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A PHOTOELECTRIC HYGROMETER

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SUMMARY

An instrument that measures small absolute humidity changes by photoelectric examination of the 9440 angstrom units absorption band of water vapor is described. The instrument consists of a small source of light which sends its radiation over an air path of less than $1\frac{1}{2}$ meters to a dispersing system. The resulting spectrum then is allowed to fall on two vacuum phototubes; one centered in the 9440 angstrom units absorption band of water vapor, the other located at 8000 angstrom units where no water vapor absorption bands exist. As the absolute humidity in the air path is varied, the phototube in the region of the band is affected; whereas the reference phototube is not. The phototubes are arranged in an amplifying circuit so as to magnify the effect of varying humidity. The instrument uses a portable microammeter instead of the sensitive galvanometer of all previous spectral hygrometers.

Humidity changes of 2 to 8×10^{-5} centimeter of precipitable water path over 143 centimeters of air path can be measured. Various suggestions for decreasing both the weight and the size of the instrument are given. An investigation of the small sensitive range of the instrument is described, and the results indicate that the device is confined to use over a small absolute humidity range with equipment available at the present time.

INTRODUCTION

The main requisites of a satisfactory hygrometer are reliability, portability, and instantaneous readings. It is well known that none of the humidity-measuring methods now in use satifies all the foregoing requirements simultaneously. One or two of these desiderata usually are sacrificed to secure the third.

With this in mind, a little-exploited method of measuring the humidity has been studied: the change in the intensity of the water vapor infrared absorption bands as the humidity of the atmosphere changes. A hygrometer based on this principle is called a spectral hygrometer. Such a hygrometer consists of a source of light which sends a beam of radiation over an air path to a dispersing system which forms a spectrum of the light source. The radiation then falls upon a detecting system. The air path contains the air the humidity of which is to be measured. The detector is placed so that one of the water vapor infrared bands will fall upon it. In addition, a reference detector is placed in a region of the spectrum wherein no water vapor bands are located. As the humidity over the air path varies, the detector in the band is affected; whereas the reference detector is not. Since the absorption is a function of the number of absorbing atoms in the optical path, such an instrument measures the absolute humidity.

A recent spectral hygrometer was constructed by Hand. (See references 1 and 2.) A single detector, a thermocouple, without any reference detector was used. The source of light was the sun, and the optical path was the whole atmosphere. The 9440 angstrom units band was used. Hettner (reference 3) has shown that the 9440 angstrom units band is weak compared to the 13,700 angstrom units band of water vapor. The weak band could be used because of the tremendous path length.

In order to make the above instrument more practicable for field use, Foskett and Foster (reference 4) used two thermocouples following the original development of Fowle (reference 5), who used bolometers. The thermocouple outputs are sent in opposite directions through a sensitive galvanometer the changes of readings of which indicate the absolute humidity over the air path. The air paths varied from 1 to 50 meters. The 13,700 angstrom units band was used.

The above devices suffer from the serious disadvantage of requiring an extremely sensitive galvanometer to read the thermocouple outputs. This renders the instrument nonportable. In addition, the requisite air paths are fairly long. This would prevent the use of the instrument in a region of very low humidity unless a very long air path were used. A long air path would make the instrument useless in the field.

In order to improve the foregoing thermohygrometers, the photoelectric hygrometer was devised. The detectors used are phototubes. It is well known that phototubes are much more sensitive than thermocouples (reference 6), and it was hoped that this fact would lead to a more portable and possibly more sensitive hygrometer. It is well to remember, however, that phototubes have their long wavelength thresholds at less than 11,000 angstrom units, which permits use of only the comparatively weak 9440 angstrom units absorption band of water vapor. In addition, the characteristic curves of all infrared phototubes exhibit rapid variation of sensitivity with wavelength in the region of the 9440 band. On the other hand, thermocouples may be used equally well in all spectral regions.

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INITIAL EXPERIMENTS

The first successful photoelectric hygrometer that indicated that phototubes could detect changes in the intensity of the 9440 band of water vapor consisted of a single photocell and amplifying tube connected to a galvanometer. The source of light was an automobile headlight bulb. The air path was inside a chamber 20 feet long. The humidity over this path was varied by adding or removing water vapor by using steam and drying agent, respectively. However, the poor control over the humidity variations prevented any accurate calibration of the instrument. The results of this experiment made it clear that some method of accurately controlling the humidity and also changing it by small amounts was necessary. In addition, it seemed probable that the optical path could be decreased to a fairly low value without serious loss of sensitivity because of the dependence of absorption on the square root of path length. This relationship holds only over a restricted range, but only a small change was involved. Much better collimation of the light beam is possible in a shorter path, and it was hoped that this would simplify the detecting problem.

EXPERIMENTAL ARRANGEMENT

The new design of the photoelectric hygrometer and calibration chamber is shown diagrammatically in figure 1. The chamber serves several important purposes: to permit accurate variations of humidity, to provide the necessary optical path, and to collimate the beam of light from the source.

The chamber consists of a brass pipe 143 centimeters long, 11-centimeter inside diameter, and wall thickness approximately 2 millimeters. At each end of the pipe is a thick circular brass plate which serves as a lens holder. The plates have central holes of such size as to contain lenses of 5-centimeter diameter. To hold the lens in place, a thin brass annulus of 5-centimeter outer diameter is screwed onto the brass plate after the lens has been mounted between two rubber gaskets. The optical path over which humidity variations occur is the distance between these two lenses - that is, 143 centimeters.

The beam of light is collimated by four annuli which are uniformly spaced down the internal length of the pipe. The annuli fit very closely inside the pipe and each has a central hole of 4-centimeter diameter. These holes are made smaller than the 5-centimeter diameters of the lenses in order to remove the ill-defined edges of the beam of light. The annuli are supported on a frame of three rods which runs parallel to the length of the pipe and is set very close to the wall of the pipe. The annuli, lens holders, and inside of the pipe are all painted black.

