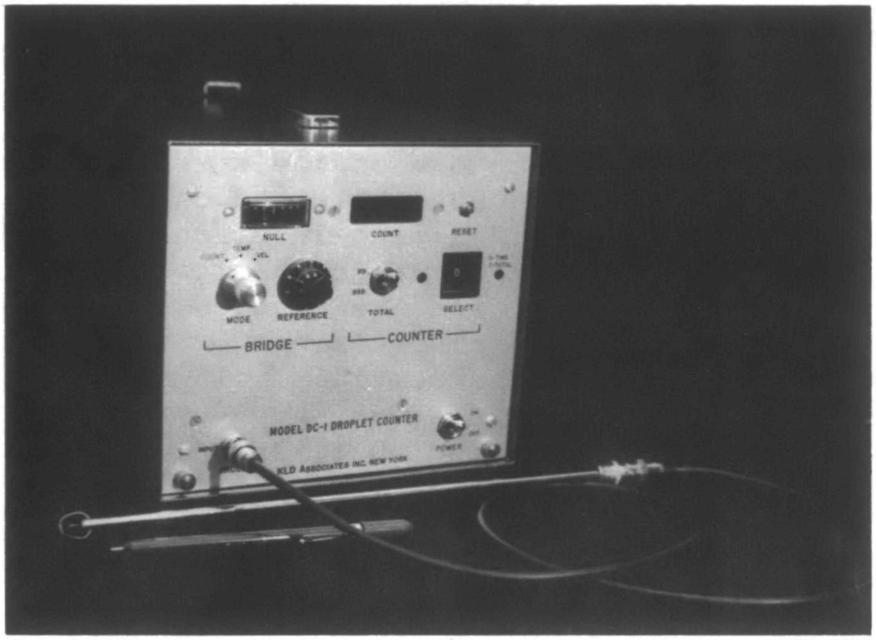


FIGURE 3: PHOTOGRAPH OF INSTRUMENT AND PROBE

Probe

The wire adopted for the sensor is platinum with a five microns diameter (.0002 inches).

In its original form, the platinum wire is covered with a thick (.1 mm; .004 inches) layer of silver. A piece of this wire is soldered to the probe and the silver is removed with nitric acid. During this etching process, the sensor electrical resistance is controlled in order to achieve four ohms resistance. The length of exposed platinum wire is approximately one millimeter.

The body of the probe is a metallic tube 6mm. (.25 inches) in diameter and 300 mm (12 inches) in length. The assembled probe is shown in Figure 3. The probe is connected to the electronic subassembly with a coaxial cable.

USE OF THE INSTRUMENT

The setting of the instrument and interpretation of the data requires the measurement of flow temperature, flow velocity, counting of droplets and timing of the operation. All these measurements are performed with this instrument without requiring any additional components. A discussion of each function follows.

Flow Temperature Measurement

The resistance of the wire sensor varies with its temperature, and this variation is used to monitor the flow temperature. Both the electrical current flowing in the sensor and the surrounding fluid determine the equilibrium temperature of the sensor. With the function selector switch in the TEMP position, the sensor operates on a very low electrical current, thereby its joule heating is negligible. The instrument acts as a sensitive thermometer that is calibrated to the resistance required to achieve equilibrium of the electrical bridge. The resistance is measured with the potentiometer mounted on the front panel.

In general, a temperature versus resistance calibration curve would be required for each probe. However, a simpler procedure is to measure the sensor resistance at the known ambient temperature and compute the sensor resistance at any other temperature using the temperature coefficient corresponding to platinum, for which $\alpha = .0038 \frac{1}{°C}$.

To simplify the computation, a temperature calibration is presented in Figure 4.

Flow Velocity Measurement

The flow velocity is measured by imposing a high electrical current on the sensor, raising its temperature approximately 150° above the ambient. The reference resistance (potentiometer) required to balance the bridge provides an indication of the actual temperature of the probe. Thermal equilibrium is reached when the electrical input power balances the heat losses to the air surrounding the sensor; such a heat transfer balance is a strong function of the air velocity relative to the probe. A velocity calibration curve is obtained by setting the function selector switch to VEL and exposing the sensor to known flow velocities while the corresponding electrical resistances are measured. Such a calibration is valid for sensors of equal diameter and material. For the five-microns-diameter platinum sensor, the calibration performed in the laboratory is presented in Figure 5. It should be noticed that changes in sensor resistance are substantial at low flow velocities, up to approximately one meter per second (3 ft per second). For higher flow velocities small errors in the resistance result in large errors in velocity. As a result of this behavior, the resistance measured at zero velocity must be precisely determined, to avoid unacceptable errors at high velocity.

A satisfactory approach to measure the no-flow resistance was developed using a shield which encloses the probe. The shielded probe then is introduced into the flow and left in place until thermal equilibrium is reached. The potentiometer is adjusted to null the bridge circuit and the value of the reference resistance R_{hss} is recorded. The shield is then removed and the probe is reinserted into the flow with the sensor axis perpendicular to the flow. The potentiometer is readjusted to null the electrical bridge and the value of R_{hsv} is recorded. The velocity is then determined from the calibration curve shown in Figure 5.

