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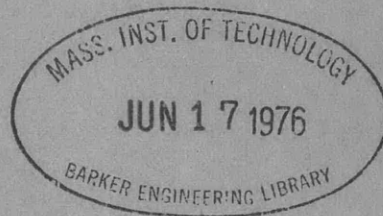
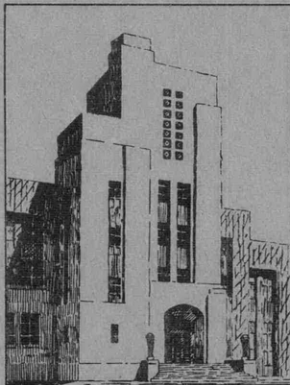
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THE DAVID W. TAYLOR MODEL BASIN

UNITED STATES NAVY

DESIGN, OPERATION, AND MAINTENANCE OF A METER
FOR RECORDING THE AIR CONTENT OF WATER IN
THE DAVID TAYLOR MODEL BASIN WATER TUNNELS

BY A. BORDEN, Ph.D.



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NAVY DEPARTMENT
DAVID TAYLOR MODEL BASIN
WASHINGTON, D. C.

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The research for finding a method for measuring the air content of water, suitable for use on the variable-pressure water tunnels, was carried out by A. Borden, Ph.D. Dr. G.G. Manov of the National Bureau of Standards was consulted on the feasibility of the plan. Except for certain modifications suggested by Dr. Borden, the air-content meter was designed, built, and calibrated by the Cambridge Instrument Company, Inc. L. Rubinowitz and L.E. Wedding helped with the installation of the instrument. W.H. Bowers aided in making preliminary tests with the air-content meter.

DESIGN, OPERATION, AND MAINTENANCE OF A METER FOR RECORDING THE AIR CONTENT OF WATER IN THE DAVID TAYLOR MODEL BASIN WATER TUNNELS

ABSTRACT

This report describes the theory and operation of the air-content meter which has been procured for use with the variable-pressure, open type water tunnels at the David Taylor Model Basin. The air content of the water is derived from a measurement of the thermal conductivity of the gases evolved when the water is scrubbed in an atmosphere of hydrogen. Certain difficulties which were encountered in pumping the water out to the instrument while the tunnel was being run under a vacuum are recounted. The results of preliminary investigations of the effect of air content on cavitation tests of propellers are also discussed.

Instructions for the operation and maintenance of the meter are given in the Appendix.

INTRODUCTION

Experience in operating the 12-inch variable-pressure water tunnel at the David Taylor Model Basin has clearly shown the necessity for controlling the air content of the water during cavitation tests on model propellers (1).^{*} Although effective methods have been developed for setting the air content at a particular value and maintaining it within moderate limits, no attempts have been made to measure its absolute value. An absolute measurement of the air content at frequent intervals during cavitation tests on propellers would not only add to the precision of the test but might also make it possible to establish laws of similitude between the model and prototype. This requires an instrument which can make determinations of the air content quickly while the tunnel is being run at reduced pressures, and which can indicate changes in the air content as they occur during the test.

EFFECT OF AIR CONTENT ON CAVITATION

Cavitation on propellers appears in two different forms, depending upon the design of the propeller blades and upon the operating conditions. The characteristics of the flow are conveniently designated as laminar or as burbling cavitation, or as a combination of the two. Laminar cavitation is characterized by a continuous separation of the water from the leading edge of the blade and by the formation of tip vortices downstream. Burbling cavitation, on the other hand, is characterized by the formation of bubbles

* Numbers in parentheses indicate references on page 19 of this report.

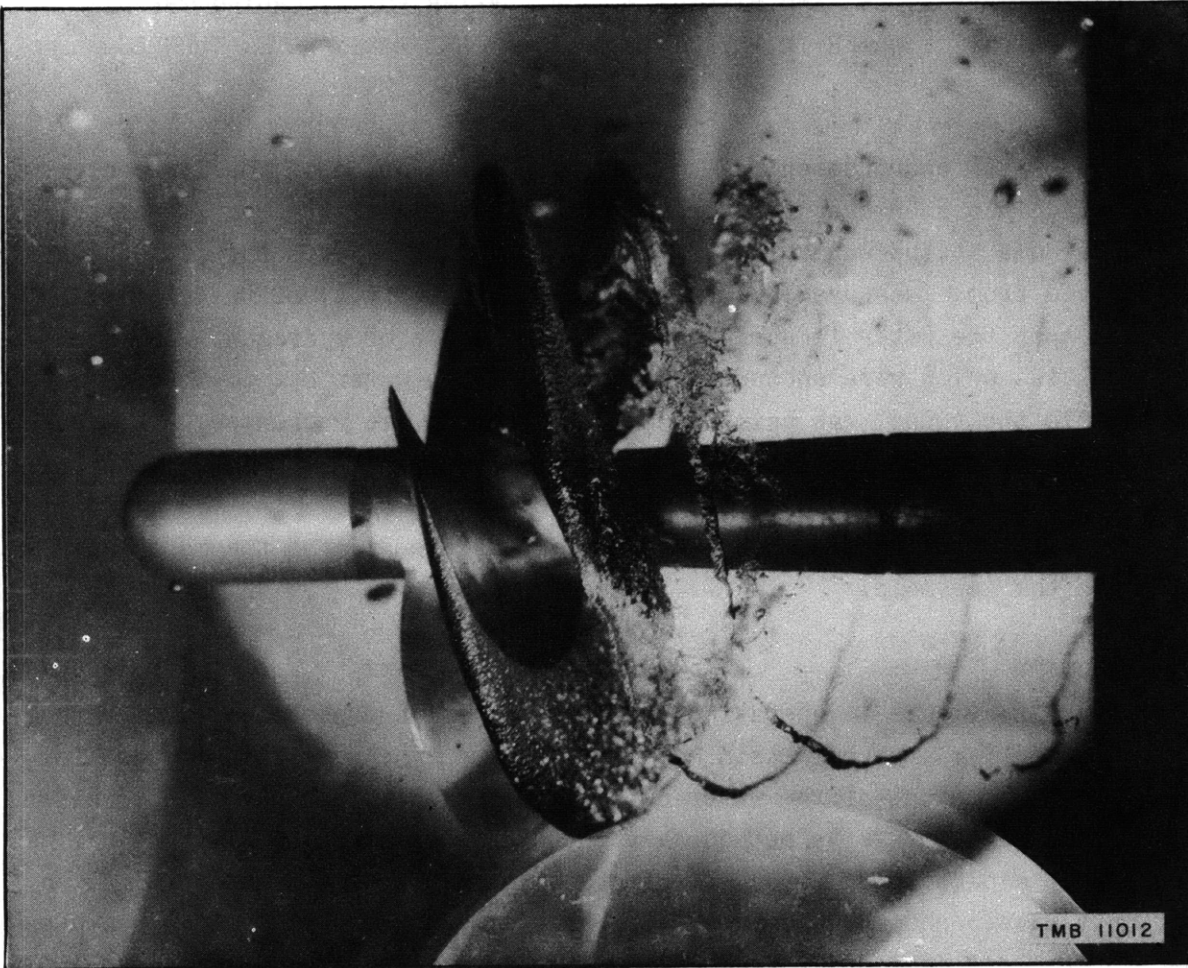


Figure 1 - Model Propeller Showing a Predominance of Laminar Cavitation

The back of each blade is half covered with laminar cavitation, and a cavitation void extends for some distance behind the blade.

which may cover a large portion of the back of the blade. The particular form of the cavitation developed depends upon the angle of attack of the propeller, the shape of the blade section, and upon the slip ratio. Most propellers exhibit both forms simultaneously but usually show a predominance of one or the other, depending upon the propeller design and the operating conditions. Typical examples of cavitation on propellers are shown in Figures 1 and 2.

