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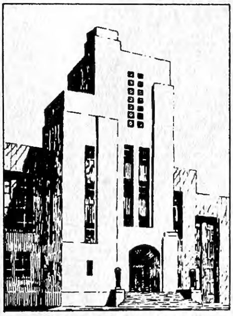
A METER FOR CONTINUOUS INDICATION OF DISSOLVED AIR IN WATER

by

H.M. Fitzpatrick
and
M.F. Harkleroad



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ABSTRACT

An instrument is described which continuously measures the concentration of dissolved gases in liquids. The operation of the instrument is based on the establishment of equilibrium between the continuously flowing liquid sample and a gas space of constant volume. The equilibrium pressure in the gas space indicates the concentration of dissolved gases. Experimental confirmation of the validity of the method is presented for air dissolved in water. The design of a practical instrument and criteria for its improvement are given.

INTRODUCTION

Methods of determining the concentration of dissolved gases in liquids find applications in such fields as medical and biological research, chemical industries, operation of steam turbines, and hydrodynamic research. The necessity for control of the air content in water used in cavitation experiments has long been recognized. Procedures for testing model ship propellers in variable-pressure water tunnels have included the standardization of the air content of the water in the tunnel.[1, 2] Whereas, in general, higher air content appears to make for inception of cavitation at higher local pressures,[3] experiments and observations on this and various other effects of dissolved air are neither complete nor in total agreement. Continued interest in the role of air, both dissolved and undissolved, in cavitation phenomena is directed not only toward the standardization of water-tunnel test procedures but also toward fundamental studies of inception, growth, and collapse of cavities and of the noise and erosion produced.

Methods employed at the David Taylor Model Basin for the determination of the air content of water used in cavitation experiments have included the Winkler chemical test for dissolved oxygen,[4] the Cambridge Instrument Company's meter which measures the thermal conductivity of the extracted gases,[2] and the method of Van Slyke.[5] In this last, the dissolved gases in a measured sample of the solution are extracted under a Torricellian vacuum and the pressure of the extracted gases is measured upon recompression to a specified volume. The various methods of measurement do not, in general, determine directly the same physical quantity, especially if the solution is of a mixture of gases having different solubilities.

This report describes a method for obtaining a continuous indication of gas content, discusses some of the principles involved in the design and operation of an instrument employing the method, presents experimental confirmation of its feasibility, and provides design information necessary for construction of a practical instrument

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[1] References are listed on page 18.

The method was developed and the instrument constructed for use with the Taylor Model Basin Flow Facility in the study of cavitation phenomena under the Bureau of Ships Fundamental Hydrodynamics Research Program (NS715-102).

Operation of the instrument is based on certain well-known principles concerning the solution of gases in liquids. The first of these principles relates to the condition for equilibrium between the concentration of dissolved gas in solution and the pressure exerted by the gas on the exposed surface of the liquid. At a given temperature, the concentration of dissolved gas will be, at equilibrium, a function of the pressure exerted by that gas on the exposed surface of the liquid. If the pressure of the gas on the exposed surface is made higher than the equilibrium pressure corresponding to the existing concentration of dissolved gas, more gas will go into solution; if the pressure is reduced below the equilibrium value, gas will be evolved from the liquid.

For most gases and liquids at moderate pressures, the relation between the concentration of dissolved gas and the equilibrium pressure is a simple proportionality. This generalization, known as Henry's Law,[6] while not essential to the operation of the instrument described here, permits a simplified description of its behavior and will be assumed in the subsequent discussion. It will likewise be assumed that the perfect gas law applies. Henry's Law states, then, that at equilibrium, the mass of gas dissolved in a given volume of the liquid is proportional to the pressure exerted by that gas on the surface of the liquid. Since the mass of free gas contained in a fixed volume at a given temperature is, by the simple gas law, likewise proportional to the pressure, the solubility of a gas in a liquid may be expressed as a *solubility coefficient* β defined as the ratio, at equilibrium, of the amounts (i.e., the mass) of gas contained in equal volumes below and above the surface. The ratio β for each combination of a gas and a liquid depends upon the temperature. Table 1 gives values of the solubility coefficients for nitrogen and for oxygen in water.*

The rapidity of establishment of equilibrium between the concentration of a gas in solution and the pressure exerted by the gas on the surface of the liquid is limited by the rates of diffusion obtaining on both sides of the gas-liquid boundary. For oxygen and nitrogen in the usual atmospheric proportions in contact with water, the imposed limitation ordinarily arises principally in the rates of diffusion of the dissolved gases within the liquid. Since the molecular diffusivity of oxygen and nitrogen in water is very low for most practical purposes,** aeration and de-aeration of water are ordinarily effected by some combination of spraying, bubbling, agitation, and other means for increasing the area of contact and for accelerating mixing within the liquid.[8]

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*The values shown in the table were derived from data in the "Handbook of Chemistry and Physics"[7] which gives values of an *absorption coefficient* α whose definition is such that $\beta/\alpha = T/T_0$. Here T is the absolute temperature at which the values of α and β apply and T_0 is the absolute temperature corresponding to 0°C.