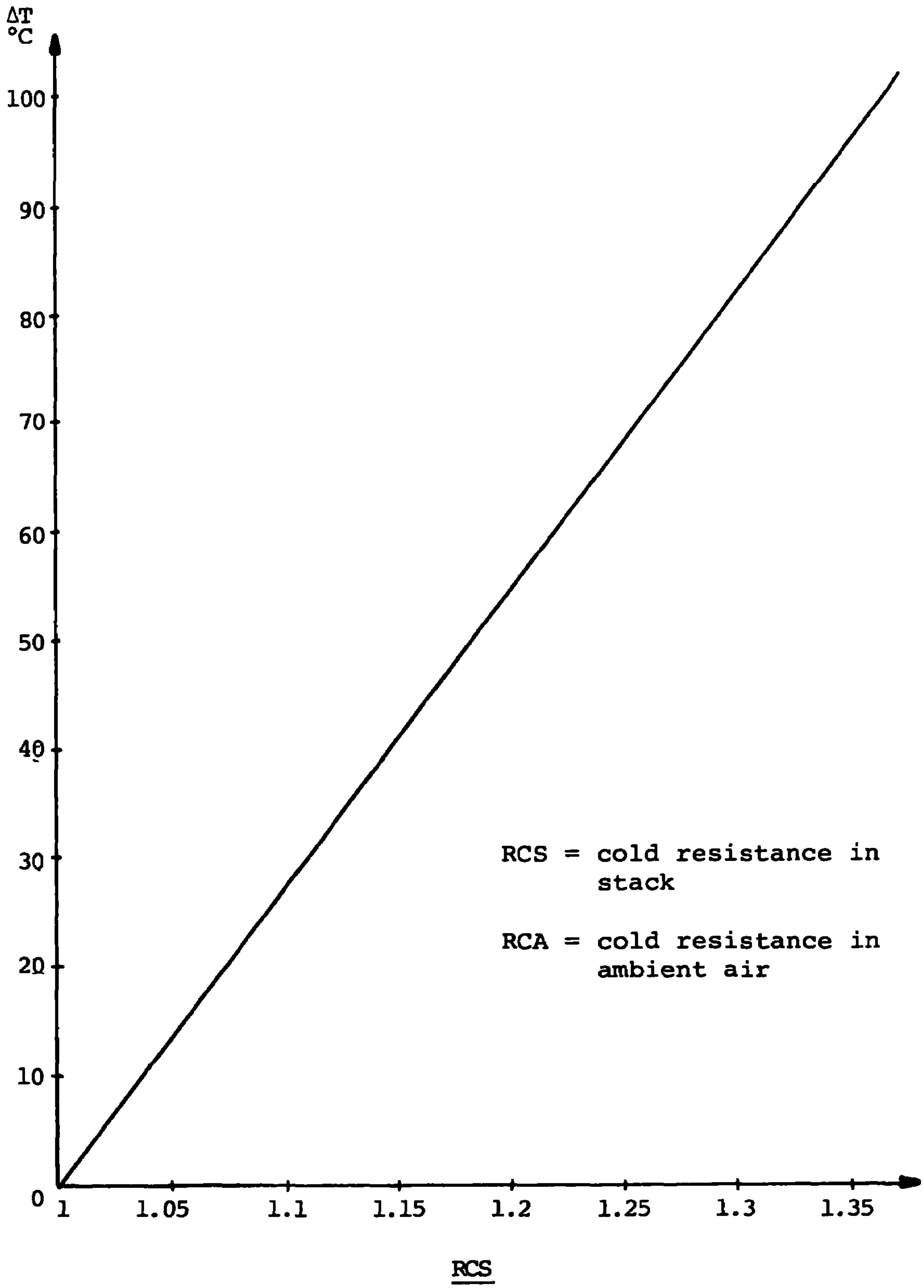


Figure 4: Temperature Calibration Curve

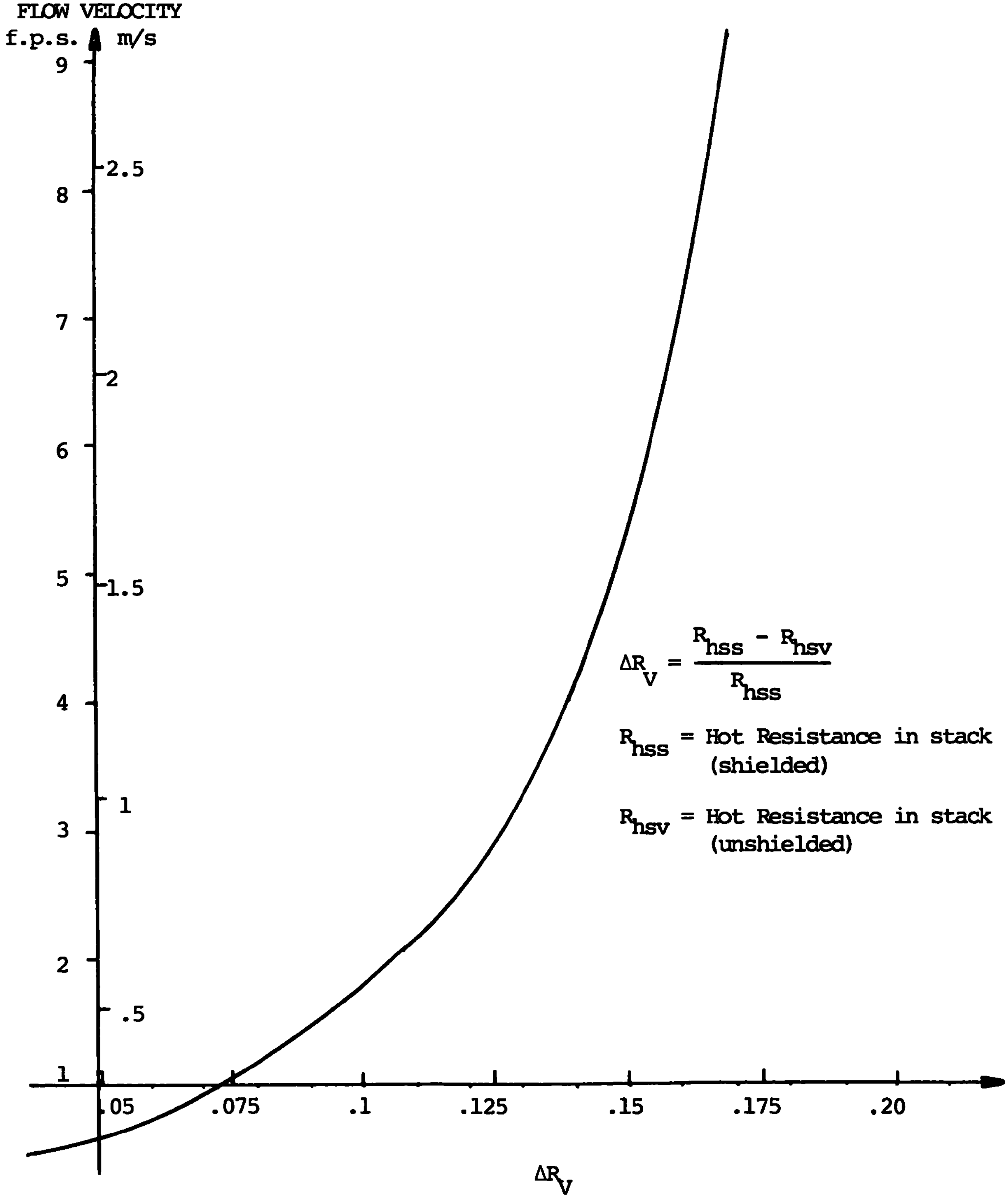


Figure 5: Air Velocity Calibration

Droplet Counting and Sizing

As previously described, the flow temperature is measured with the function selector switch on TEM. The reference resistance, RCS, from the temperature measurement is increased by a factor of 1.5 and this value set on the potentiometer. The function selector switch is set to COUNT and the bridge balance meter will automatically balance itself because the feedback power amplifier is in the circuit.

The reset button is pressed to clear all counters and the interaction of droplets with the sensor may be observed with the channel switch in position 7, corresponding to TOTAL count. After the counting cycle is finished (after 99 or 999 droplets, as selected by the operator, or 99.9 seconds interval as dictated by the instrument clock), the number of droplets in each one of the six channels plus the time interval are recorded. For each channel the average droplet diameter D_i can be computed using the resistance ladder network values.

The droplet concentration n_i corresponding to the channels is computed with the expression:

$$n_i = \frac{N_i}{V \cdot t \cdot \ell \quad (2D_i + d)} \quad \text{Drop/cm}^3 \qquad (i = 1,6)$$

where

N_i droplets counted in the i^{th} channel

V flow velocity (cm/sec)

t time interval (sec)

ℓ sensor length (cm)

D_i average droplet diameter for the i^{th} channel

d sensor wire diameter; 5×10^{-4} cm

The sensor length may be measured under a low power microscope or its value computed from the cold resistance value, since a five micron platinum wire has a resistance of 39 ohms per cm. The sensors delivered with the instruments are 1 cm long.

SECTION V

LABORATORY AND ANALYTICAL STUDIES

As presented in Section IV, the principle of operation of the DC-1 appears simple, but to achieve a good correlation between liquid droplet sizes and the amplitude of the electrical signal, several complicated effects required careful investigation. An important aspect of this project was the verification of underlying assumptions behind the principle of operation. For example, the heat transfer between the wire and droplet is much more complicated than the idealized model of Section IV. Also, the mechanism of droplet attachment bears an important relationship to the performance of the device. These types of investigation were necessary to optimize the performance of the instrument and to better define its range of operation. Some of these studies were analytical while others were experimental.

A discussion of the laboratory apparatus to calibrate the DC-1 is also included. An essential part of the laboratory equipment is the means of generating droplets in a known size range. Several techniques were required for this project as presented in the latter part of this section.

The laboratory experiments of the sensor principle involved three basic studies:

- Droplet-wire attachment mechanism
- Amplitude and shape of the electrical signal
- Hot-wire versus hot-film sensors.

Each of these topics is described below.

Droplet and Wire Attachment Mechanism

Ideally, each droplet should surround the wire and establish a close thermal contact over a well-defined portion of the wire. An ample amount of theoretical and experimental information is available in connection with the capture of droplets by bodies of different geometry and materials. The majority of this work deals with the performance of filters. However, little, if any, information is available on the droplet capture phenomenon when the wire is heated to a substantial temperature. Consequently, work was done in the laboratory to gain knowledge of the attachment mechanism under condition of heating.

The attachment of droplets to wires of different diameters and temperatures was observed using a low magnification microscope. A high speed electronic flash synchronized with the electrical pulses from the probe permitted photographing various stages of droplet attachment; and, from these photographs, a thorough understanding of the phenomenon was developed. Result of such work shows that droplets with a diameter larger than twice the wire diameter are centered with respect to the wire, and the droplet shape remains spherical. No tendency to slide along the wire was detected. During the evaporation of the liquid, the shape remains approximately spherical. It was observed that high speed droplets are sliced by the wire. The thin water film left on the wire causes a thermal effect similar to the actual droplet. Of course, the evaporation time for this thin film is substantially shorter than an attached droplet, but no appreciable difference in the peak electrical signal is detected.

As computations predict, the experimentally observed surface tension effects are stronger than inertial effects for small droplets. Droplets in the millimeter diameter range experienced an acceleration of a few "g" when touching a 10-micron diameter wire. Accelerations of the order of 1,000 "g" are estimated for droplets approximately 10μm in diameter. The effect of eccentric collision between droplets and the wire is not a problem for small droplets moving at slow speed. For instance, at a velocity of 3 m/sec (10 ft/sec), the electrical signal for droplets 100μm in diameter was unaffected by eccentricity collisions. For the same velocity, the 1 mm diameter droplets produced electrical signals which were significantly affected by eccentric collisions.