The bottom sections of each of the four annuli are filed away to permit filling all the sections of the pipe with water through a single stopcock at the "source end." Sufficient water is admitted to cover all the bottom of the pipe up to a maximum depth of about 1 centimeter above the lowest part. To eliminate spurious reflections, it is important that the water level never reach the path of the light beam. The water level is indicated by a simple open-end manometer.

Thermometer holders are soldered into the walls of each of the sections into which the pipe is divided by the annuli. The holders in the first four sections contain single thermometers and the last holder, the one closest to the source, a double thermometer. (See fig. 1.) The thermometers are set into rubber stoppers which are placed in the above thermometer holders. Thermometer number 5 (see fig. 1) has a wick attached to it. As a result, thermometers 5 and 6 act as a psychrometer.

Thermometer bulbs 1 and 3 are above the water surface; bulbs 2 and 4 are below. The psychrometer arrangement is in the air above the water with the wick on the wet bulb dangling into the water. Care was taken to see that none of the thermometers is in the light path.

A coil of copper tubing through which water may be circulated is soldered around the outside of the pipe. Adjoining this, on the outside, is a thin layer of asbestos. This is surrounded by a coil of closely wound heating wire and another layer of asbestos. Finally, a roll of gauze is wrapped around the last layer of asbestos to hold it in place. By sending a current through the heating coil, the temperature of the water may be raised, thus changing the absolute humidity of the air above the water. The absolute humidity can also be controlled by circulating hot or cold water through the copper tubing.

In order to avoid any condensation of water vapor on the lenses at each end of the pipe, it is necessary to keep them warmer than the rest of the chamber. For this purpose, two thin coils of wire are mounted on thin rings of 4.8-centimeter diameter and are held in place next to the outer surfaces of the two lenses. It was found that a current of 0.25 ampere in these coils heated the lenses sufficiently to prevent condensation under all experimental conditions. As a further precaution against condensation effects, the coils are heated at all times by 0.4 ampere.

The light source was mounted on a holder rigidly attached to one end of the pipe. The source was a 6- to 8-volt, 21-candle power, Mazda-1129, automobile headlight bulb. The bulb voltage, 8 volts, was supplied by two heavy-duty storage batteries that were always kept fully charged. Wear on the batteries was equalized by using only four of the batteries' six cells and alternating the cells used from day to day. To minimize the chance of bulbs burning out during a run, bulbs were discarded after 25 hours of use.

The source holder allows adjustment of the position of the source with respect to the first lens. This lens has a strength of +10 diopters. The source is set 10 centimeters from this lens, and thus a nearly parallel beam of light is sent down the calibration chamber. The beam then strikes the second lens, identical with the first, and enters the "detection box." (See fig. 1.) The pipe is rigidly attached to the wooden detection box by means of a metal clamp which is clamped to the pipe and is bolted to the front plate of the detection box.

The converging beam of light that emerges from the second lens then passes through a Wratten 88A, infrared transmitting, gelatin filter and then is allowed to strike another +10-diopter lens placed 20 centimeters from the second lens. The filter is needed to remove the second order visible spectrum which overlaps with the first order infrared. A parallel beam of light emerges from the third lens. The beam then strikes a diffraction grating. A replica on collodion having 14,438 lines per inch was found satisfactory. The diffracted beam then passes through a fourth lens, of 50-centimeter focus, and strikes the front plate of the amplifier box. A set of four baffles is placed between the second lens and the diffraction grating in order to remove any stray reflections and also to help collimate the light beam.

A 40-centimeter section between the second lens and the grating serves no function but is included for experimental convenience. A metal rod pinned to a point directly beneath the +2-diopter (fourth) lens and attached to the front of the amplifier box allows movement of that box along the circumference of a circle of 50-centimeter radius. This enables the desired wavelengths to be focused on the phototubes in the amplifier box.

The zero and negative orders of the spectrum and all positive orders above the first are prevented from striking the front plate of the amplifier box by means of two wooden baffles. These are mounted so as to act as two light traps on each side of the first-order spectrum. (See fig. 1.)

The front plate of the amplifier box is carefully made, since it contains the most important adjustment of the entire apparatus. (See fig. 2.) The front plate is of 1/8-inch brass. On it are two slits, each 1.16 centimeters wide and 3.75 centimeters high and with 4.71 centimeters between slit centers.

The 4.71-centimeter spacing is chosen so that when the 9440 angstrom line (in the center of the water vapor absorption band) is at the center of one slit, a position at 8000 angstrom (outside of the absorption band) is at the center of the other slit. The 9440 band was located by using the second-order lines of the mercury arc spectrum and then interpolating. Once the band had been found and the amplifier box moved so that the center of the band struck the center of the proper slit, the box was fixed in place.

The height of the slit on the short wavelength (reference) side of the spectrum can be changed by means of a screw, 1/32 inch in pitch, which raises or lowers a movable plate in front of this slit. This plate is mounted on a split nut so as to remain fixed once it has been set in place by the screw.

The front plate is screwed to two brass side plates and the resulting combination is joined to a flat brass bottom plate. The removable top, back, and portions of the sides of the amplifier box are made of a single sheet of galvanized iron. The brass plates and the galvanized iron cover serve as an electrical shield for the apparatus in the amplifier box.

A phototube is mounted back of each of the slits. The cathode of each of the phototubes is symmetrically mounted with respect to the center of its corresponding slit on the front plate. The phototubes are supported at their bases by means of a rigid socket holder and at their tops by a Lucite holder. This was done to prevent any motion of the phototubes relative to each other and the slits.

The amplifier circuit is shown in figure 3. The whole circuit except for the filament battery (a storage battery), the plate and screen supply (a small $22\frac{1}{2}$-volt dry cell with various voltage taps), and the portable 0-200 microammeter was inside the amplifier box.