**The observed values of the molecular diffusivity for oxygen and nitrogen in water are of the order of $2 \cdot 10^{-5}$ cm^2/sec.

TABLE 1

Solubility Coefficients for Oxygen and Nitrogen in Water

Temperature deg C	Oxygen	Nitrogen
0	0.0489	0.0235
10	0.0394	0.0193
20	0.0333	0.0166
30	0.0289	0.0149
40	0.0264	0.0136

A second principle relevant to the operation of the instrument is known as Dalton's Law.[6] Dalton's Law states that in a mixture of two or more gases, each gas behaves independently of the other gases present, the equilibrium concentration of each gas in solution being determined by the partial pressure exerted only by that gas on the exposed surface of the liquid and by its own solubility in that liquid. A consequence of this behavior is that the relative proportions of the dissolved gases may be different from the corresponding relative proportions in the gas mixture with which the solution is in equilibrium. A pertinent example is the case of a solution consisting of oxygen and nitrogen in water, in equilibrium with the ordinary atmosphere. The solubility coefficient of nitrogen is only about one-half that of oxygen. Consequently, the dissolved gas, when extracted, proves to be a mixture of the two gases in the proportion of two volumes of nitrogen to one volume of oxygen though the atmosphere is a mixture having the proportions of four volumes of nitrogen to one volume of oxygen.

The instrument described in this report makes use of the principles outlined above and in the following section to establish an equilibrium condition between the gas pressure in a fixed volume in a closed chamber and a continuously flowing sample of liquid passing through the chamber. In the construction whose evaluation is discussed, water is sprayed into the chamber through one or more "atomizing" nozzles. The necessary surface exposure and mixing take place not only in the spray itself but also in a film of liquid on the inside walls of the closed chamber, especially in the upper part of the film which is supported and agitated by the impinging spray. This arrangement was selected for tests on the basis of apparent simplicity rather than for maximum effectiveness in mixing. Various other types of scrubbing and absorption devices are known and used in industry.[8] It is recognized that either analysis or experiment may prove some of these more effective than that chosen. Results obtained indicate that the method used is a valid and practical one and that it provides a continuous reading with acceptable accuracy. Further development may be aimed at increasing the rapidity of response which, at present, does not allow significant indications of changes in air content of the inflowing sample within a period of less than about 10 minutes.

THEORY

PRINCIPLE OF OPERATION

The basic components illustrating the principle of operation are sketched in Figure 1. A continuously flowing sample of the liquid is sprayed into the upper part of a closed chamber and subsequently falls to the bottom or runs down the inside walls of the chamber. Liquid is continuously withdrawn from the bottom of the chamber; the inflow and outflow rates are controlled so that the volume of the gas space in the upper portion of the chamber remains constant. The outflowing sample liquid, once having passed through the meter chamber is either returned to the reservoir from which it was taken or disposed of in whatever manner is convenient. Thus, the sample liquid being exposed to the gas space within the chamber is renewed continually. If, with respect to its dissolved gas content, the incoming liquid is in equilibrium with the partial pressure of each gas trapped in the gas space in the upper portion of the chamber, no net exchange of gas will take place between the flowing liquid and the gas space. If, however, the partial pressure of any gas in the gas space is different from the pressure corresponding to equilibrium with the concentration of that gas in solution in the incoming liquid, an exchange will take place and gas will be evolved or absorbed by the liquid until the quantity of that gas in the gas space is just sufficient to exert the pressure corresponding to equilibrium with the concentration of that gas in the incoming liquid. The result is that the pressure in the chamber approaches an equilibrium value indicative of the concentration of dissolved gas in the sample liquid. The pressure is measured by any ordinary means connected to the chamber. Proper account must be taken of the pressure due to the vapor of the solvent.