In order to study this effect of eccentric collisions, a stream of 300 micron drops was generated with a vibrating rod. The sensor was mounted with its axis perpendicular to the trajectory of the droplets and moved sidewise to achieve a variety of eccentric collision conditions. The test results from one set of experiments in the laboratory are shown in Figure 6. The results are for droplets

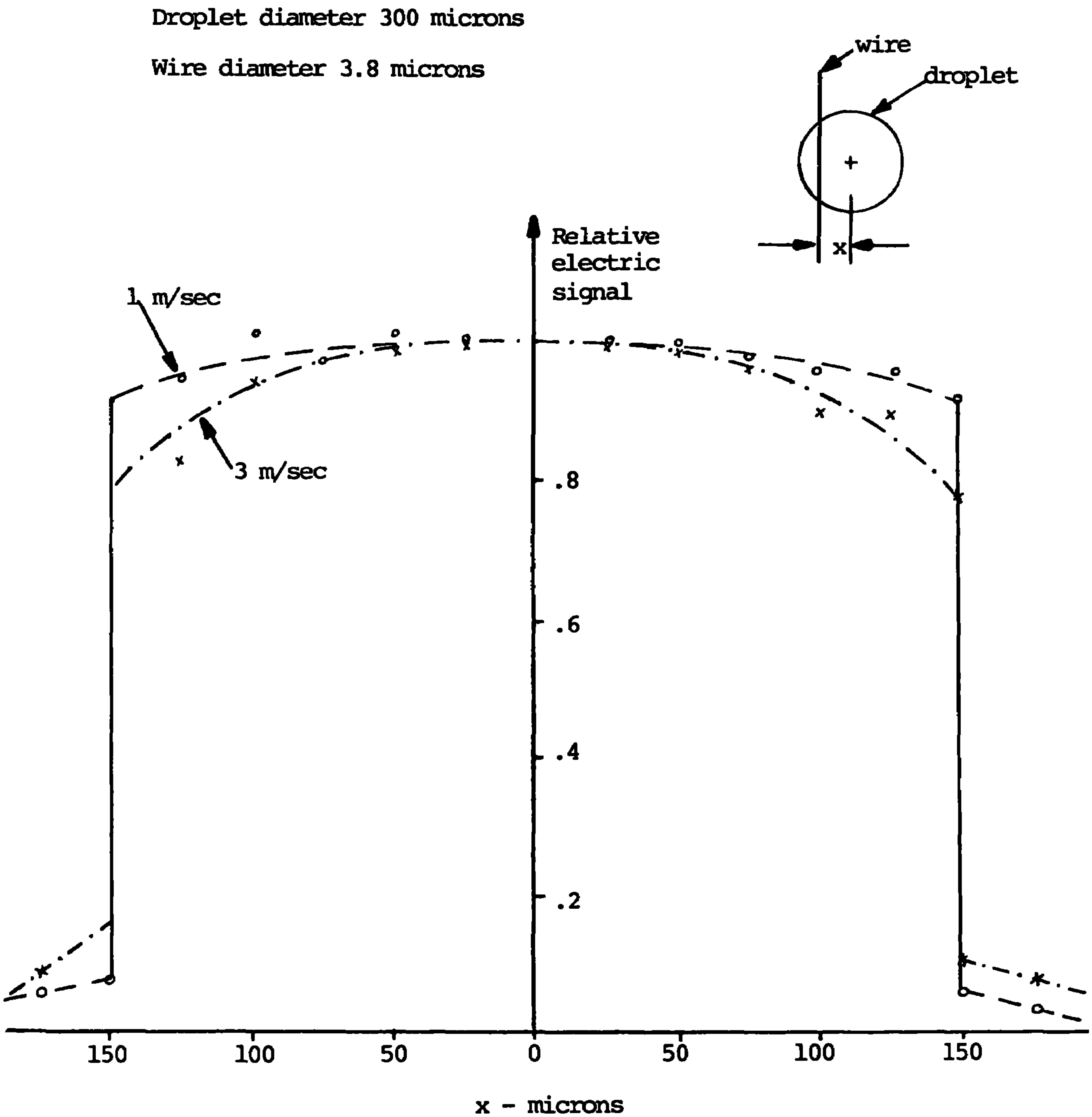


Figure 6: Effect of Eccentric Collision on Signal Output

300μm in diameter and for velocities of 1 m/sec. and 3 m/sec. The electrical signal is normalized with respect to the peak amplitude corresponding to a perfectly centered collision. Each of the plotted points represents the average value from several experiments. The small scattering of the data is due to small variation in droplet size and fluctuation in the trajectory. The recorded data for the eccentricity $\chi \geq 150\mu m$ was repeatedly checked and verified. These small signals are due to the aerodynamic flow attached to the droplets and was readily eliminated from the signal processing by selective filtering.

These studies determine the operating limitations for the measurement of large droplets. For large droplets (near 600μm), the flow velocity must be low (1 to 2 m/sec) to allow the droplet to center itself. For smaller droplets the flow velocity may be substantially increased without affecting the attachment mechanism. The limitation arises from the air turbulence which, at high flow velocity, induces high frequency electrical noise masking the droplet signal. Tests performed on low turbulence flow at 50 meters per second with droplets 20 microns in diameter did not show appreciable errors as compared to the results obtained for a flow velocity of 3 meters per second.

Amplitude and Shape of the Electrical Signal

For the purpose of discussing the electrical response of the sensor to interacting water droplets and in order to identify the relevant parameters, this discussion is restricted to hot wire sensors, excluding hot films. Assume a wire of length ℓ and diameter, d. The resistance, R, of such wire at a temperature, t, is related to its resistance, R_o, at a reference temperature by

$$R = R_o [1 + k (t - t_o)]$$

where k is the resistance temperature coefficient.

A thermal equilibrium condition is established between the electrical heating of the wire and the heat transfer to the gas stream. When a water droplet of diameter, D, attaches to the wire, the thermal equilibrium condition of the wire-droplet is altered. Except for very small sizes, the water droplet thermal capacity is much larger than the thermal capacity of the wetted portion of wire. Also the thermal conductivity of both water and wire material is so high that, for all practical purposes, the temperature of the wetted portion of wire is made equal to the water temperature. Then the resulting voltage pulse, δV, measured at the wire terminal as a result of the droplet attachment is

$$\delta V = - R_o I k \frac{D}{\chi} (t - t_o)$$

where I is the electrical current flowing in the wire. The same electrical current heats the droplet, delivering an electrical power

$$W = R_o \frac{D}{\chi} I^2$$

which increases the droplet temperature and causes evaporation.

A typical electric signal obtained during the droplet-wire interaction is shown in Figure 7. The initial fast decay during the droplet attachment depends on the attaching mechanism and is completed in approximately ten microseconds.

After attachment, the droplet is heated, increasing its temperature almost linearly as a function of time until evaporation and shrinkage takes place. The duration of the signal is a function of the droplet size and the power dissipated per unit length of wire. As a rule, the time required for a complete evaporation is proportional to the square of the droplet diameter. By increasing the wire temperature, the evaporation time is decreased.
Another important factor was observed during this study; large droplets are in general sliced through by the wire as a result of dominance of inertial forces over surface tension forces. The water layer which is momentarily left on the wire covers a length of wire equal to the droplet diameter. As a result, the peak electrical signal during the attachment portion is almost unaffected while the decay after the peak is substantially shorter.