A series of experiments (2) have been made in the 12-inch water tunnel to study the effect of variation of air content upon the operating conditions of different propellers. It was found that, whereas a propeller showing only laminar cavitation was not affected appreciably by the amount

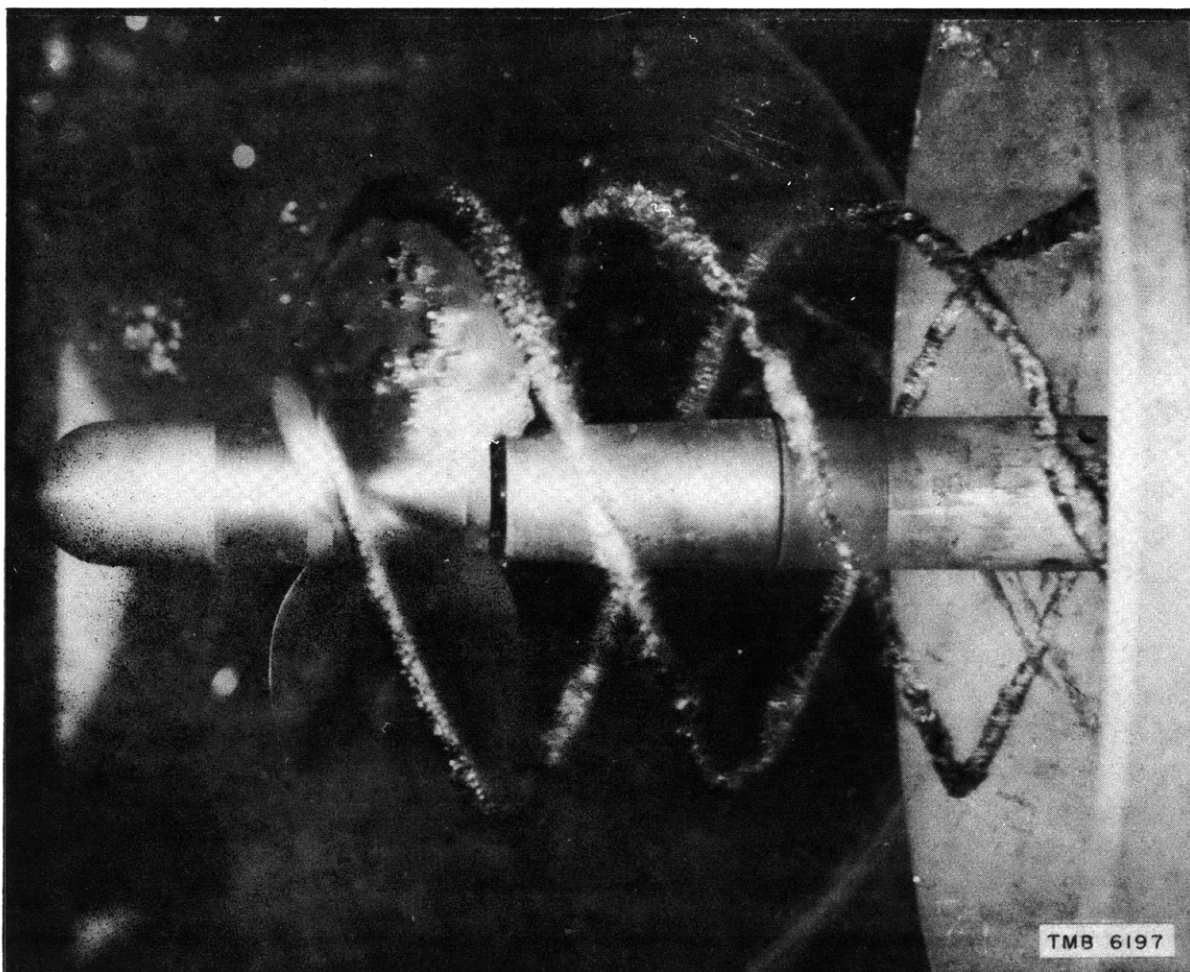


Figure 2 - Model Propeller Showing a Predominance of Burbling Cavitation

Heavy tip vortices extend down over the leading edge, and a fairly wide area of the blade is covered with burbling cavitation.

of dissolved air, one having a predominance of burbling cavitation showed marked differences as the air content of the water was varied. At high air contents the blades were almost completely covered with bubbles even at low water speeds; as the water became deaerated, a lower absolute pressure or a higher water speed was required to produce the same degree of cavitation. As a result of these tests it has become standard practice at the Taylor Model Basin to test the air content of the water in the water tunnels by testing a propeller whose behavior is very sensitive to changes in air content.

When gas is brought into contact with a liquid, it dissolves in the liquid until, when equilibrium has been established, a definite amount of gas has passed into the liquid. The equilibrium concentration of the gas in the

liquid is proportional to the partial pressure* of the gas on the surface of the liquid, and decreases with a rise of temperature. Under equilibrium conditions, the gaseous or vapor phase above the liquid consists both of the gas and of the vapor of the liquid in a certain concentration. By a slight extension of the term, the partial pressure of the vapor of the liquid may be called simply the vapor pressure of the liquid as modified (slightly) by the dissolved gas. It will be convenient, also, to call the partial pressure of the gas itself in the gaseous phase the vapor pressure of the gas dissolved in the liquid. According to the laws of gaseous solution, at a given temperature the vapor pressure of a dissolved gas is proportional to the concentration of the dissolved gas in the liquid.

If the partial pressure of the gas on the liquid is raised above the vapor pressure of the dissolved gas, more gas will go into solution. If the partial pressure of the gas on the liquid is less than the vapor pressure of the dissolved gas, gas will be evolved from the solution.

Cavitation bubbles are usually formed about dust particles in the liquid or about rough protrusions on objects in the fluid stream. Dr. E.N. Harvey and his associates at Princeton University (3) (4) have made an exhaustive study of the conditions under which bubbles form in a liquid. They found that whereas bubbles form only at extremely large negative pressures in liquids entirely free from nuclei, bubbles form very readily in ordinary liquids which are not free of dust particles. The observations are further confirmed by studies of the flow of water through venturi tubes. Van Iterson (5) describes an experiment in which powdered coal was added to water which was circulated through venturi tubes, to increase the number of nuclei available for bubble formation. Although no quantitative pressure measurements were made, cavitation was found to start at pressures considerably higher than usual.

If the air content is high, cavities may form in a liquid at pressures considerably above the vapor pressure of the liquid, indicating that the cavities contain evolved air as well as water vapor. This is borne out by the work of Numachi and Gutsche (6) (7) who have made a series of studies on the effect of air content on the cavitation and flow of water through venturi tubes. Numachi has developed a method for measuring the air content of the water and has found that the incipience and degree of cavitation are very sensitive to changes in air content.

Both the air content and the cleanliness of the water have been found to affect the cavitation on propellers under test in the water tunnels

* When a gas is made up of several component gases, the pressure exerted by each component is its partial pressure of the total pressure. The partial pressure of each gas in a mixture of gases is proportional to the relative amount (by volume) of that gas in the mixture.

at the Taylor Model Basin. Although there is no satisfactory way of controlling the number of bubble-forming nuclei, the water is frequently filtered to remove particles of dirt. Under normal operating conditions the pressure in the water tunnel is reduced to a few inches of mercury at the test section. After the tunnel has been run for a short time, the water becomes deaerated, if not to equilibrium, at least to a point where the rate at which air is evolved is rather slow. If unusually low pressures are being used in the tunnel, air is bled into the water stream in an effort to maintain a constant air content.

MEASUREMENT OF THE AIR CONTENT OF WATER

Although the importance of controlling the air content of the water during propeller tests has been recognized for some time, it was not until recently that an instrument was procured at the Taylor Model Basin for this purpose. For several years the air content has been set by running a standard propeller at the beginning of a test and check-running it again at the end. This procedure is time-consuming, and the exact value of the air content is still not known. A detailed account of this method for setting the air content is described elsewhere, along with general testing procedures (1).