Types 917 and 919 RCA vacuum phototubes were used. They have identical operational characteristics. The tubes differ in that the 917 has the external anode connection at the top, while in the 919 the cathode is connected to the top. A glance at figure 3 shows that a neat triangular connection from the top caps of the two phototubes and the grid of the RCA type 38 vacuum tube will satisfy the circuit requirements. All tubes have thin bands of cerasin wax around the glass surface below their top caps in order to prevent surface leakage. The low voltages on the 38 are needed to prevent any residual gas ionization and grid emission that would tend to occur because of the high input resistance of the 38 which is of the order of the dark resistance of the phototube.

The theory of operation of the circuit follows: The output of the 38 depends upon the voltage between ground and the common junction of the two phototubes. If the light intensity on the 917 is increased, its resistance will drop and the voltage between the grid and ground will decrease. The output of the 38 will decrease. A similar argument holds for a decrease of light intensity on the 917. An analogous argument holds for light intensity changes on the 919 phototube. In order to see how to obtain the maximum voltage changes for a given change in luminous intensity, it is necessary to examine the role of the photocell characteristics. A perusal of figure 4 indicates that each phototube acts as the load for the other. The load line of each tube is, therefore, the inverse characteristic curve of the other tube. The control grid voltage of the 38 depends upon the intersection of the two phototube characteristic curves. Figure 4a shows the operating point when the light intensities on the two tubes are very nearly equal; 4b, when the intensity on the 917 is a little greater than on the 919; and 4c, when the reverse of the conditions of 4b is true. In each of these cases, consider what happens to the operating point of the 38, O_1, as the intensity of light on one of the phototubes changes by a small amount. Only in figure 4a is there an appreciable change. If the intensities of light on each of the phototubes are not very nearly equal, there will be no measurable change in the operating point and hence in the output of the 38 because the saturated portions of the phototube characteristics are nearly flat. On the other hand, if the conditions of figure 4a are simulated, very small changes of intensity, such as those caused by absorption of light by water vapor molecules along a 143-centimeter path, will give rise to significant changes in the operating point and 38 output. The apparently ideal operating position, with the two curves symmetrically disposed, gives rise to circuit instability. The circuit is therefore utilized with the operating point somewhat off to one side. This balance arrangement also partially compensates for changes in the source intensity.

The region of allowable intensity change is not very large; however, intensity changes due to the 9440-angstrom absorption band are also extremely small. The above circuit is well suited to follow such small changes.

The purpose of the adjustable slit mask now is evident. Since the two phototubes are in two different spectral regions in which their sensitivities are widely different, it is necessary to have a device for equalizing the product of intensity and sensitivity for the two phototubes. This is done by adjusting the mask on the slit in front of the reference phototube.

The 917 phototube is placed in the region of the band; the 919, in the reference region. Figure 3 shows that a decrease in intensity in the region of the band, relative to that on the reference cell, due to, say, increased absorption, will increase the resistance of the 917, raising the grid voltage and hence output of the 38.

The detection box has a wooden cover through which the screw attached to the slit mask passes. This enables adjustment of the slit from the outside without disturbing conditions in the box. The humidity conditions in the detection box are kept constant by inserting small cardboard containers filled with anhydrous calcium chloride.

The combination calibration chamber and detection box is mounted on a set of four legs; one at the source end, one at the junction of the two parts of the equipment, and two on the detection box. The legs rest on a rigid wood table.

EXPERIMENTAL PROCEDURE FOR CALIBRATION

The method of calibrating the instrument that was ultimately chosen is the following:

The water in the bottom of the pipe is heated slowly. Since the water surface is fairly large and the volume of the pipe is quite small, the air in the pipe is quickly saturated with water vapor at the saturation value for the water temperature. Since the water is heated slowly, the saturation humidity of the air follows that characteristic of the water temperature. In this way it was found possible to increase the precipitable water path by extremely small amounts. Since the thermometers were accurate to 0.1° C, such small changes could be determined very accurately. The thermometers all were checked against one another at several temperatures and were found to agree to within ±0.1° C.

The temperature of the saturated vapor was determined by averaging the readings of thermometers 2, 3, and 4. (See fig. 1.) Since 2 and 4 are in the water, they gave values within 0.2° C of each other. Thermometer 3 would tend to be slightly higher because it was in the air in the pipe unless the system was heated slowly. Upon heating the system from the outside, the air, having a much lower heat capacity than the water, would tend to increase its temperature much more rapidly than the water. The rate of heating was adjusted so that thermometer 3 was always very close to the readings of 2 and 4.

The readings of the psychrometer combination (T5 and T6) were always within 0.1° C of each other indicating the close proximity to saturation. Because the air was not circulated, this result is not very significant. However, these thermometers were usually 0.5° or so higher than the central ones due to exposure to oblique rays from the source, and possibly due to proximity to the heated end units.

Thermometer 1 usually was about half a degree higher than the others, probably because it was located close to the separately heated second lens.

Although there were "hot spots" at each end of the chamber due to the presence of the source and lens heaters, these covered only small regions of the pipe. The average of the readings of the three central thermometers covering nearly three-fourths of the length of the pipe was thus the true temperature of the saturated vapor within ±0.25°.

During a run, it was important to prevent condensation on the first and second lenses because condensation will decrease the light intensity on both phototubes. Since the two positions of the spectrum are not affected to the same degree, the operating point of the 38 will shift owing to condensation as well as to humidity changes. The small lens heating coils were always heated with 0.4—ampere to prevent condensation under all experimental conditions.

All runs were taken in the range between 20° and 30° C. This range was chosen because of its proximity to the usual room temperatures. It also gives sufficiently small precipitable water paths to show the power of this method of humidity measurement.

The cold water circulating in the copper tubing was used to cool the water in the pipe below 20° C in order to prepare the system for a run. The water flow then was stopped. No runs were taken by cooling the water from 30° to 20° C. This was decided against for the following reasons: First, it is very difficult to control the rate of flow of cooling water to the accuracy desired; second, the cold water coming in contact with the metal pipe would cool the pipe quickly. Any warm vapor in contact with the pipe would condense out quickly with the consequent possibility of filling the air in the pipe with droplets of water. These droplets would produce an effect similar to that produced by condensation on the lenses.