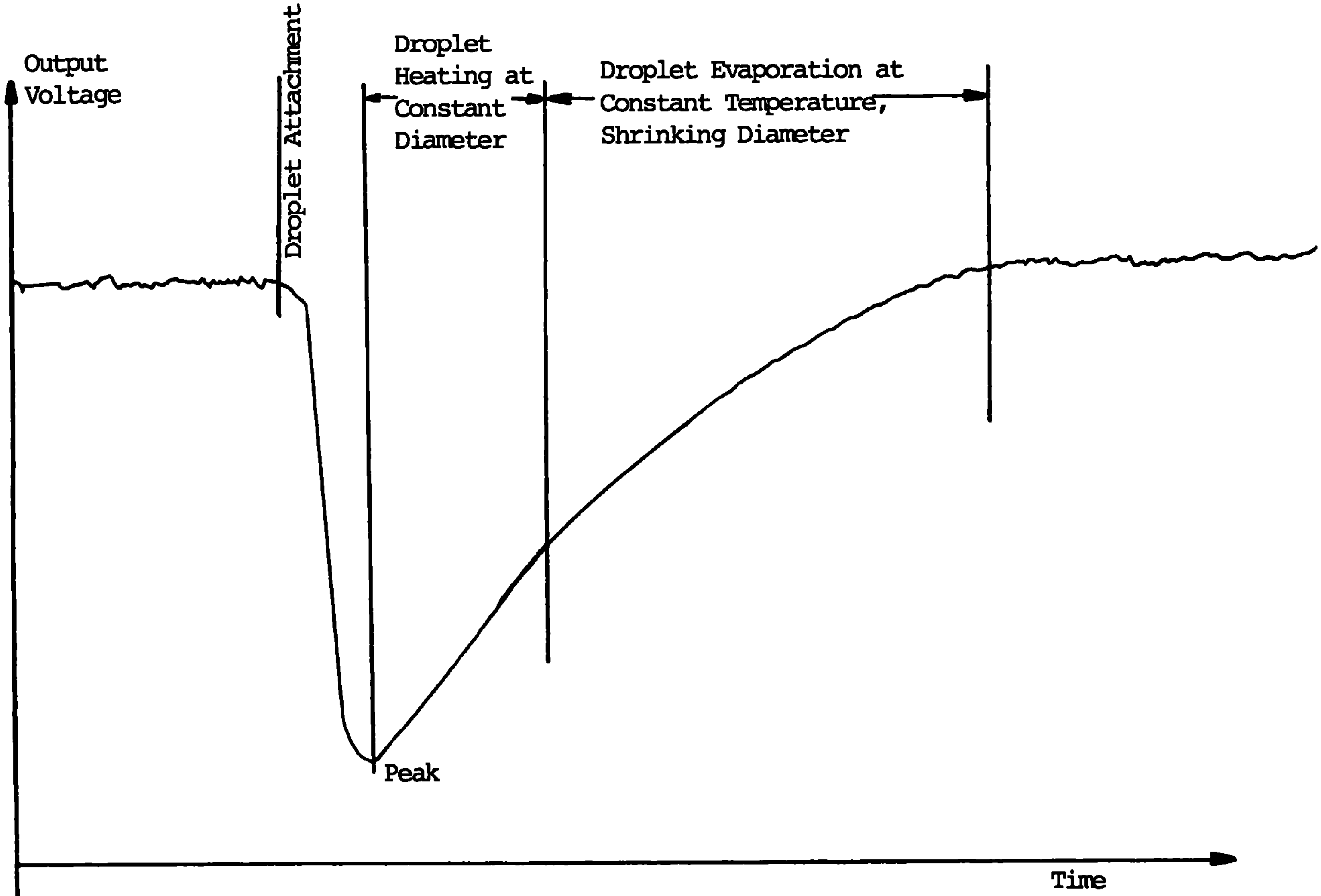


Figure 7: Typical Sensor Electrical Output

For the conditions of operation selected for the DC-1, the average signal duration is of the order of four milliseconds. This time interval does not necessarily reduce the sampling rate to four milliseconds between droplets. Other droplets interacting with other portions of the wire generate the proper peak electrical signal, which occurs in the initial 10 microseconds. If two droplets are attached to a small portion of wire, the electrical signal is less than the calibrated amplitude for each drop. The final configuration of the instrument is designed to measure up to 500 droplets per second.

The sensitivity of the probe (ratio of peak voltage, V, to captured droplet diameter, D) is given by

$$\frac{V}{D} = \frac{RI}{\ell} (n-1)$$

where

R is the probe operating resistance (hot)

I is the current flow in the sensor

ℓ is the length of the heated wire

n is the overheat ratio $\frac{R}{R_o} = 1.5$

Typical values of these parameters for a five-micron platinum wire are:

R = 4 ohms

I = .04 Amps

ℓ = 1 mm

For these values, the sensitivity of the probe becomes

$$\frac{V}{D} = 12 \quad \text{(microvolts per micron)}$$

For droplets with $D \leq 2d$ (d is the wire diameter), this law does not apply. For such small drops the signal amplitude is reduced because the thermal inertia of the wire is important as compared to the thermal inertia of the droplet, resulting only in a partial cooling of the sensor. The change in behavior for the small drops is clearly shown by the attached calibration curve (Figure 8). In the region above 20μm, the actual probe sensitivity is less than the theoretical value because of the electronic circuit (filtering and feedback power amplifier) which has been introduced in the implementation of the final design.

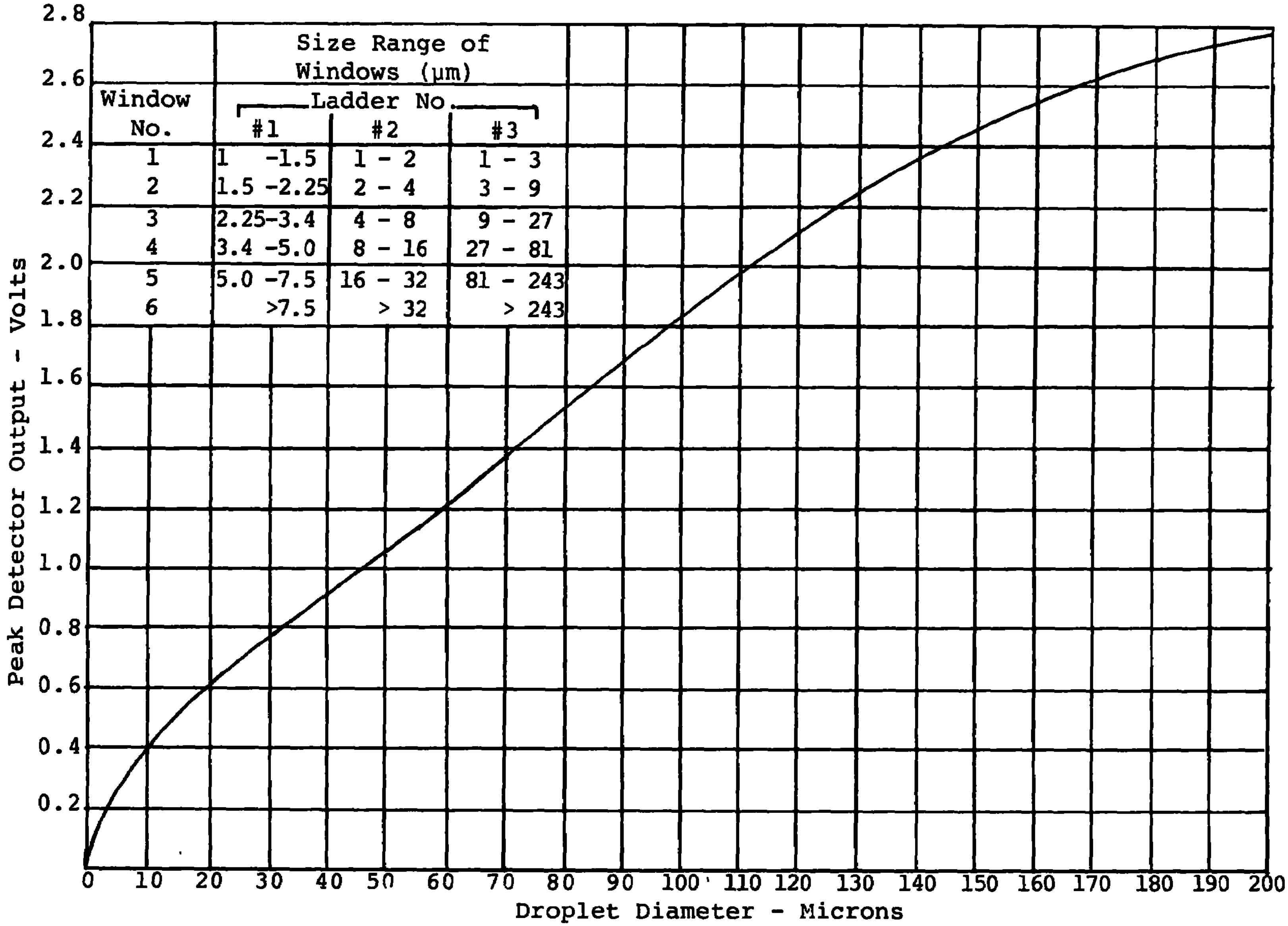
Hot Wire Versus Hot Film Sensor

The laboratory work with a probe constructed from a small diameter wire (5μm) is always susceptible to mechanical breakage during handling and use. Consequently, several concepts were considered to make the probe more rugged. The use of a hot-film probe appeared most advantageous and its operating characteristics were investigated experimentally in the laboratory.