The air content of water has been determined in a number of ways, some of which are direct measurements, while others depend upon a determination of the oxygen content of the water. Although the amount of oxygen dissolved in pure water is a known fraction of the total gas content, this may not be true of the water in the tunnel. In fully aerated water the normal ratio of nitrogen to oxygen dissolved in the water is two to one. During cavitation tests at reduced pressures, air is continually bled back into the tunnel to hold the air content constant. Since air contains four parts of nitrogen to one part of oxygen and since the water is not saturated, a larger proportion of nitrogen may be dissolved than would normally be the case. This would upset the normal ratio and an oxygen determination would not give an accurate measure of the air content.

The oxygen-nitrogen ratio might also be upset if the water of the tunnel were contaminated. Bacteria feeding on organic material in the water of the tunnel could absorb a large fraction of the dissolved oxygen. Measurements made at the Cambridge Instrument Company in Ossining, New York, indicate that tap water is only 80 per cent saturated with oxygen. Since the same water is used in the Taylor Model Basin tunnels for many months, there would be some doubt as to the relative amounts of oxygen and nitrogen on this account also. Hence, only direct methods for measuring the air content were

considered in designing an instrument for measuring the air content of the water in the tunnel.

Most of the direct methods for measuring air content consist in extracting air from the water under a vacuum and measuring the pressure with a manometer. Instruments of this type are described by Numachi (6) and Van Slyke (8). Professor F.M. Lewis uses a similar apparatus in conjunction with the variable-pressure water tunnel at the Massachusetts Institute of Technology. The water is scrubbed under a vacuum by forcing it through a small orifice a number of times. The pressure of the evolved air is read on a manometer. Since the rate at which air comes out of solution decreases exponentially with time, considerable time is required to make a reliable determination. Numachi's apparatus requires an hour to evolve 80 per cent of the air and about three hours to make an accurate determination. The instruments used by Professor Lewis and Van Slyke require about an hour to give a determination which is accurate within a few per cent. Because of the long time delay, a method of this type would not be useful for measuring the air content of the water during propeller tests. Since the air content of the water of the tunnel is continually changing, an instrument is needed which can give a determination in a few minutes and which can register changes in air content quickly.

CAMBRIDGE DISSOLVED-AIR RECORDER

The instrument which has been adopted for use at the Taylor Model Basin depends upon a direct measurement of the vapor pressure of the dissolved air by a thermal-conductivity method (9) (10). Water is pumped through the instrument at a uniform rate and a continuous record of the air content is made by an automatic recorder. This is a modification of an instrument which has been used successfully for many years for measuring the oxygen content of boiler feed water (11). Through collaboration with the Cambridge Instrument Company the instrument was modified to record larger air contents than had previously been measured. Scales are available from which either the air content of the water or the vapor pressure of the dissolved air may be read directly.

DESCRIPTION OF THE AIR-CONTENT METER

In the operation of the instrument, air is scrubbed from the water in an atmosphere of hydrogen. The air content is determined by comparing the thermal conductivity of this hydrogen-and-air mixture with that of pure

hydrogen. Two identical cells containing electrically heated platinum wires are mounted in two arms of a Wheatstone bridge as shown in the upper part of Figure 3. One of the platinum wires is surrounded by an atmosphere of pure hydrogen and water vapor, and the other by the mixture of hydrogen and air from the scrubbing-tower atmosphere. When the composition of gas in the two cells is identical, the bridge balances. When, however, the exposed spiral is surrounded by an atmosphere of hydrogen and air, the resistance of the wire is increased due to the decreased thermal conductivity, and the bridge is thrown out of balance.

The circulation of water through the instrument is as shown in Figure 3. The sample water from the tunnel enters the instrument at a rate of about a pint of water per minute. Part of the water rises in a constant-head tower where it overflows and is collected in an exit tank; the rest flows through the temperature regulator to the analyzer. The flow is adjusted so that a small quantity of water can be seen in the sight glass at all times. This adjustment controls the rate of flow of the water and the pressure of the gas in the thermal-conductivity cell. At the analyzer the water circulates around the block containing the sensitive cells and maintains them at a uniform temperature. Finally, the water enters the scrubbing venturi tube where it is scrubbed in an atmosphere of hydrogen. Air is liberated from the water until the partial pressure of the air in the scrubbing tower is in equilibrium with the air dissolved in the water. The gas mixture diffuses into the comparison cell where its thermal conductivity is measured relative to that of pure hydrogen. The excess gas is gradually dissolved by the test water which leaves the analyzer through the overflow cup.

The hydrogen gas, which is generated by a small electrolytic cell, diffuses into the analyzer through a filter which prevents the hydrogen-air mixture from diffusing back. If the pressure builds up in the scrubber, less hydrogen can pass through the filter and the pressure increases in the electrolytic cell. The increased pressure forces the water level of the cell down, thereby decreasing the immersed area of the hydrogen electrode and the rate of generation of hydrogen. If, on the other hand, the pressure in the analyzer is low, the water level rises and hydrogen is generated at a faster rate.

The zero of the instrument may be checked by opening the zero-check valve shown in Figure 3. The water then bypasses the scrubbing venturi tube and flows directly to the exit tank. The flow of water past the opening to the scrubbing tower reduces the pressure in the scrubbing chamber. Thus the chamber is gradually filled with pure hydrogen from the electrolytic cell and the galvanometer needle moves toward zero air content. About 45 minutes is required to attain complete equilibrium.

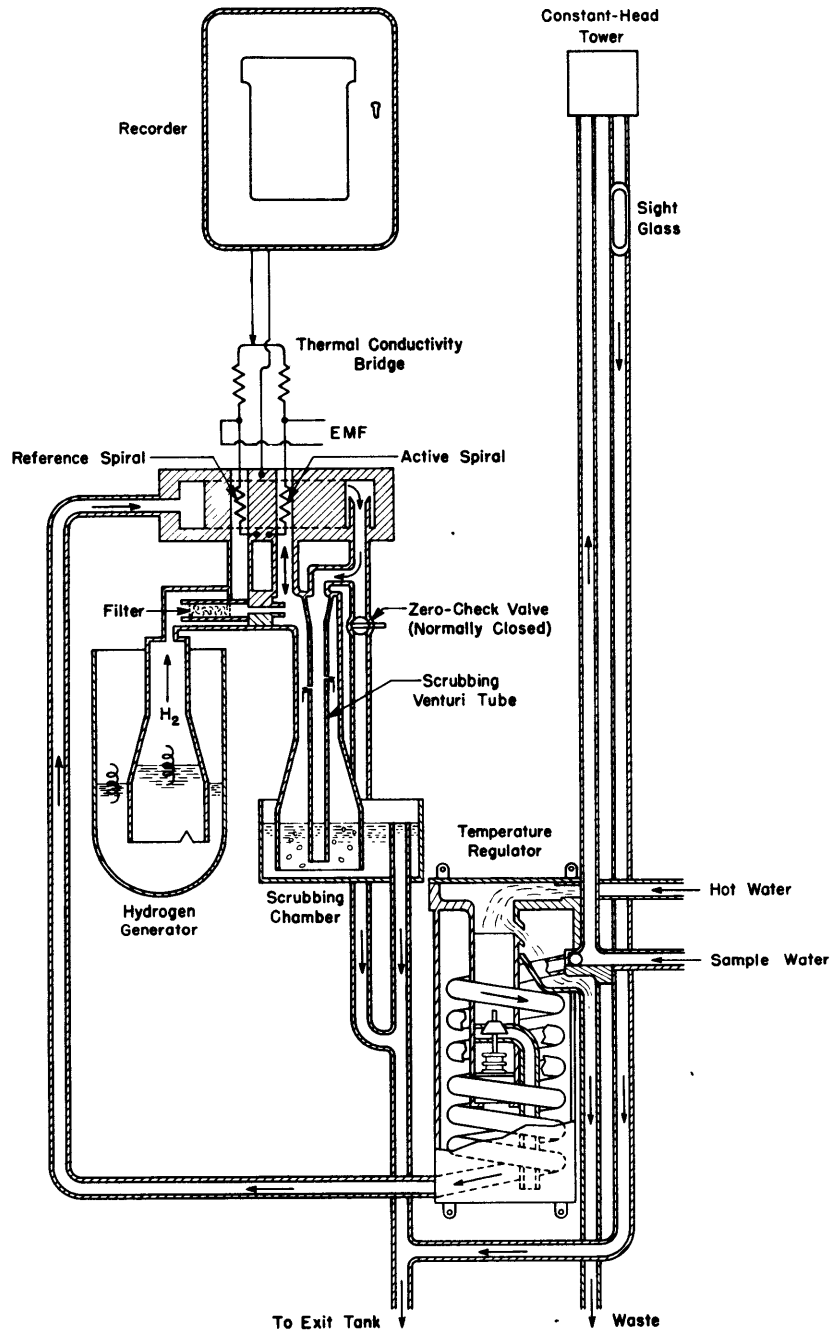


Figure 3 - The Air-Content Meter

Instructions for the operation and maintenance of the air-content meter are given in the Appendix.