The supplies of water in the pipe, the drying agent, and the lens heating current were always closely checked. Source batteries were checked for full charge. Amplifier and source were turned on and allowed to come to equilibrium. The slit adjustment was fixed from outside the chamber by means of the projecting screw. The phototubes were so operated that their characteristic curves intersected along their flat portions. The point of intersection was somewhat above the point corresponding to exactly equal photocell response for reasons of stability discussed earlier. Under these conditions the circuit was found to be stable despite the high circuit sensitivity.

Several sets of data were taken in order to determine the general shape of the calibration curve and then one reference run was obtained. All succeeding runs were matched to this run by adjusting the variable slit so that the microammeter reading for a given average temperature agreed with the value obtained in the reference run. The matching was usually done for a low value of the temperature. The matching was accomplished by rotating the 1/32-inch pitch screw a few degrees. This adjustment was necessary since source voltages were not exactly the same from day to day, and because of mechanical jarring of the apparatus between runs.

In order to translate the experimental data (temperature of saturated vapor vs. microammeter readings) into precipitable water path vs. microammeter readings, it is necessary first to know the value of the saturation absolute humidity as a function of temperature. A curve giving this relationship was obtained from data contained in standard handbooks and listed in the second column of table I.

In order to calculate the precipitable water path L in an air path, p centimeter, of cross section, B square centimeter, for air saturated with d grams per cubic meter of water vapor, proceed as follows:

The mass of water in the path p is

$$Bpd/10^6 \text{ grams}$$

The volume of water in this path is the above-mentioned value divided by the density of water or

$$Bpd/10^6 \text{ cubic centimeters}$$

If this is condensed into a cylinder of height L and cross section B,

$$Bpd/10^6 = BL$$

and therefore

$$L = pd/10^6 \text{ centimeters}$$

Since p is 143 centimeters (the additional length of air path in the detection box is not included, since humidity conditions over this portion of the air path are maintained at a constant value) the precipitable water paths are found from equation

$$L = 143/10^6 \, d \text{ centimeters}$$

The end effect due to the source being in the room 10 centimeters from the first lens was approximately constant because the conditions in the room changed very little throughout the course of the experiments.

In order to obtain a calibration curve, several runs were made. A smoothed curve was drawn through the experimental points.

Figure 5 shows the final calibration curve thus obtained of the photoelectric hygrometer. Each point on this curve is taken from the smoothed curve and represents a dozen or more observations. The data used were obtained over a $2\frac{1}{2}$-month period.

DISCUSSION OF RESULTS

Of primary importance in estimating the usefulness of the device is the minimum change of precipitable water path necessary to produce a noticeable deflection on the microammeter. Taking the slope of the curve at each end of the experimental range, the following results are arrived at:

The photoelectric hygrometer has a sensitivity of 1.7×10^{-5} centimeter of precipitable water per microampere at the low end of the calibration curve, and 8×10^{-5} centimeter of precipitable water per microampere at the high end of the calibration curve.

These results are somewhat independent of the actual humidity range used. In a different humidity range (in which the precipitable water paths over 143 centimeters differ from the values in fig. 5), it is necessary only to vary the slit adjustment screw until it again causes the phototube curves to intersect in the critical region. This adjustment practically compensates for the change in absolute humidity.

To determine the minimum detectable change of density at any temperature range, the foregoing results can be used as follows:

It is shown that

$$L = 143d/10^6 \quad .$$

where

L = precipitable water in 143 centimeters of air, cm

d = saturation density of water vapor, gm/m^3

An average sensitivity of 5×10^{-5} centimeter per microampere is assumed. Therefore

$$\Delta L = 143 \ \Delta d/10^6$$

and

$$5 \times 10^{-5} \text{ cm}/\mu\text{A} = (143/10^6) \ \Delta d/\Delta I$$

where ΔI is the change of microammeter reading. Since the minimum detectable change of the microammeter reading was 1/4 microampere, $\Delta d(\text{minimum}) = 0.087$ gm/m^3 is minimum detectable Δd for the 20° to 30° C range of density of saturated water vapor.

Assuming that the absorption is proportional to the one-half power of the number of atoms in the line of sight (reference 7) leads to the result that:

$$I = I_0(1 - K\sqrt{d})$$

where K is a constant. The microammeter reading I is proportional to the light intensity in the region of the absorption band; I_0 is the intensity in the region of the band for no absorbing atoms in the line of sight.

Therefore

$$\Delta I/\Delta d = C/\sqrt{d}$$

or

$$\Delta d/\Delta I = r\sqrt{d}$$

where r and C are negative constants. From Δd minimum for the 20° to 30° C range r can be calculated. Using $d = 25$ gm/m^3 (this is approximately the average value for the 20° to 30° C range; see table I) gives

$$r = 0.087/(0.25\sqrt{25}) = 0.070$$

therefore

$$\Delta d/\Delta I = 0.070\sqrt{d}$$

Since minimum detectable I is one-fourth of a microampere,

$$d(\text{minimum}) = 1/4\ (0.070)\ \sqrt{d} \quad \text{gm/m}^3$$

$$d(\text{minimum}) = 0.017\ \sqrt{d} \quad \text{gm/m}^3$$

The percentage error in any value of d is found by taking

$$d(\text{minimum})/d \times 100$$

Table I has been constructed, using the above calculation which assumes that the changes of d are very small.

TABLE I

Temperature (^{o}C)	Saturation density of water vapor (gm/m^3)	Minimum detectable change of density (gm/m^3)	Accuracy (percent)
50	83.2	0.16	0.19
40	51.1	.12	.24
30	30.35	.094*	.31
20	17.3	.071*	.41
10	9.41	.052	.55
0	4.85	.037	.77
-10	2.15	.025	1.2
-20	.89	.016	1.8
-30	.34	.0099	2.9
-40	.12	.0059	4.9

*Experimentally verified assuming a slight extrapolation. All other values are computed.