The film probe is very rugged and operated for a long period of time without any mechanical failure. However, the response characteristic of the film probe is inferior to the wire probe. Specifically,

1. The film probe has insufficient sensitivity for small droplets. The electrical response of the sensor to small droplets decays rather rapidly for $D < 2d$. For the wire, such conditions are reached for droplets below ten microns. For commonly available films, almost the entire specified range of droplet diameter (1μm to 600μm) falls under these unfavorable conditions.

2. There is a large contact surface between the droplets and film. Consequently, large droplets tend to attach to the film and can only be removed by evaporation. The evaporation can require up to 1/10 of a second during which time a portion of the probe cannot be



Window No.	Size Range of Windows (μm) Ladder No. #1	#2	#3
1	1 -1.5	1 - 2	1 - 3
2	1.5 -2.25	2 - 4	3 - 9
3	2.25-3.4	4 - 8	9 - 27
4	3.4 -5.0	8 - 16	27 - 81
5	5.0 -7.5	16 - 32	81 - 243
6	>7.5	> 32	> 243

Figure 8: Calibration Curve

used for droplet sensing. Therefore, the film probe tends to have a low sampling rate.

Because of these disadvantages, the wire probe is considered more suitable for measurements in scrubbers and demisters.

ANALYTICAL STUDIES

The analytical studies performed under this project were used to interpret experimental results and to assist in the selection of the material for the sensor. Several studies of the transient thermal response of the probe were performed.

Initially, a study of the radial temperature distribution was undertaken assuming a one-dimensional analysis with various boundary conditions representing the interface between the wire and the droplet.

Using tungsten as the material for the transducers, the results showed that the radial temperature distribution becomes approximately uniform in less than 10^{-6} seconds after the droplet attaches. Consequently, the assumption that the wire is at the droplet temperature appears justified in the vicinity of the droplet.

Another analysis was undertaken to investigate the longitudinal heat transfer along the wire and to establish the validity of the idealized model described in Section IV. This analysis includes the heat transfer to the surrounding air. The differential equation representing the problem is

$$\rho c_p T_t = k\, T_{xx} + Q - \bar{h}\,(T - T_a)$$

where

Q is a source term for the electrical heating

$\bar{h}\,(T - T_a)$ is the heat transfer from the wire to the air

The equation was analytically solved for a droplet of generic size at some position x_o along the wire. With the general analysis, it is possible to study the longitudinal heat transfer from the instant of droplet attachment until complete evaporation. However, the laboratory measurements are restricted to a few milliseconds after droplet attachment, and consequently, the analysis was further simplified to this short-time interval. Then the solution becomes:

$$\theta = \frac{x}{2\sqrt{\pi\alpha}} \int_0^t \frac{\theta_d(t-\tau)}{\tau^{3/2}} \exp\left[- \gamma\tau - \frac{\eta(x)}{\tau}\right] d\tau$$

where

$$\gamma = \frac{H}{\rho c_p} \qquad \left[\frac{1}{sec}\right]$$

$$\eta(x) = \frac{x^2}{4\alpha} \qquad [sec]$$

$$\alpha = \frac{k}{\rho c_p} \qquad \left[\frac{in^2}{sec}\right]$$

$$\theta = T-T_o \qquad [°F]$$

$\theta_d = T_d-T_o$; T_d droplet temperatures [°F]

H = equivalent steady state film coefficient

$$\left[\frac{BTU}{in^3 sec\ °F}\right]$$

With this model, the time and space distribution of the wire temperature was determined for three candidate materials: tungsten, platinum and nickel. The results and conclusions from the analytic study are:

1. An equilibrium longitudinal temperature distribution is established in a few milliseconds. The radial cooling of the wire is much faster than the longitudinal cooling.

2. By eliminating electrical signals at frequencies below two kHz most of the effects of the longitudinal cooling on peak signal amplitude are removed.

3. Nickel has the most suitable properties (e.g., low value of diffusivity and low value of density), leading to a minimum longitudinal cooling. However, nickel wire is not readily available in small diameters except for nichrome alloy, which has an unacceptable low temperature coefficient. Tungsten wire exhibited the worst thermal behavior of the three materials. Platinum wire is a good compromise, since its thermal response was almost equivalent to nickel.

Tests performed in the laboratory with both tungsten and platinum wire corroborate the analytical study.

USEFUL LIFE OF SENSORS

A variety of tests were performed to determine the useful operating life of the sensors. Several sensors with promising performance characteristics were subjected to continuous operation under a spray operating with tap water. The wire temperature of operation was set for a convenient signal amplitude ($\sim$150°C) while the wire resistance was monitored. Observation under a medium power microscope was used to detect accumulation of contaminants and mechanical damage.

Specifically, the following sensors were used:

3.8 microns diameter tungsten wire

5 microns diameter tungsten wire

- 20 microns diameter tungsten wire
- .5 mm diameter ceramic rod with a platinum film and quartz coating
- 3 microns diameter platinum wire
- 5 microns diameter platinum wire

In all cases accumulations of deposits on the wire were detected after one or two hours operation. After ten hours of operation a change in the operating characteristics was detected. The hot wire resistance measured was decreased, indicating a stronger cooling due to the dirt accumulation. Observation under a microscope showed that the accumulation was larger and less uniform on tungsten than on the other sensors.

Tungsten wires with diameters of 3.8 and 5 microns lasted, on the average, six and ten hours respectively before breakage. Overheat values of 1.4, 1.5 and 1.6 were used and a slight tendency to reduce the sensor life was correlated to the higher overheat. The reasons for the mechanical failure are not clear; gradual reduction on the wire cross-section due to corrosion does not seem to be significant since no important changes in the cold wire resistance were noticed prior to breakage.

Platinum wire (3μm in diameter) lasted, on the average, twelve hours before breakage. Five microns platinum wire seldom broke even after fifteen hours of operation with substantial accumulation of dirt.

Film sensors did not break and showed accumulation of dirt after twenty-five to thirty hours of continuous operation.

EXPERIMENTAL APPARATUS

The laboratory experiments with the droplet sensor required two types of basic equipment:

1) Apparatus for studying the attachment mechanism of the droplet to the wire and a means of calibrating the sensor

2) Equipment to generate droplets in the size range of interest.

In the following two sections, the equipment for the laboratory experiments is described.

Equipment for Studying Droplet Attachment and Calibration

The function of the apparatus is to provide information on the diameter of the water droplet interacting with the sensor together with the corresponding electrical signal. The resulting correlation between the amplitude of the electrical signal and the droplet diameter is the data necessary to calibrate the sensor.

The approach adopted for these experiments was optical, where the interacting droplet is observed under a microscope during its attachment to the hot wire. A photographic camera records the image of both the wire and the droplet, and a permanent record is obtained to study the attachment mechanism and to provide the calibration data. Since the interaction time is short, an electronic flash is used to stop the motion at the instant of droplet contact, thereby no appreciable shrinkage due to evaporation takes place and accurate calibration data is obtained. The duration of the flash is approximately one microsecond, which is compatible with movement and shrinkage of the droplet in the diameter range of interest. The electronic flash provides a bright background for the hot wire; both wire and droplet appear dark with sharp boundaries. Several other illumination arrangements were studied in the laboratory for dealing with droplets which have a diameter less than 10µm. Such small droplets are difficult to locate along the wire which is itself 5µm in diameter. Figure 9 shows the arrangement of the main components. The photographic camera is a Polaroid operating with Type 107 film. Magnifications up to 100 were used; the limits being set by the need to photograph the entire wire length (~1 mm) into the 10 cm diagonal linear dimension of the photograph. A standard Leitz compound microscope was used with a x50 magnification in the objective lens. The microscope specimen holder was adapted for the support of the probe, and advantage was taken of the micrometric positioning set-up to properly position the wire in the microscope field.