Although the air-content meter was designed and calibrated to measure the amount of air dissolved in water, it may also be used for measuring

the vapor pressure of the dissolved gases. In its operation, as water is scrubbed through the venturi tube, air is evolved until equilibrium is reached, and the partial pressure of the evolved air in the scrubbing chamber has become the vapor pressure of the air dissolved in the water. Since the thermal conductivity of the gas in the sensitive cell is proportional to the amount of gas liberated from the water, the operation of the meter depends upon a measurement of the vapor pressure of the dissolved gases. As the air content of water at a particular temperature and pressure is proportional to the vapor pressure of the air dissolved in the water, the meter may be calibrated to read air content. On the other hand, since the operation of the meter depends upon a measurement of the vapor pressure of the dissolved gas, it may just as readily be calibrated to read the vapor pressure of the gases dissolved in the water.

The air-content meter was originally calibrated by the Cambridge Instrument Company to measure the air content of water in cubic centimeters of dissolved air at 0 degrees centigrade per liter of water under standard pressure and at some particular temperature of the test water. A constant pressure is maintained by the constant-head tower of the instrument. In this use the temperature at the analyzer is held constant at a particular value by the temperature regulator. As the temperature of the test water varies between 65 degrees fahrenheit and 85 degrees fahrenheit with changing seasons, two calibration scales were required to be furnished with the instrument: one used when the temperature control is set at 75 degrees fahrenheit and the other when the temperature control is set at 85 degrees fahrenheit. These scales may be screwed in place on the meter so that the instrument is direct-reading.

The vapor-pressure scale for the air-content meter is calibrated to read the vapor pressure of the dissolved air in feet of water. Since it is necessary to measure the vapor pressure of the dissolved air at the temperature of the test water, the temperature control of the instrument is not used.

The scale for measuring the vapor pressure of the dissolved air was constructed at the Taylor Model Basin with the aid of the air-content scale for the 85 degrees fahrenheit temperature control. The pressure of the dissolved air was assumed to be 1 atmosphere at the point on the scale where the water was fully saturated with dissolved air. Since the partial pressure of the dissolved air is proportional to the air content of the water, the vapor-pressure scale was divided to make it proportional to the air content in units of feet of water.

Although the vapor-pressure scale of the instrument was calibrated for a temperature of 85 degrees fahrenheit at the analyzer, calculations have

shown that the same calibration should hold with a sufficient degree of accuracy for other water temperatures encountered in the water tunnel. If the instrument is operated at a lower temperature, the vapor-pressure reading of the dissolved gases would be somewhat lower than the true value, owing to the decreased thermal conductivity of the gases about the active spirals in the Wheatstone bridge circuit. Careful consideration, however, based on the known variation of thermal conductivities of hydrogen and air with temperature, indicate that, for the temperature changes occurring in practice, the error in the vapor-pressure reading of the instrument should not exceed two or three per cent. For practical purposes this error is considered negligible.

SETTING THE READING OF THE AIR-CONTENT METER

In its normal operation the air-content meter requires considerable time to reach equilibrium after an appreciable change in air content. It is possible, however, to hasten the establishment of equilibrium in a few minutes by the proper manipulation of the zero-check valve and the electric current through the hydrogen generator.

If the meter is approaching the true value of the air content from above, it can be brought quickly to lower values, closer to the true value, by putting it into its zero-check position for about a minute. This is done by turning the zero-check valve shown in Figure 3 to its vertical position. The water bypasses the scrubbing venturi tube and the analyzer fills with hydrogen from the hydrogen generator. When an approximately correct reading is reached, the instrument may be put into its usual operating condition.

If the meter is indicating, at the moment, too low a value for the air content, it may be brought to higher values by switching off the current to the hydrogen generator for a few minutes. As the water is scrubbed through the venturi tube, the atmosphere of the analyzer becomes richer in evolved air and the meter registers higher air contents.

CALIBRATION OF THE AIR-CONTENT METER

The original calibration of the air-content meter covered a range from zero air content to full saturation. After the meter had been tested during cavitation tests on propellers, it was found that a range in air content from zero to 5 cubic centimeters of dissolved air per liter of water would be sufficient and far more desirable. This conversion was made by inserting a suitable resistor into the Wheatstone bridge circuit and adjusting its value to make the meter read full scale for an air content of 5

cubic centimeters of dissolved air per liter of water. Since the functional relationship between air content and the scale readings of the meter was known, a new scale was constructed for the meter. The meter was calibrated for the new sensitivity by a Winkler test (12) which measures the amount of oxygen dissolved in the water. The final adjustment of the resistor in the Wheatstone bridge circuit was made after the meter was calibrated.

Although air contains four times as much nitrogen as oxygen, oxygen is about twice as soluble in water as nitrogen. Under normal conditions the gas content of water is 33 parts oxygen to 67 parts nitrogen. This ratio is maintained at all pressures during deaeration of the water. During cavitation tests, however, air is continually bled into the tunnel water to take the place of the air that is being removed. Since the water is no longer saturated, air may now go into solution in the ratio of 4 parts of nitrogen to 1 part of oxygen, the normal ratio for air. Thus the normal gas content ratio of the water is upset, and there is no way of knowing the relative amounts of the two gases.

Since the thermal conductivities of oxygen and nitrogen are nearly the same, the air-content meter cannot differentiate between them but measures the combined vapor pressure of the two gases evolved during the scrubbing action of the analyzer. Due to the different solubilities of the two gases the meter would fail to give the true volumetric gas content if the normal gas content ratio were appreciably upset. At a pressure of 1 atmosphere a sample of water fully saturated with dissolved nitrogen at a temperature of 75 degrees fahrenheit has a gas content of 14.5 cubic centimeters at 0 degrees centigrade per liter of water. Under the same conditions a sample of water fully saturated with dissolved oxygen has a gas content of 28.1 cubic centimeters at 0 degrees centigrade per liter of water (13). Since the vapor pressure of the dissolved gas is 1 atmosphere in either case, the air-content meter would read the same.

Since the true gas content of the water corresponding to a given reading of the meter varies with the relative amounts of nitrogen and oxygen, the meter was calibrated for the normal ratio of 33 parts of oxygen to 67 parts of nitrogen in the water. Although the ratio of gases dissolved in the water of the tunnel may depart from this value, the instrument will indicate the normal air content which has the same gaseous pressure as the sample of water under test. Inasmuch as the amount of gas liberated in cavitation bubbles is also presumably proportional to the vapor pressure of the dissolved gases, without distinction between nitrogen and oxygen, the air-content meter should give a reliable cavitation index, whatever the proportions of dissolved gases.