As a semi-quantitative check on the calibration curve, the following experiment was performed:

A hose, 1 centimeter in bore, was placed so that a stream of air could be blown across the light path, between the source and lens 1. Keeping the humidity conditions in the calibration chamber fixed, the observer blew a steady stream of air across the light path. The circuit was set so as to be on the steep part of the calibration curve. Under the above conditions a deflection of about 1 microampere was obtained.

If it is assumed that the air blown across the path is saturated at 37° C (saturation density = $43.9/10^6$ g/m^3) the change of precipitable water path produced over the 1-centimeter region influenced by blowing is $1 \times 0.0439/10^3 = 4 \times 10^{-5}$ centimeter of precipitable water. From figure 5 such a change of precipitable water path should give rise to microammeter changes of nearly 1 microampere.

It is thus shown that an accuracy of 0.3 to 0.4 percent can actually be obtained in the range 20° to 30° C. Calculation indicates that the instrument should yield the values calculated in table I for other temperature ranges. The calibration chamber did not permit verification of these calculations.

ATTEMPTS TO INCREASE THE SENSITIVE RANGE OF THE INSTRUMENT

Before considering the attempts to increase the sensitive range of the photoelectric hygrometer, it is well to consider the fact that the instrument measures the absolute humidity. This is a more difficult task than is the measurement of relative humidity. In the temperature range -40° to +40° C, the former varies over three decades on the common logarithmic scale; whereas the latter varies over only two decades. This makes it impossible to use a single meter with the photoelectric hygrometer unless a range switching device is used.

An examination of figure 5 reveals a disadvantage of the present photoelectric hygrometer, the comparatively small sensitive range. Although the instrument is extremely sensitive, its limited range requires continual resettings to make it serviceable for the various humidity ranges that might be encountered. A series of investigations was undertaken to learn the causes of the narrow sensitive range, and to attempt to increase the sensitive range of the instrument.

1. Higher Phototube Voltages

An examination of figure 4 shows that the high sensitivity of the instrument is due to the almost flat characteristics of the phototubes. A simple expedient to increase the sensitive range would be to increase the voltage on the phototubes. This would proportionally increase the region wherein the straight lines could intersect. However, it is well known that vacuum phototubes exhibit the phenomenon of residual gas ionization (reference 8) at voltages above 25 volts. This ordinarily causes no difficulties in using such phototubes. But, if a constant-calibration, high-sensitivity device is desired, it is extremely important. Attempts to increase the voltages on the phototubes to 45 volts led to instabilities in the instrument.

The occurrence of residual gas cannot be avoided. Even if the phototubes could be evacuated satisfactorily, the highly volatile caesium on the cathode would begin to vaporize and furnish residual gas. The only alternative is to decrease the potential gradients in the phototube itself. The small diameter of the anode of the phototube gives rise to high fields which lead to ionization of the residual gases. If the anode were of a larger diameter, it might be possible to use the phototubes at higher anode voltages without running into the instabilities mentioned above.

2. Use of Gas-Filled Phototubes

An examination of figure 4 shows that the small sensitive range is the price paid for the very high sensitivity of the photoelectric hygrometer. It was thought that some sacrifice of sensitivity could lead to a greater sensitive range. Comparing figure 6 with the set of curves in figure 4 shows that gas-filled phototubes may be expected to yield a larger sensitive range with a decreased sensitivity for the instrument.

A set of experiments with the photoelectric hygrometer using RCA 918 gas-filled phototubes in the same circuit as shown in figure 3 was undertaken. The experiments confirm the usual results found when attempting to use gas-filled phototubes for constant calibration devices. The tubes revealed prominent fatigue effects which would make the instrument unsatisfactory.

In order to obtain data on the tubes without fatiguing them, a mask was placed over the source of light. A reading was taken with the mask off and then the mask was put on and the humidity conditions were changed. The tubes were then exposed to the light long enough to give a reading on the microammeter. The procedure was then repeated.

The most startling result was the remarkable inconsistency of the data. The calibration curve never remained the same from one experimental run to the next. However, each calibration curve by itself revealed that the sensitive range could be made to cover a 20° C temperature range. In addition, the sensitivity of the instrument was about one-fifth of that obtained with vacuum phototubes. However, the sensitivity also varied from one experiment to another. It may be concluded that gas phototubes cannot be used in such a highly sensitive device.

3. Use of Other Amplifying Tubes

Another line of attack was to attempt to extend the lower portion of the calibration curve. The very great slope in the calibration curve in this region is due to the fact that the light intensities on the two phototubes are exactly the same. If the calibration curve is followed, then the curve should flatten just as at the upper end of the curve. This could possibly give a longer sensitive region to the calibration curve. However, as the relative light intensities vary in this direction, the operating point of the 38 tube is being shifted toward the cut-off point. In fact, by following the calibration curve, it is found that the very steep portion goes all the way down to zero current - that is, the cut-off point is reached.

The proximity to cut-off suggests using a tube that has remote cut-off characteristics. This would increase the length of the lower portion of the calibration curve. However, the amplifying tube, since it has a large input resistance (the phototube) must be operated at reduced voltages to prevent gas current and grid emission. Since ~~the~~ characteristics of tubes are quite different in these circumstances than under the usual operating conditions, the proper tube cannot be picked by consulting a tube manual. In addition, the grid of the amplifying tube must float at a proper voltage. Because of the very high phototube resistance, the grid cannot be fixed at the proper operating point by using a grid leak and battery. For example, one important feature of the 38 tube is that it happens to float at a very convenient point.

A number of tubes which might meet the requirements of remote cut-off and proper grid floating characteristics were next examined. Of the many types of tubes available at the present time, most could be rejected because it was known that they did not meet one or the other of these requirements. Two tubes which superficially appeared to meet the requisites were tested. The first, a 6 SK 7, which is a remote cut-off pentode, was found at reduced voltages to float cut-off. The other, an 89, was found to be satisfactory with regard to the above desiderata, but had a much lower grid-plate transconductance than had the 38. No tube better than the 38 was found in these tests.