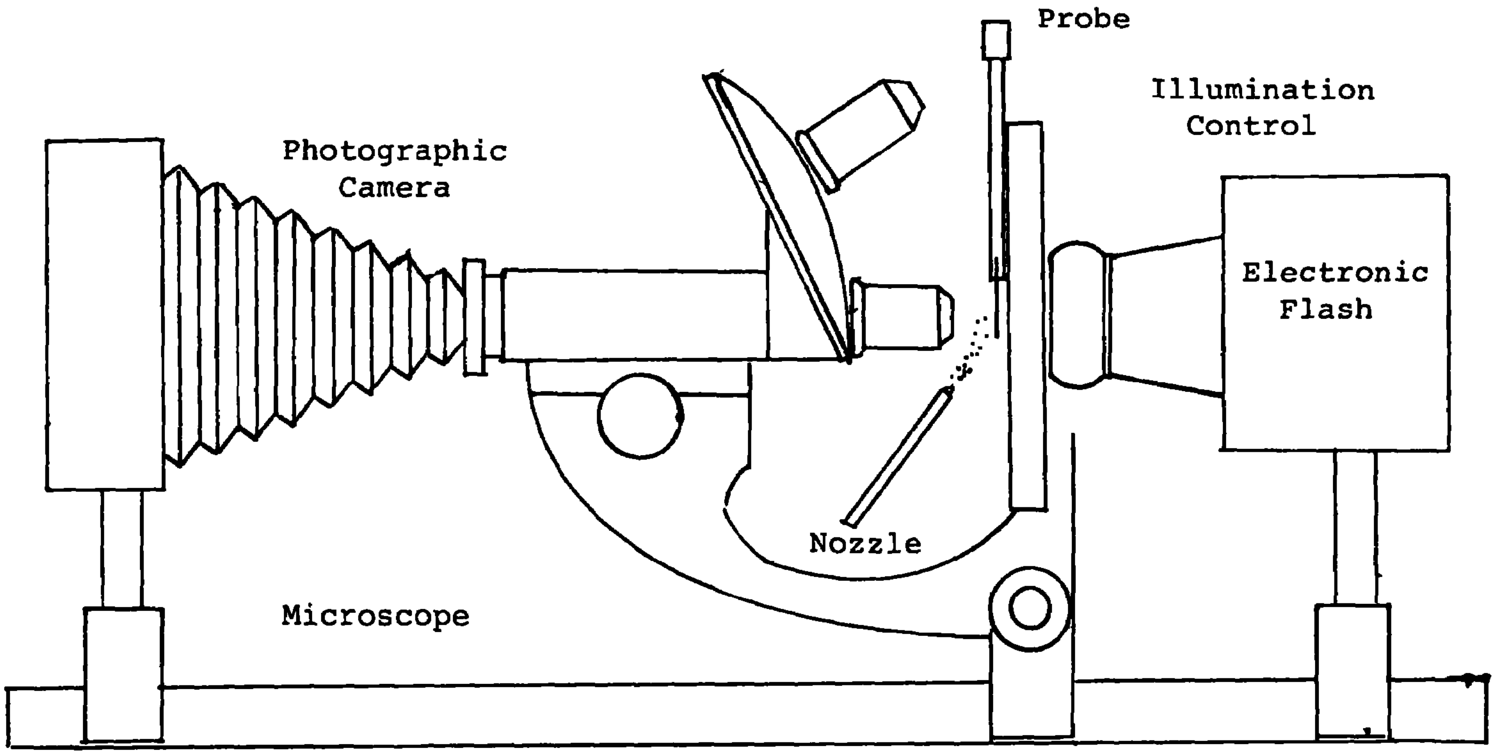


Figure 9: Equipment Arrangement for Calibration

The calibration of a sensor requires an oscilloscope picture of the electrical signal taken simultaneously with the droplet picture. Such synchronization is accomplished with the circuit shown in Fig. 10. A controlled power supply feeds a resistance bridge, one of whose arms is the hot wire. The electrical signal resulting from the interaction of the droplet with the hot wire is filtered to remove low frequencies due to air turbulence and it is displayed on an oscilloscope. The same signal is amplified and fed to a trigger circuit which controls the oscilloscope sweep. The start of the sweep is also used to trigger the electronic flash. Every effort was made to reduce to a minimum the delay between droplet to wire contact and operation of the flash, in order to prevent distortion and/or evaporation of the droplet. This apparatus was used to obtain data from hundreds of droplets which varied in size from 5μm to 600μm. Three such droplet photographs are shown in Figure 11 along with the corresponding electrical signatures from the sensor.

Droplet Generators

The generation of droplets over the total specified size range (1μm to 600μm) with low velocity and low turbulence could not be achieved using a single technique. In the course of the investigation, the following approaches were used:

- Saturated steam
- Vibrating capillary
- Micropump
- Rotating disc
- Berglund Liu generator

The saturated steam was generated with an electrical heater in contact with a metallic tube which had one end in water. The water was supplied to the heater by capillary action. This technique was used to generate droplet sizes below ten microns.

The vibrating capillary consisted of a metallic tube put into vibration with an electromagnet. An audio frequency generator was the source of power for the electromagnet and both amplitude and frequency were adjusted to achieve