The calibration of the air-content meter was made by two oxygen determinations, before and after oxygen was added to the water. Since the water of the tunnel was near 80 degrees fahrenheit the temperature control was set for 85 degrees fahrenheit. First, the water of the tunnel was circulated rapidly at low pressure for several hours, until the air content was reduced to about 1 cubic centimeter of air per liter of water. Several determinations of the oxygen content were made by Winkler test. Then pure oxygen was bled into the tunnel and dissolved in the water. When the meter registered nearly full scale, several new oxygen determinations were made. The difference in these two sets of determinations gave the increase in the concentration of oxygen. From these data and the relative solubilities of oxygen and nitrogen the equivalent change in air content was calculated on the basis of 67 parts of nitrogen to 33 parts of oxygen in the water. From the ratio of the scale reading of the instrument and the computed increase in air content, a correction factor was found for the scale. Finally, the meter was made direct-reading by adjusting one of the resistors in the Wheatstone bridge circuit of the instrument.

As soon as a scale had been constructed for measuring the air content of water at one temperature, it was possible to construct scales for measuring it at any other temperature from the known variation of air content with temperature (12). A second air-content scale was constructed for a temperature control of 75 degrees fahrenheit.

INSTALLATION OF AIR-CONTENT METER ON THE WATER TUNNEL

Figure 4 shows the installation of the air-content meter on the water tunnel. The test water is taken from the bottom of the tunnel ahead of the impeller. At this point the pressure is about 15 feet of water when the tunnel is run under a vacuum. A small screw pump raises the water to the instrument. Only part of the water goes to the instrument, the rest is returned to the top of the tunnel. The rate of flow is controlled by two needle valves, 1 and 2 in Figure 4. Valve 2 creates a back pressure just sufficient to keep a small amount of water overflowing in the constant-head tower.

The pump used for raising the water to the instrument has a water seal on the packing around the shaft to keep air from leaking in. This is accomplished by installing a small bypass line from the high-pressure side of the pump into the packing box around the shaft.

The water which flows from the analyzer joins the water from the constant-head tower and drains into a small tank at the base of the instrument. Here the flow of water back to the tunnel is controlled by a float valve. The vacuum above the free surface of the tunnel is usually sufficient

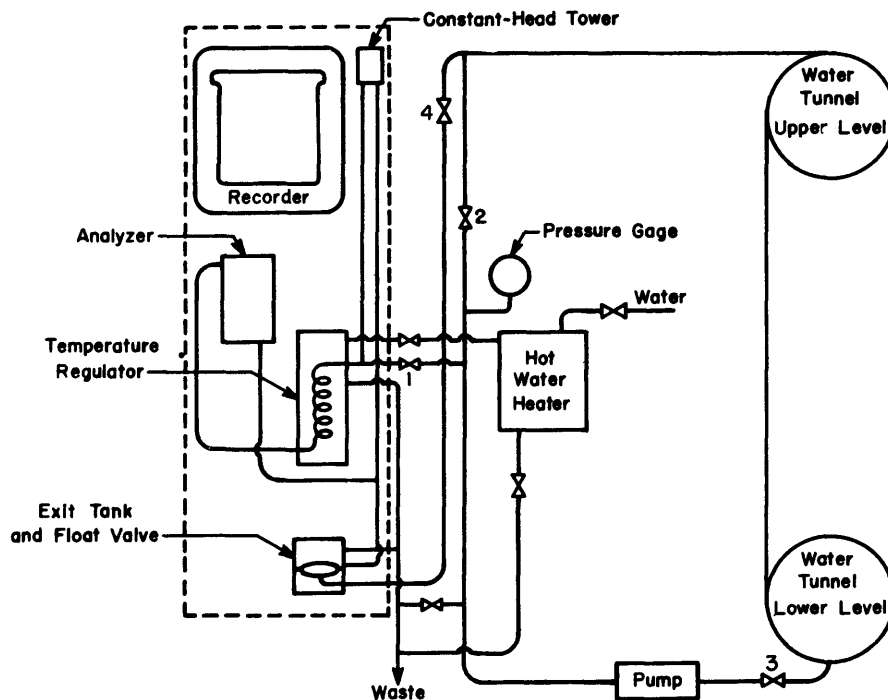


Figure 4 - Installation of the Air-Content Meter on the 12-Inch Water Tunnel

to draw the water back. The drain tank is provided with an overflow which takes care of the test water when the tunnel is operating at higher pressures. During cavitation tests when the pressure at the test section is low, it is important to have an effective means of returning the water to the tunnel to maintain a constant water level in the test section.

Considerable difficulty was originally encountered with slugs of air which entered the piping system of the meter, especially when the tunnel was being operated at low pressures. Once air pockets occurred in the pipes, the flow practically ceased until they were eliminated. Sharp bends and loops in the pipes were avoided wherever possible to prevent the trapping of air.

When the instrument was first installed, the water for air-content determination was taken from the side of the lower section of the tunnel. Although the air-content records were quite steady at low water speeds, sharp irregularities were encountered when the water was circulated rapidly. Bubbles of air often remained entrained in the water even at the lower level and presumably were swept into the line leading to the air-content meter. Although these bubbles were too small to affect the flow appreciably, they were large enough and numerous enough to impair the air-content record. As bubbles

rise, this difficulty was overcome by taking the test water from the bottom of the lower tunnel section at the downstream end. After this change was made, spurious fluctuations in the air-content record were largely eliminated.

PRELIMINARY INVESTIGATIONS WITH THE AIR-CONTENT METER

In tests of ship and propeller designs at the Taylor Model Basin, models are scaled down from the prototype according to Froude's law of similitude. In addition to changes in linear dimensions, velocities, thrusts, and other factors, it is necessary to make a reduction in pressure in the same ratio as the reduction in linear dimensions. All the necessary changes except the scaling down of the pressure can be made in open-water self-propelled tests in the model basin. As long as the propeller is not to be used in the cavitation range, the pressure correction is unimportant. Since some ship propellers are known to cavitate under certain operating conditions, it is necessary to know under what conditions cavitation begins and how it affects the performance of the propeller. In order to obtain similitude in pressure between the model and full scale, propellers are tested under reduced pressures in the water tunnel.

Although the law of similitude requires that the pressure for the model test be reduced by the same ratio as the linear dimensions, experience has shown that this reduction in pressure produces insufficient cavitation as compared with that found on ship trials. Comparison between ship trials and model-propeller tests indicates that the pressure should be reduced between 10 and 20 per cent more in order to duplicate the test conditions. Although all propellers tested do not require the same correction factor, it has become standard practice to apply a correction factor of 85 per cent to the calculated pressure for cavitation tests.

The value of the pressure-correction factor has been found to vary appreciably with changes in the air content of the water. This is probably due to the fact that the cavities are filled not only with water vapor but also with air evolved from the water. Although the pressure is corrected for the vapor pressure of the water, a further correction is needed for the vapor pressure of the dissolved gases. The amount of gas evolved depends not only upon its concentration and the pressure of the water but also upon the mobility of the gas molecules in the water and the lifetime of the bubble. Thus, the derivation of a proper correction for the pressure will not be easy and may vary for different propellers and different operating conditions. It will probably be necessary to accumulate considerable data before the role of dissolved gases in water can be fully understood.

Before the present air-content meter was procured, the air content was set by deaerating the water until the proper correction factor was obtained for a certain propeller which was chosen as a standard. This propeller, which shows a predominance of burbling cavitation, has an assumed pressure-correction factor of 85 per cent and is extremely sensitive to changes in the air content of the water. For this reason, this propeller was used in the preliminary investigations with the air-content meter.

Preliminary tests with the air-content meter consisted in finding a relation between the air content of the water and the pressure-correction factor for the standard propeller. The tests were begun in the summer of 1944 when the temperature of the water in the tunnel was between 85 degrees and 95 degrees fahrenheit, and were continued during the following winter when the temperature of the water was about 70 degrees fahrenheit. It was found that the air content necessary to give standard conditions varied with temperature. With the temperature near 90 degrees fahrenheit the air content was about 2.9 cubic centimeters per liter of water, but near 70 degrees fahrenheit it increased to about 3.5. Although this represents a large change in air content for a relatively small change in absolute temperature, calculations showed that the vapor pressure of the dissolved air was substantially the same. In view of this discovery an attempt was made to correlate the pressure-correction factor of the standard propeller with the vapor pressure of the dissolved air.