In summary, it can be said that the problem of extending the sensitive range of the hygrometer was examined, but no simple or satisfactory proceduresfor so doing were found.

SUGGESTIONS FOR IMPROVING THE PRESENT PHOTOELECTRIC HYGROMETER

From the results of the preceding section, it seems probable that the use of the photoelectric hygrometer is best confined to a small temperature range. Comments on constructional features are given below. The crucial features of the present device are the following:

1. The single most important factor in the whole instrument is the slit mask. This should be made carefully and the finest possible thread should be cut onto the adjusting screw.

2. The source of light used in these tests requires a comparatively high current. The batteries supplying it should be of the heavy-duty, long-life variety. They should be fully charged.

3. The instrument should not be made in two sections which are bolted together. It was found that although the two sections were joined rigidly, the junction would bend as persons moved over the floor of the laboratory. In other words, the bending of the floor under the experimenter's weight was sufficient to change the position of the pipe in space and thus alter the position of the beam of light on the slit system. This difficulty was overcome by setting the whole apparatus on a large, sturdy table and then supporting the table at three points. Building the instrument in one piece would easily eliminate this difficulty.

4. The accuracy of calibration would be improved at lowered absolute humidities by using a more accurate temperature control on the calibration chamber. By controlling the temperatures to 0.01° C and by reading the output of the amplifier more accurately than was possible on the 0 to 200 microammeter, it will be possible to reduce the errors in the experimental values to well below 1 percent and also reduce the measurable precipitable water path changes to below 10^{-6} centimeter.

The following suggestions should enable a marked decrease to be made in the weight and size of the apparatus:

1. The length of the air path should be reduced by at least a factor of 2. The 143-centimeter length was chosen only for convenience.

2. Lenses 2 and 3 should be eliminated. This section of the chamber is not really needed. Lens 2 should be replaced by a flat plate of glass. Lens 3 then will be no longer needed.

3. A grating of 25,000 lines per inch should be used. This will give the same photocell separation of 4.71 centimeters between 8000 and 9440 angstroms at a distance of less than 20 centimeters.

4. The waste space in the detection box should be eliminated.

5. The whole apparatus should be made of a light metal, such as aluminum.

6. Much smaller lamps, such as flashlight bulbs, should be tested as possible sources of light. This would enable much lighter batteries to be used. The heater of the 38 requires only 0.2 ampere at the reduced voltage and a light battery can be used for this.

7. To obtain a more sturdy detector than a microammeter, another stage of direct current amplification could be used and the output could be read on a milliammeter.

New York University,
New York, N. Y., October 1944.

REFERENCES

1. Stair, R., and Hand, I. F.: Monthly Weather Rev., vol. 67, 1939.

2. Hand, I. F.: Monthly Weather Rev., vol. 68, 1939, p. 95.

3. Hettner, G.: Annalen der Physik, vol. 55, 1918, p. 476.

4. Foskett, L., and Foster, N.: Bull. Am. Meteorological Soc., vol. 24, no. 4, April 1943.

5. Fowle, F. E.: Astrophysical Jour., vol. 35, 1912, p. 149, and vol. 37, 1913, p. 359.

6. Strong, John: Procedures in Experimental Physics. Prentice-Hall, Inc. (New York), 1938, pp. 397-399.

7. Condon and Shortley: The Theory of Atomic Spectra. Cambridge Univ. Press (London), 1935.

8. RCA Phototube Manual. RCA Mfg. Co., Inc. (Harrison, N.J.)

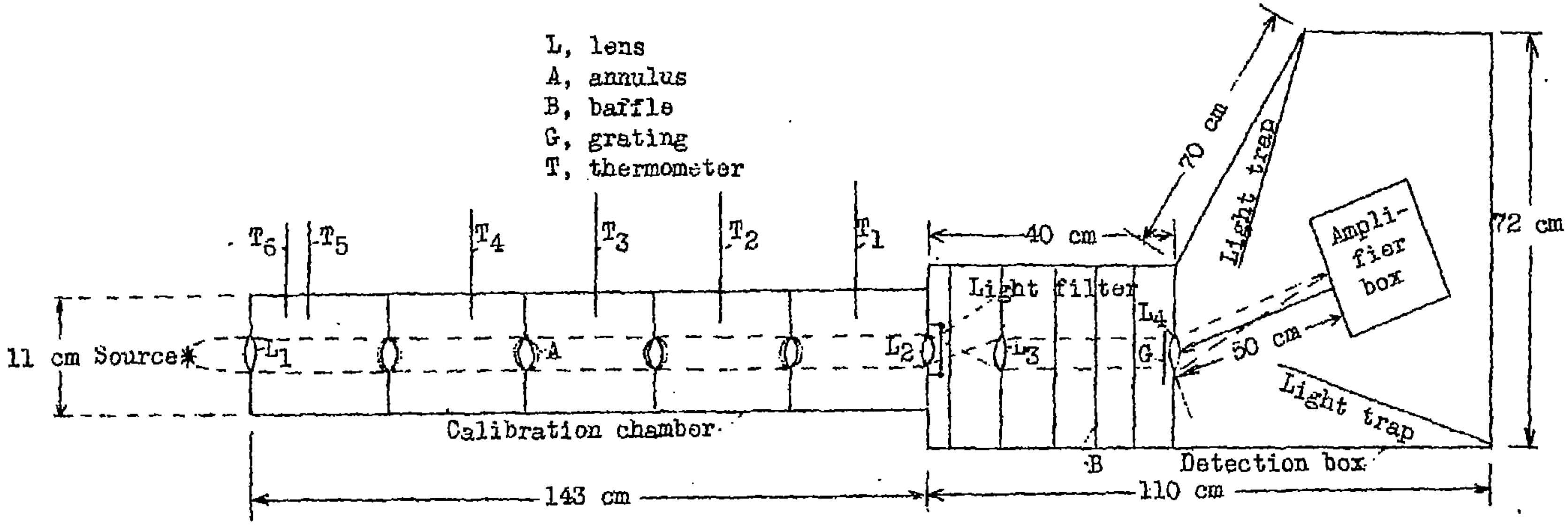
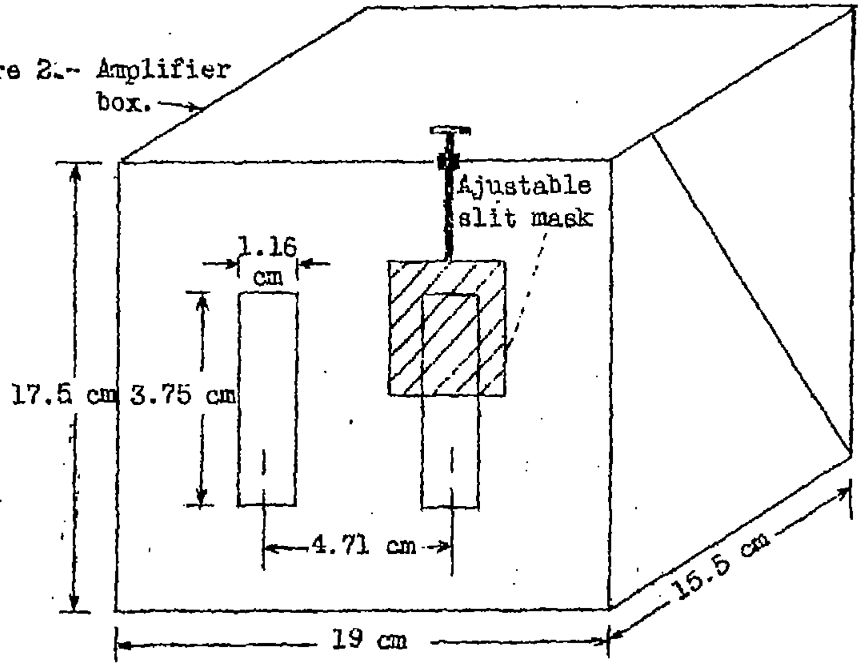