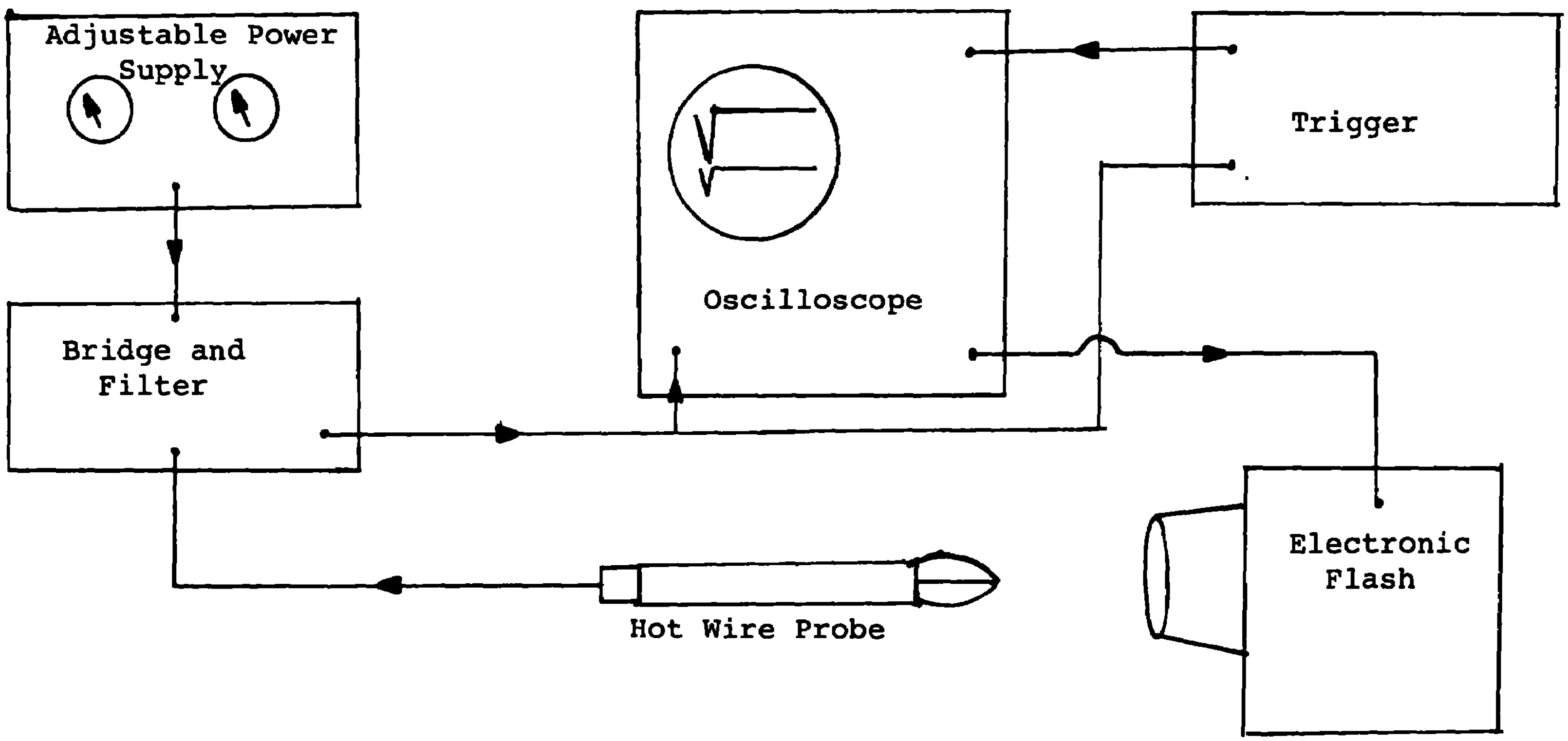


Figure 10: Calibration Circuit

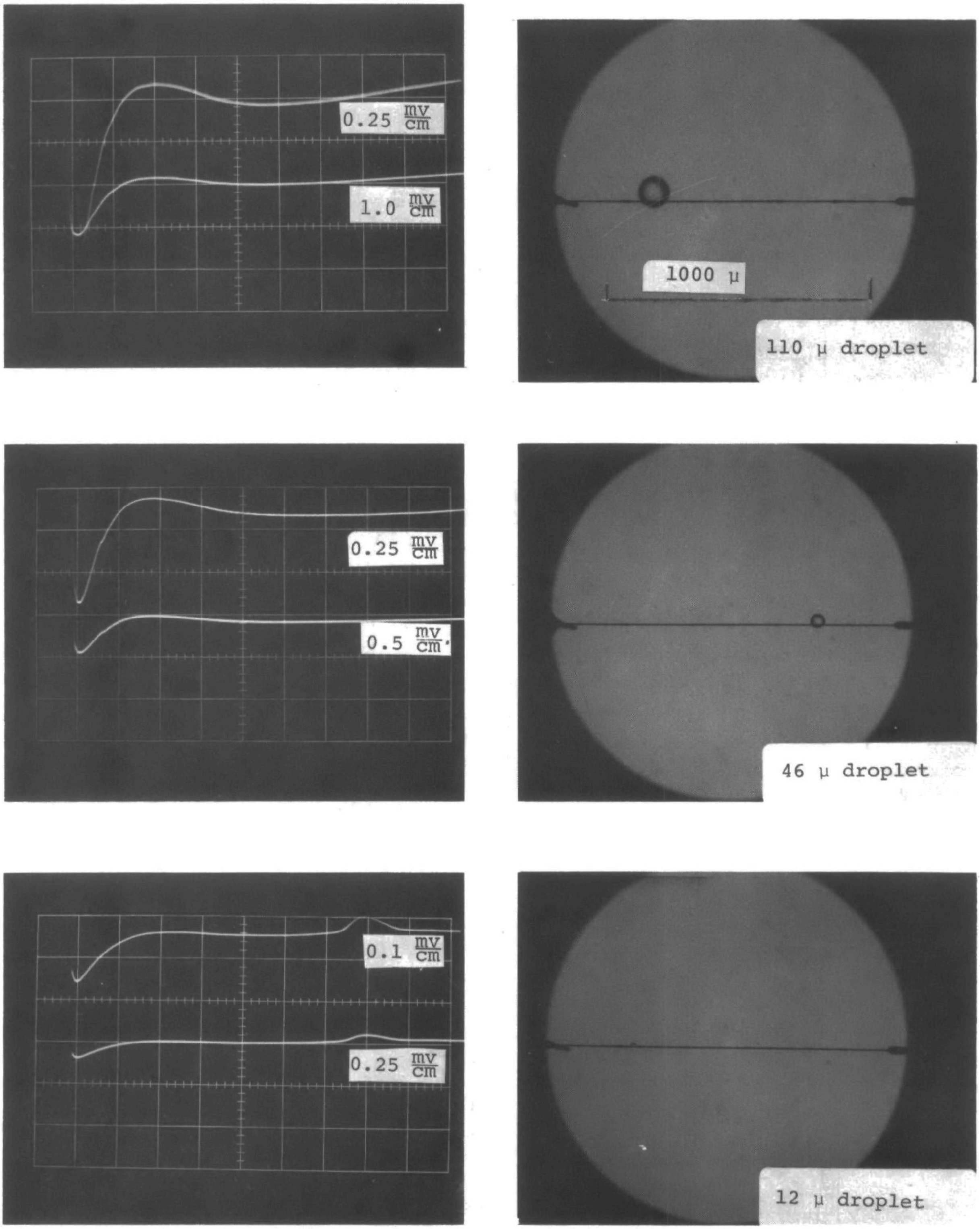


Figure 11: Typical Droplets and Electrical Output

mechanical resonance. Water was fed to the tube through a restriction. The size of the droplet is a function of the maximum acceleration at the tip of the capillary tube where the droplet forms. The minimum droplet diameter generated by this apparatus was fifty microns using the highest acceleration. Repeatable droplets with a diameter of approximately one hundred microns are achieved without difficulty. The trajectory and separation of these droplets remains consistent for extended periods of time. Because of the consistency of this device, it was used in the study of the eccentric collision phenomenon reported under the section entitled Laboratory Experiments and Results.

The micropump droplet generator uses pressure surges on a metallic tube to eject small droplets out of a restriction. Such pressure surges were created with a flattened portion of a brass tube being impacted with an electromagnetic hammer. The trajectory of the droplet could be controlled but a range of droplet diameters was always present. Typical diameters were between twenty to one hundred microns.

The rotating disc is a well-known device for generating droplets. A jet of water is aimed near the center of the rotating disc and the water slowly flows to the edges of the disc where it breaks into small droplets because of centrifugal forces. The disc is attached to an electrical motor whose speed is varied to achieve different distributions of droplet sizes. A chamber surrounding the disc allows for the selection of a small portion of the droplets being generated. Droplet diameters from thirty microns to larger than one millimeter were obtained with this device in the laboratory.

The Berglund Liu monodisperse droplet generator is a rather sophisticated instrument which ejects droplets through small orifices as a result of the pressure surge created with a piezo electric crystal. The crystal is activated from an oscillator. Three orifice diameters are available: five, ten and twenty microns diameter; the corresponding water droplet diameters are 13, 23 and 45 microns. The droplet diameter is repeatable and the droplets can be ejected at a low speed. The device was used extensively in our studies. However, operation of the generator involves a learning period and keeping the device in operation is tedious and time consuming.

In all the experimental work, the droplet sizes were actually measured using the photographic records rather than assuming the generators produced a monodispersion.

SECTION VI

FIELD TESTING

Several facilities using scrubbers and mist eliminators were investigated for possible use during the evaluation of the instrument. The final selection was a group of mist eliminators which were attached to scrubbers used to clean the exhaust of diesel engines operating with either standard diesel fuel or methane. This facility is located at the Nassau County Sewage Treatment Plant, Wantagh, Long Island, New York. Five such units are installed and normally only one operates at a given time.

A cross section of a demister is shown in Figure 12. Every effort was made to minimize interference with the normal operation of the plant and to avoid modification of the demisters. Since the demister is located on top of the building, all measurements were taken by lowering the probe down the open stack which was approximately 5 feet high. The probe was mounted on a pole which was flexible enough to pass the spinner blades and reach the region where the spray nozzles are located. A jig was clamped to the stack and used to position and hold the probe in the desired region of the flow field.

A power line was installed to operate the instrument and auxiliary equipment. In particular, an oscilloscope was used during most of the tests to determine the level of the turbulence signal and the response of the droplet measuring instrument. A magnetic tape recorder was also used to record pertinent signals which then were analyzed in the laboratory.

Great importance was placed on the actual use of the instrument under field conditions. The basic purpose of the field studies was to obtain performance data which was then used to modify and improve the device. The major observations and results from these studies are summarized below:

1) It was observed that the droplet size population at the demister chamber extended below the specified minimum size of 10 microns. Also the flow velocity was somewhat higher than expected,