A series of tests were undertaken to study the effect of temperature changes in the water of the tunnel on the relation between the pressure-correction factor of the standard propeller and the scale reading of the air-content meter. The temperature control of the instrument was not used so that the scale readings were proportional to the vapor pressure of the dissolved air. Several points were found for different air contents at room temperature, and then the temperature of the water was raised about 15 degrees to 86 degrees fahrenheit. This was done by inserting three 4000-watt heaters into the jet of the tunnel. The water was heated for about eight hours during the night, and the tests were continued the next day.

In Figure 5 the pressure-correction factor for the standard propeller is plotted against the scale reading of the air-content meter for both temperatures. Both sets of points fall along the same line, indicating that the pressure-correction factor depends upon the vapor pressure of the dissolved air rather than upon the actual air content of the water, and that it is independent of the temperature. This is further borne out if these points are plotted on the same curve with data taken during the previous summer. The air-content meter was being used without the temperature control at that

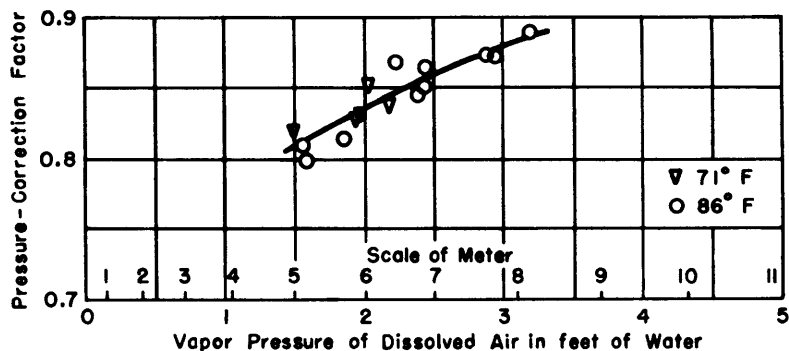


Figure 5 - Variation of Pressure-Correction Factor with Vapor Pressure of Dissolved Air at 71 Degrees and 86 Degrees Fahrenheit

No temperature control was used.

time and the temperature of the water varied between 85 degrees and 95 degrees fahrenheit. This curve is shown in Figure 6.

The points in Figures 5 and 6 show considerable scatter. In the usual operating conditions for determining the correction factor with the standard propeller, the water is circulated rapidly at low pressure. Under these conditions the water of the tunnel is constantly deaerating and it is difficult to bleed air into the tunnel at just the proper rate to keep the air content constant. It is likely that many of the points were recorded

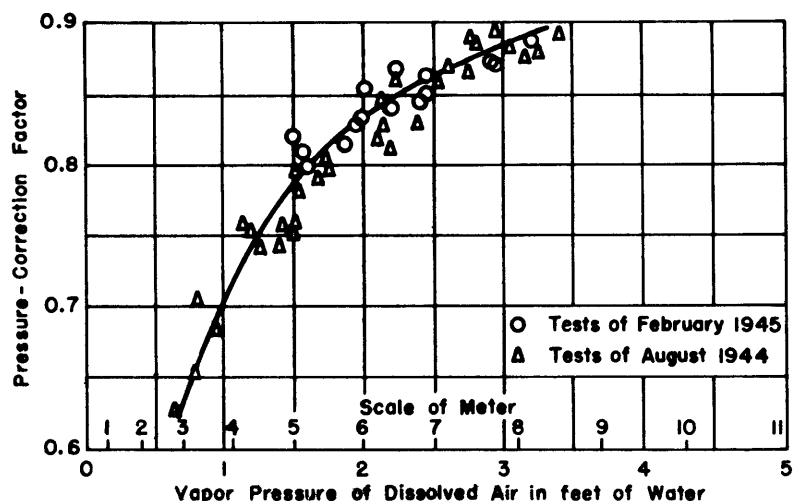


Figure 6 - Variation of Pressure-Correction Factor with Vapor Pressure of Dissolved Air

No temperature control was used.

before the instrument had reached complete equilibrium. It is also possible that the pitch and condition of the blade surfaces of the propeller changed slightly with continued use.*

A typical air-content record made during a propeller test is shown in Figure 7. The air content was set with the standard propeller near the

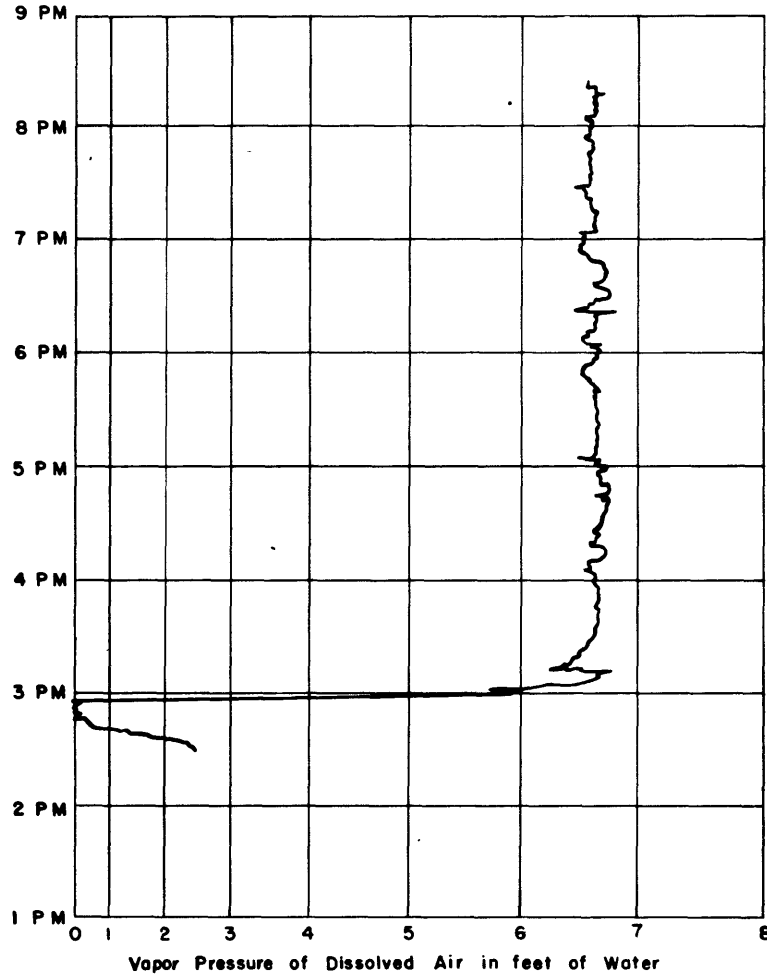


Figure 7 - Typical Air-Content Record Made during a Propeller Test

The zero of the instrument was checked at the beginning of the test. The instrument was put into normal operation for measuring the vapor pressure of the dissolved air.

beginning of the record. During the test the air content was held within narrow limits by controlling the rate at which air bubbles were bled into the tunnel.

* A brass model of the standard propeller has been made which is stronger than the former one and is less likely to be damaged in service. These measurements will eventually be repeated with the new propeller, allowing more time for the instrument to come to equilibrium between runs.

The results of the preliminary investigations suggest that a true cavitation index should be a function of the dissolved air in somewhat the same way as it is a function of the vapor pressure of the water. Thus the cavitation index

$$\sigma = \frac{P - p_w - xp_a}{q}$$

where P is the absolute static pressure,

p_w is the vapor pressure of the water,

p_a is the vapor pressure of the dissolved air, and

q is the dynamic pressure.

x is an undetermined coefficient, independent of p_a , which is obviously always less than 1.0. The value of x will depend upon the rate at which the dissolved air can migrate through the water and come out of solution, and upon the lifetime of the cavity.