Figure 1.- Diagram of apparatus.

Figure 2.- Amplifier box.



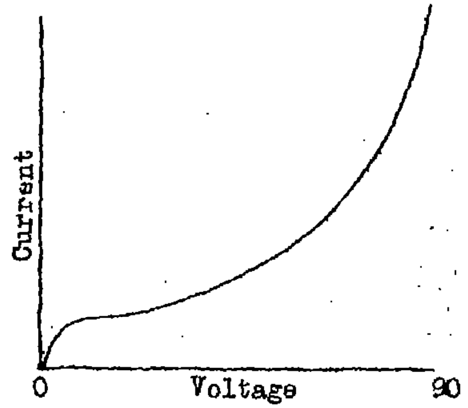


Figure 6.- Characteristic curve of a gas filled phototube.

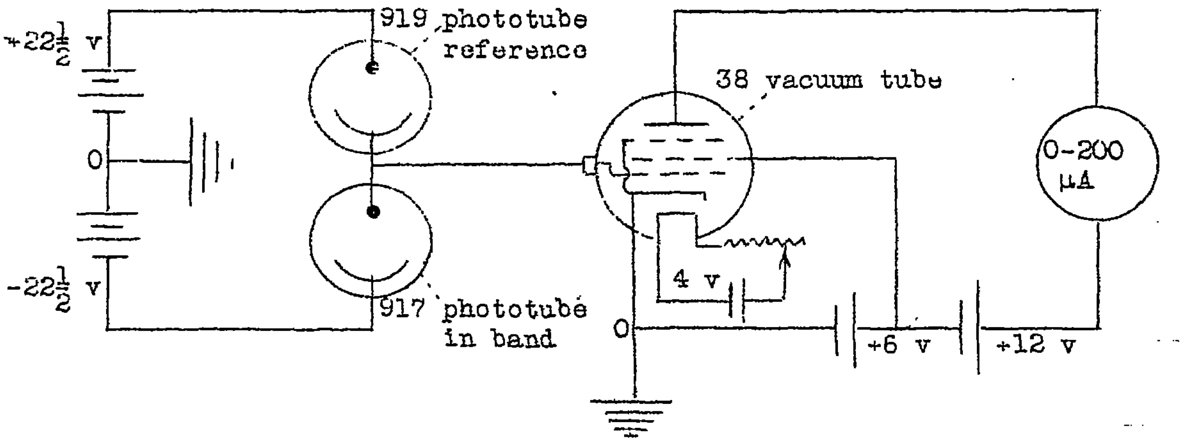


Figure 3.- Circuit diagram of amplifier.