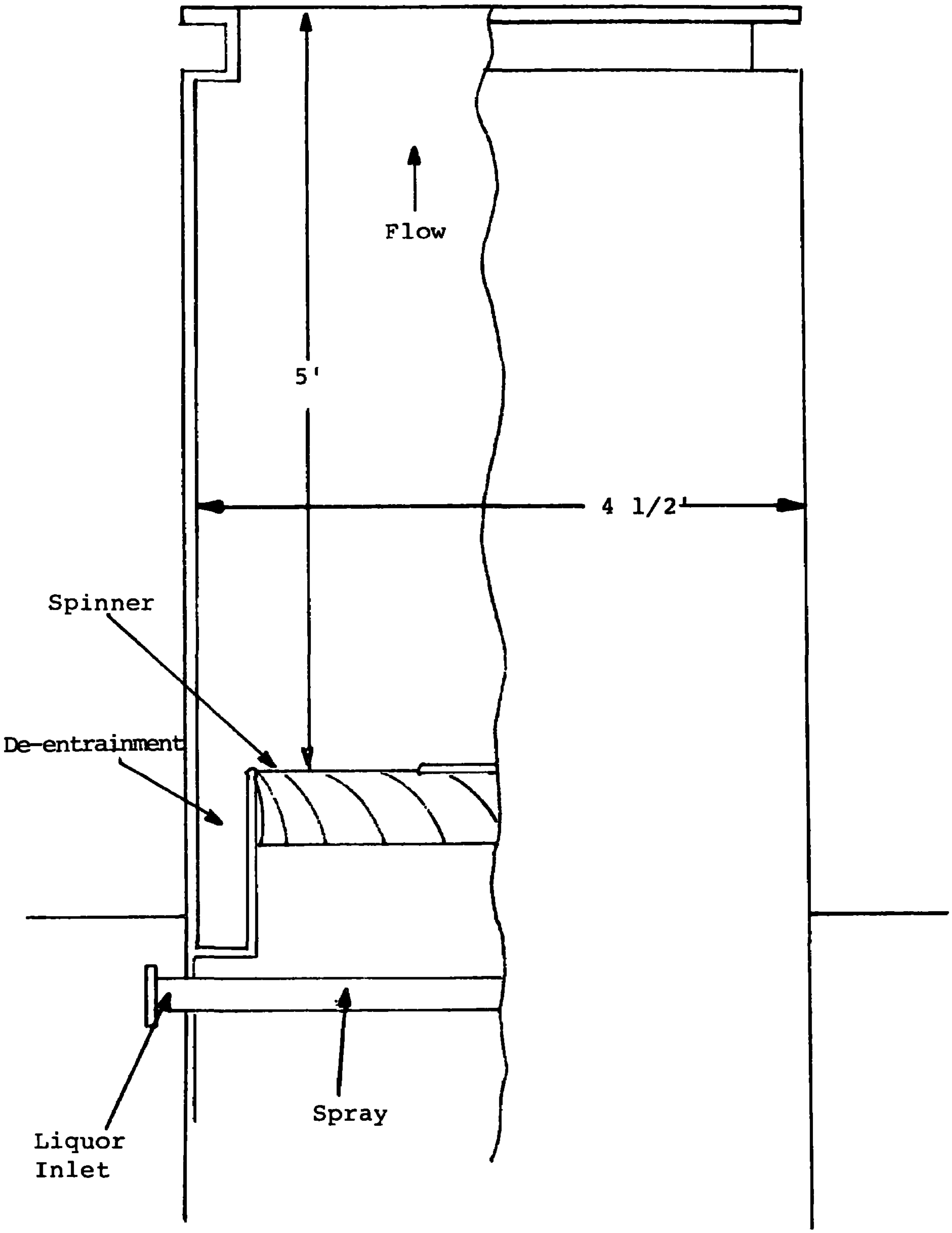


Figure 12: Demister Cross Section

reaching three meters per second (ten feet per second). The flow turbulence was also very high.

2) A program of modifications of the instrument was carried out to satisfy these stringent operating conditions. Most of the effort was for improving the electrical filter characteristic to reject signals generated by turbulence and to increase the sensitivity for small diameter droplets. These modifications were sucessfully made, and the instrument now can measure droplets as small as 1μm at a flow velocity up to 3 m/sec.

3) When using the instrument, the operator must avoid strong turbulence conditions. The DC-1 circuit is designed to discriminate the low frequency and low signal levels of the turbulence from the high frequency signals from droplets. However, under extreme turbulent flow conditions, counting errors can occur.

4) Some secondary problems were noted during the tests. For example, strong electrical interference caused false counting during a phase of the field testing. The device was modified by introducing a proper filter of the power line. All such secondary problems are corrected in the final instruments.

5) The probe operated successfully for many hours of testing without failure. If a probe did malfunction, it was caused by mishandling.

6) There were particles in the flow, but their presence did not affect the measurement nor did they break the platinum sensor.

7) The DC-1 measuring device is considered operational and ready for field usage.

In the following three sections, the temperature, velocity and droplet field measurements are briefly described.

TEMPERATURE OF THE DEMISTER FLOW

The temperature of the flow did not change substantially over an extended period of time, fluctuating around ±2°C. At the axis of symmetry of the scrubber, a temperature of 56°C is observed, while close to the walls 50°C is reached. Below the spinner the temperature increases to 62°C. These results were compared against measurements performed with a mercury column thermometer. Both measurements showed discrepancy of up to two degrees. In the laboratory, the agreement between the instrument temperature and the calibrated thermometer temperature was close to a degree.

MEASUREMENT OF VELOCITY

The probe was enclosed in a wire cage to protect the sensor from strong impacts against the wall. The no-flow conditions were determined by wrapping the probe cage in aluminum foil and inserting it into the demister. The probe was held in place until equilibrium conditions were reached. With the function switch on VEL (velocity), the corresponding value of reference resistance (R_{hss}) required to balance the bridge was measured and recorded.

The shield was removed and the probe located at various points in the stack flow to measure and record the corresponding values of R_{hsv}; i.e., the reference resistance which balances the bridge. From these measurements the velocity is determined for each location.

For these measurements, the sensor wire should be perpendicular to the flow since the cooling effect varies with the cosine of the angle between wire axis and velocity vector. To perform this alignment the probe itself is used, modifying at each point its angular location for a maximum meter reading.

The flow distribution in the demister is rather complicated, with a strong rotary motion superimposed on the axial motion. Fluctuations in the velocity are present so average values were measured over a period of approximately ten minutes. The velocity at one foot from the wall was between 3.0 and 3.1 meters per second. The velocity at the center of the stack was between 2.8 and 2.9 meters per second. Due to the operation of the diesel engine the flow shows a pulsation of the order of ten cycles per second.

MEASUREMENT OF DROPLETS

With the instrument as originally designed (minimum droplet size ten microns), a low counting rate was observed. Estimates of the droplet concentration were performed based on the opacity of the plume, and it was concluded that most of the droplets were smaller than ten microns in diameter. The instrument was modified to satisfy those conditions.

For most of the field study, a particular resistance ladder was used to obtain measurements down to one micron. The bin sizes were:

Bin	Lower Limit (μm)	Upper Limit (μm)	D_i (μm)
1	1.0	1.8	1.40
2	1.8	2.5	2.15
3	2.5	6.0	4.25
4	6.0	40.0	23.00
5	40.0	160.0	100.00
6	160.0	--	

Large fluctuations in the concentration were observed so that the average from several measurements extending over periods of ten minutes was computed. The time required to achieve a total count of 999 droplets varies between 20 and 600 seconds.

The measurements were performed along the axis of symmetry of the stack and 6 inches from the wall. Starting from the top of the stack, measurements were made every two feet until the spinner was reached. Table 1 presents the data obtained from a typical sequence of measurements.

		BIN 1		BIN 2		BIN 3		BIN 4		BIN 5	BIN 6
stack position	time interval (sec)	N_1	n_1	N_2	n_2	N_3	n_3	N_4	n_4	N_5	N_6
top center	130	505	160	290	81	170	32	0	0	0	0
top side	105	380	150	251	89	208	50	1	.6	0	0
2' center	140	550	160	285	74	175	31	0	0	0	0
2' side	131	620	196	310	87	215	41	2	1.3	0	0
4' center	122	590	204	205	63	63	12.5	3	2	0	0
4' side	135	670	210	267	74	140	25	22	.6	0	0
6' center	93	580	200	312	124	133	36	12	.6	0	0
6' side	83	630	315	252	113	182	55	53	2.6	0	0
6 1/2' center	87	540	260	246	104	153	44	5	.5	7	0
6 1/2' side	68	545	332	271	148	190	70	90	.8	25	7

TABLE 1 - Typical sequence of measurements

N_i = count, i^{th} bin; n_i concentration, i^{th} bin [droplet/cm^3]

SECTION VII

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16. ABSTRACT

The report describes the design, development, and field testing of a concept to measure liquid droplets in the size range from 1 to 600 micrometers. The measurement probe is a platinum wire 5 micrometers in diameter. With the probe electrically heated to a predetermined temperature, changes in the probe resistance are related to the size of the impinging droplets in the gas flow. The electrical signals from the probe are processed and used to classify the droplets into six different size ranges or bins. Two prototypes, consisting of the probe and electronic processing unit, were constructed and tested in the field. Actual droplet distributions and concentrations were measured successfully.

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