There are many variables in bubble formation and model propellers which are affected quite differently by variations in the vapor pressure of dissolved air, depending on whether laminar or burbling cavitation predominates. Therefore considerable experimentation will be required to determine a proper physical concept of the coefficient x .

CONCLUSIONS

The air-content meter is proving itself very useful in setting and controlling the air content of the water in the 12-inch water tunnel during cavitation tests. Tests can begin as soon as the meter is brought to the required reading. Considerable time can be saved since the laborious task of setting the conditions with the standard propeller can be eliminated. During the tests variations in air content are recorded as they occur and may be corrected for by bleeding sufficient air into the tunnel to hold the meter reading fixed.

Preliminary tests with the air-content meter have shown that cavitation is affected by the vapor pressure of the dissolved air rather than by the actual air content of the water. Now that it is possible to measure and control the vapor pressure of the dissolved air, fundamental research on the nature of cavitation can be carried out in the water tunnel. As the work continues it may become possible to establish conditions of similitude between model propellers and their prototypes which will include the effects of dissolved air in the scaling down of pressure.

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APPENDIX

OPERATION AND MAINTENANCE OF THE AIR-CONTENT METER

DIRECTIONS FOR OPERATING THE AIR-CONTENT METER DURING CAVITATION TESTS

The installation of the air-content meter on the 12-inch water tunnel at the Taylor Model Basin is shown in Figure 4.

Before starting the flow of water through the meter, Valves 2, 3, and 4 should be open. Valve 1 should be kept closed until the vacuum has

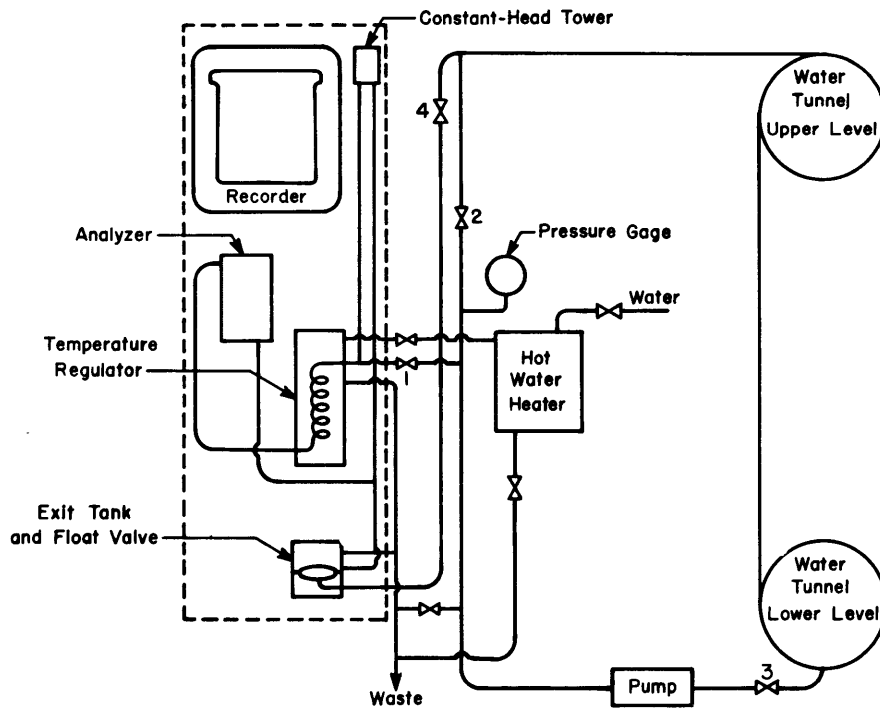


Figure 4 - Installation of the Air-Content Meter on the 12-Inch Water Tunnel

been put on the tunnel, otherwise, the exit tank will overflow and the water level of the tunnel will change. After the pump is started and the vacuum has been put on the tunnel, the flow of water through the meter may be regulated by adjusting Valves 1 and 2. It is best to keep a back pressure of about 20 or 30 pounds per square inch just ahead of Valve 2. This pressure may be read on the pressure gage indicated in Figure 4.

Once the flow of water through the instrument is started, the meter should be turned on. There are three electrical switches: one controls the power pack, one controls the recorder mechanism, and the third turns on the current for the hydrogen generator.

If the vacuum is removed from the tunnel for only a few minutes, for example, to change a propeller, the instrument need not be turned off. During the time that the vacuum is off the tunnel, however, the test water does not return to the tunnel but collects in the exit tank. If the tunnel is closed and if the vacuum is put back before the water in the exit tank overflows to waste, the level of the tunnel will not change and there will be no interruption in the air-content record.

If, however, the tunnel is to be opened for a longer period, the flow to the meter should be cut off by closing Valve 1 of Figure 4. If the zero-check valve is left in its usual operating position, no air can get into the analyzer and the meter will not drift very far from its equilibrium position.

When the test is finished, the flow of water through the instrument should be cut off by closing Valve 1 of Figure 4 before the vacuum is removed from the tunnel. If no air is allowed to get into the analyzer, less time is required for the instrument to reach equilibrium when it is used again. Valves 2, 3, and 4 may be left open.

REGULAR MAINTENANCE OF THE AIR-CONTENT METER*

1. Electrolyte of the Hydrogen Generator. The level of the electrolyte in the hydrogen generator should be checked frequently to make sure that it comes between the two lines etched on the glass. Although the hydrogen generator is originally filled with a 10 per cent solution of sodium hydroxide, the level should be maintained by adding distilled water through the hole in the cover. If the liquid looks dirty, it should be replaced by a fresh solution.

* Most of the material in the second, third, and fourth sections of this Appendix was obtained from the Instruction Book which was supplied with the air-content meter (14).

2. Standardization. About once a month the recorder should be standardized by turning the manual standardizing knob found on the front of the recorder at the left of the chart. This adjustment should bring the galvanometer needle to the center third of its range. If it does not, the Resistor L in the power pack should be adjusted until the recorder brings the needle within this range. If the flag at the front of the recorder reaches the first chart line, it indicates that the meter needs to be standardized.

3. Electrical Zero. The electrical zero of the thermal conductivity meter may be checked by turning the zero-check valve to its vertical position. The water will then leave the apparatus through the zero-check valve in front of the analyzer, thus bypassing the scrubbing chamber. The liquid level in the hydrogen generator will rise, thus increasing the rate of hydrogen generation. The hydrogen will be sucked out of the analyzer by the sample water passing through the exhaust tube. The instrument should be allowed to run in this manner until it has drawn a straight line on the chart. If this line does not coincide with the zero reading on the scale, it should be adjusted by the electrical zero adjuster on the panel board of the thermal-conductivity meter block, shown in Figure 8, until it does.

4. Current through the Thermal-Conductivity Bridge. The current through the thermal-conductivity bridge should be checked while the instrument is operating on zero-check. After the current in the power pack is turned off, the plug in the upper socket on the panel board of the power pack should be removed and pushed into the jacks marked "STD," observing the proper polarity. When the current in the power pack is turned on again, the recorder should deflect to the long red line near the top of the scale. If it does not, the Resistors C (coarse) and E (fine) in the power pack should be adjusted until it does. The power should be turned off again while the plug is being returned to the upper socket on the panel board. If the power for the power pack is not turned off while removing or replacing the plug, the capacitor in the power pack may discharge through the platinum spirals and damage them. If the current through the thermal-conductivity bridge requires appreciable adjustment, it may be necessary to reset the zero of the meter while it is still on zero-check.

5. Servicing the Recorder. The operation and servicing of the recorder are described in Leeds and Northrup Direction Books STD 1235 and STD 11212. Certain parts of the recorder require lubrication once a month.