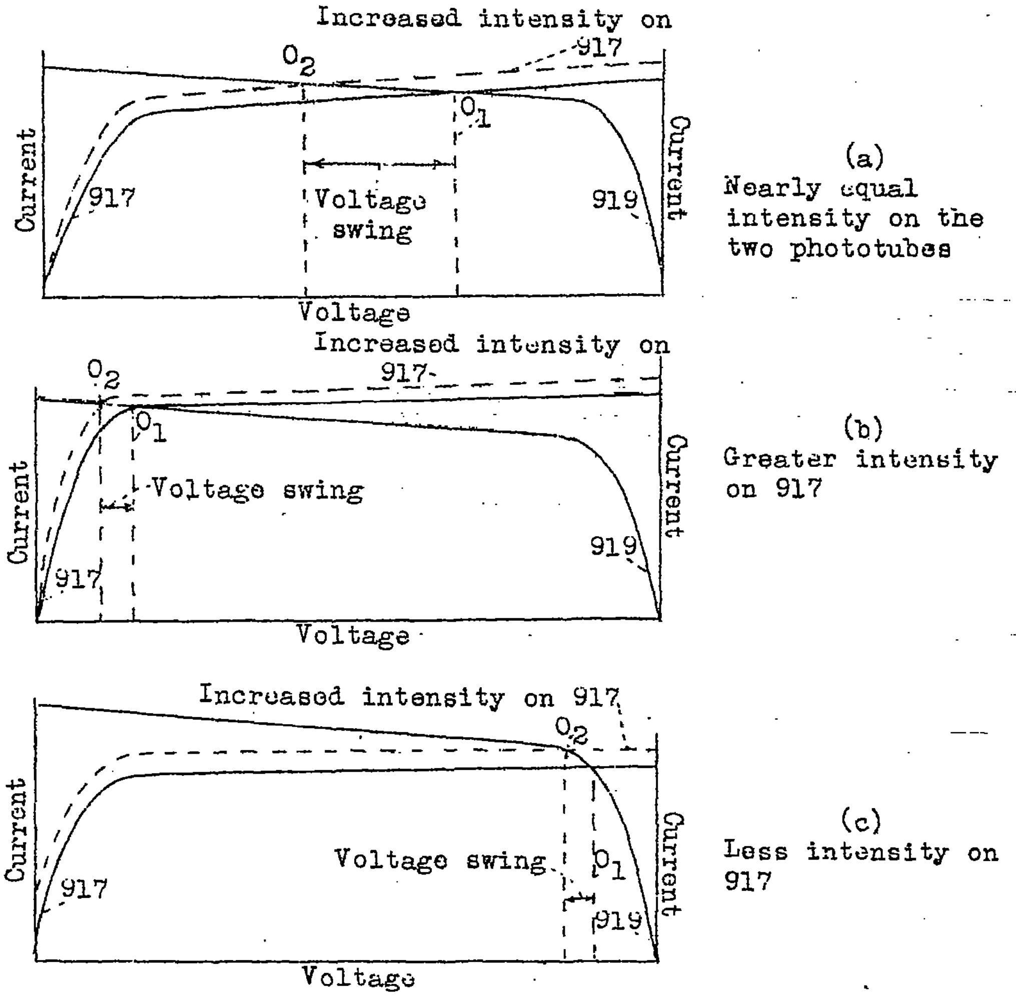


Figure 4.- Theory of operation of amplifier.

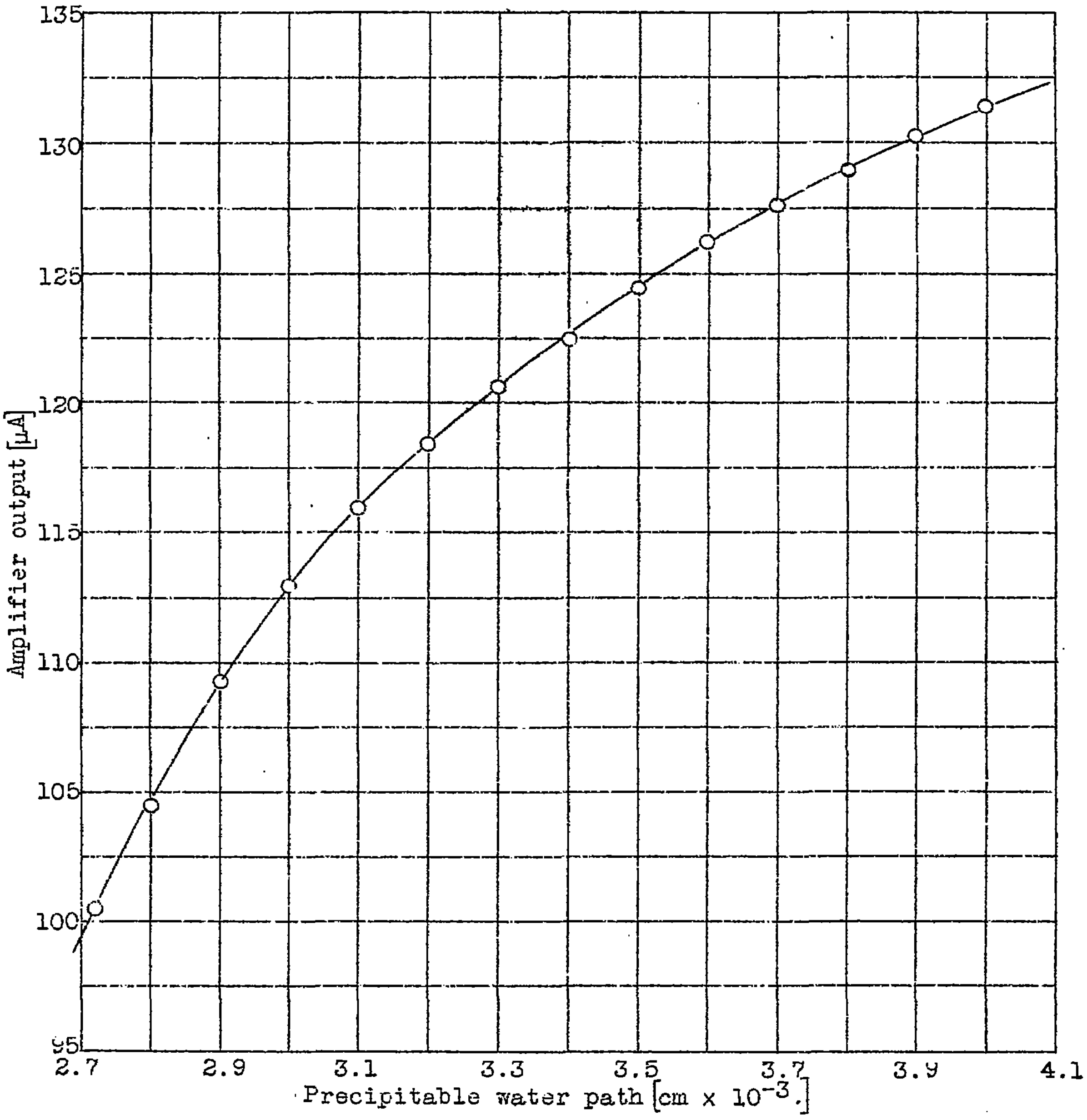


Figure 5.- Calibration curve.