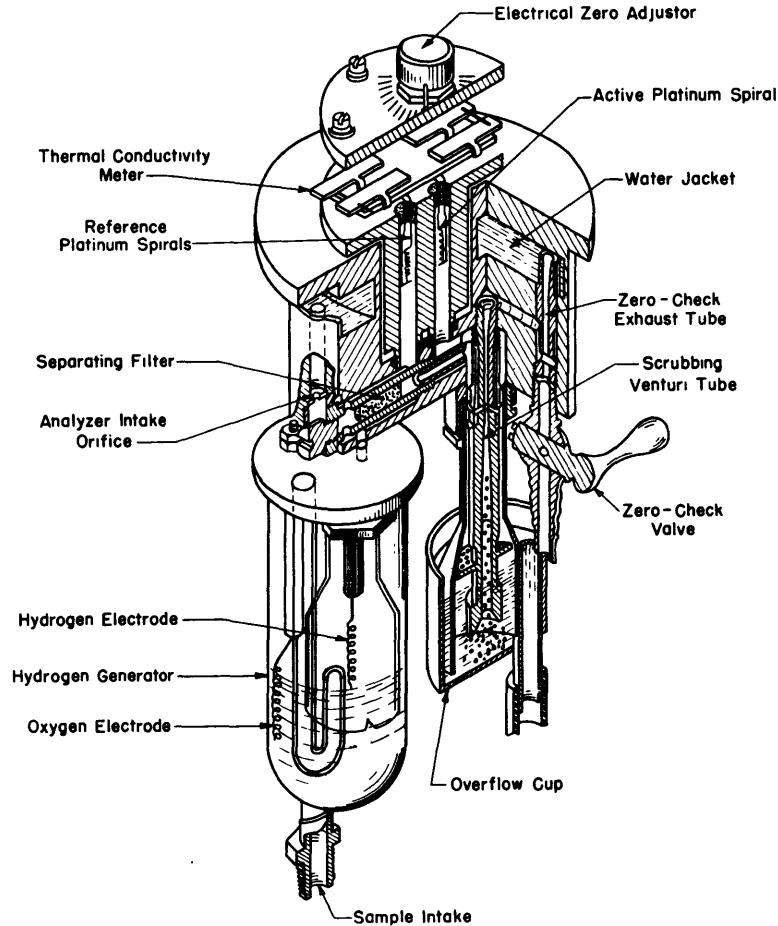


Figure 8 - Assembly of the Gas Analyzer of the Cambridge Dissolved-Air Recorder

UNUSUAL MAINTENANCE AND CORRECTION OF DIFFICULTIES

1. Sample Flow. When the instrument is operating properly, there is some overflow at the constant-head tower. Although the rate of flow through the instrument is not critical for its proper operation, a lower than normal flow usually indicates a stoppage of water in the passages and is a method of detecting trouble before it affects the readings. The rate of flow of water through the meter may be checked by collecting the sample after it has left the overflow cup. If the flow is appreciably less than 350 cubic centimeters of water per minute, the analyzer needs to be cleaned.

2. Zero-Check Exhaust Tube. If the rate of flow through the instrument is low, the zero-check exhaust tube may easily be removed for cleaning. The position of the exhaust tube just above the zero-check valve is shown in Figure 8. Once the zero-check valve has been removed, the exhaust tube may

be unscrewed from the meter body by a screwdriver. The cross passage between the exhaust tube and the scrubbing chamber may be cleaned with a pipe cleaner after removing the clean-out plug at the right side of the analyzer body. All parts should be reset firmly to avoid leaks.

3. Scrubbing Venturi Tube. The water enters the scrubbing venturi tube from the zero-check exhaust tube as shown in Figure 8. This venturi tube may be affected by small burrs or deposits that would hinder the proper scrubbing action. The scrubbing venturi tube may be removed for cleaning with the aid of a small hexagonal socket wrench. If the sample water is not properly scrubbed, insufficient hydrogen will be dissolved in the water. The hydrogen generator will no longer be able to control such a small flow of hydrogen, and the electrode will intermittently break surface with the electrolyte. This action will cause a wavy line if the instrument is reading about one-third scale or higher. The end of the scrubbing venturi tube should be immersed in the water of the overflow cup, and no gas bubbles should pass under the scrubbing-chamber bell. All gas should be dissolved in the sample water.

4. Water Saturation of the Active Spiral. Both platinum spirals of the thermal-conductivity bridge are surrounded by saturated water vapor as well as by the other gases. The reference spiral is sealed in an atmosphere of pure hydrogen and water vapor. The water saturation of the gas about the active spiral is assured by a small wick wrapped around the scrubbing venturi tube. This wick is kept moist by small bleed holes that lead into the sample stream. If this wick is not in place, the water will flow out of the tip of the venturi tube through the bleed holes and stop the scrubbing action of the analyzer. This action can easily be recognized by a stream of water passing down the outside of the scrubbing venturi tube.

5. Hydrogen Generator. The level of the electrolyte in the hydrogen generator should come between the etched lines on the generator bowl. During operation, the tip of the inner electrode should just touch the electrolyte but the outer electrode should always be immersed in the liquid. If the tip of the hydrogen electrode accumulates dirt from the solution, the generation of hydrogen will become erratic; this will cause a wavy line on the record.

6. Separating Filter. The reference and active sides of the analyzer are separated by a small cotton filter which stops the gas in the scrubbing chamber from diffusing into the reference side. The position of the filter is shown in Figure 8. If this filter becomes wet, it will offer too much resistance to the flow of hydrogen from the hydrogen generator and the level of

the water in the scrubbing bell will rise into the meter body. In this condition the wick should be removed and replaced.

7. Air Leaks. Air leaks into the sample stream will cause an increase in the dissolved air reading. Leaks into the hydrogen generator or scrubbing chamber will cause fluctuations in the reading which are difficult to predict.

The gas system may be checked for leaks by running the meter on zero-check until a zero reading is obtained. Without otherwise disturbing the instrument, the sample flow should be turned off and the zero-check valve should be turned to its horizontal position. The hydrogen generator should be turned off by opening the switch at the right side of the analyzer. If no leaks exist, the instrument will come to a steady reading no more than a few scale divisions from the original setting. If air is leaking into the system, the reading will gradually increase. The rate of increase will depend upon the size of the leak and its proximity to the thermal-conductivity spirals. If the leak is in the hydrogen generator, its effect will be very slow.

RECOGNITION OF ERRORS FROM THE RECORDER CHART

1. Chart Errors Possible While Operating the Recorder with Totally Deaerated Water.

a. Erratic readings are almost always due to trouble in the electrical system. These readings may be above or below the zero line.

b. Erratic readings that drift above the zero line but are not instantaneous in nature are usually caused by leaks into the gas system.

c. Changes in the zero setting may be attributed to a change of adjustment of the recorder galvanometer.

2. Chart Error While the Instrument Is Reading a Sample Containing Dissolved Air.

a. Low erratic readings could be due to the absence of a separating filter as shown in Figure 8.

b. Readings which are low by about 50 per cent could be caused by hydrogen bubbling under the scrubbing-chamber bell.

c. A wavy record while reading above one-third scale could be caused by insufficient scrubbing of the sample water. This is probably due to burrs or foreign matter in the cross holes of the scrubbing venturi tube.

d. A wavy line could also be caused by the collection of foreign matter on the tip of the hydrogen electrode.

e. Improper standardization of the recorder will cause an unpredictable error of the calibration which is proportional to the deflection.

f. Changes in calibration due to the incorrect setting of the current adjustment are proportional to the deflection.

3. Chart Errors Apparent While the Instrument Is in the Zero-Check Condition.

a. An unduly long time to check zero may be caused by insufficient hydrogen generation. The hydrogen-generation current while checking zero should be 200 milliamperes.

b. Sharp jumps in the record when running at zero may be due to improper functioning of the zero-check exhaust tube. This should be well cleaned of any foreign material or burrs to eliminate sample water finding its way into the scrubbing chamber.



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