It is manifest that an instrument operating on the principle just described will give the correct indication if the flow of liquid through the chamber is slow enough so that actual equilibrium is maintained between the outgoing liquid and the gas trapped in the gas space. This is true since, in the limit of extremely slow flow and long exposure, the pressure of each gas in the gas space will, in fact, reach equilibrium with the concentration of dissolved gas in the liquid. It is necessary to determine by experiment, however, whether the instrument can be made to operate under practical requirements, such as workable physical size and flow rate, sufficiently rapid approach to equilibrium, and freedom from perturbation of the equilibrium pressure caused by the methods employed to produce the required amount of mixing and exposure of the liquid. These requirements are closely interdependent. An understanding of the relations involved will be facilitated by a

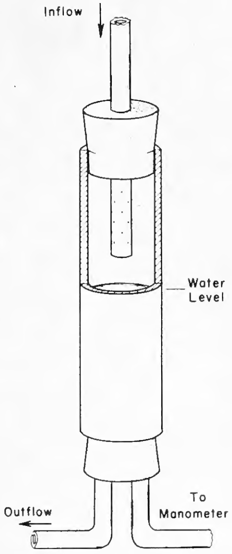

Figure 1 - Basic Form of Meter Chamber

discussion of the manner in which the gas pressure in the chamber approaches the equilibrium value.

RESPONSE TO FLUCTUATIONS IN INPUT

Considering first the case of a single gas dissolved in the inflowing sample, let the instantaneous pressure of that gas in the gas space be denoted by p and let the equilibrium pressure corresponding to the concentration of dissolved gas in the inflowing sample be P. Denote by Q the volume flow rate of the liquid sample. The temperature will be considered to be constant. The inflowing sample carries dissolved gas into the chamber at a rate such that if it were completely extracted and added to the gas space of volume V, the rate of increase in pressure would be $PQ\beta/V$. This follows from the definitions given for the flow rate Q, solubility coefficient β, and equilibrium pressure P. Similarly, if, in passing through the chamber, the sample liquid is brought into complete equilibrium with the existing pressure p in the gas space, there will be carried out from the chamber an amount of dissolved gas sufficient to reduce the pressure in the gas space at the rate $pQ\beta/V$. The net rate of change of pressure in the gas space will then be $(Q\beta/V)(P-p)$.

In general, however, the exchange of gas between the sample liquid and the gas space will not be complete so that the actual rate of change of pressure will be given by an equation of the form

$$\frac{dp}{dt} = \frac{1}{\tau}(P - p) \qquad [1]$$

where τ has been written for $V/Q\beta\eta$. The factor η, which will be called the *mixing efficiency,* has some value between zero and unity. Thus the mixing efficiency η represents the actually utilized fraction of the capacity of the flowing sample for carrying dissolved gas into or out from the chamber. Its value depends upon the area of exposure, the intimacy of mixing, and the degree of agitation as well as upon the molecular diffusivity in both the gaseous and liquid phases.

It is instructive to consider the case in which, at time $t = 0$, the pressure p in the gas space has some arbitrary value p_0 and the equilibrium pressure P remains constant for subsequent time, corresponding to some constant concentration of dissolved gas in the inflowing sample. This condition may be recognized as corresponding to a sudden change (at time $t = 0$) in the concentration of dissolved gas in the inflowing sample after previous establishment of equlibrium. The time function describing the response to such a "step" change in the input is sometimes called the *indicial response*[9] and is a useful characterization of the behavior of an instrument with respect to fluctuations in the quantity being measured. In the case being considered, the integral of Equation [1] gives the response:

$$p = p_0 + (P - p_0)(1 - e^{-t/\tau}) \qquad [2]$$

The significance of the *indicial response function* $(1 - e^{-t/\tau})$ is readily apprehended. Equation [2] states that the response of the instrument to a suddenly occuring step change in the concentration of dissolved gas in the incoming sample is not an immediate corresponding step change in the pressure p but rather an asymptotic exponential approach to the new reading with "response time" (i.e., time required for the reduction by a factor $1/e$ of the departure of the reading from the new equilibrium) equal to τ.

It is, of course, essential to the usefulness of the instrument that the response time $\tau (\equiv V/Q\beta\eta)$, be made reasonably short. It is desirable, in fact, to make the rapidity of response as great as possible. This can be accomplished by making the gas-space volume V small and the flow rate Q and mixing efficiency η high. Since the mixing efficiency cannot be made greater than unity, the practical problem becomes one of maximizing the ratio of the flow rate to the volume of the gas space while maintaining adequate exposure and mixing. The desirable choices of gas-space volume, flow rate, and mixing efficiency militate against one another in various ways so that it is difficult to determine the most suitable compromise in design. Thus, an extremely small gas volume would make for rapid response, but a small volume is somewhat incompatible with the combination of a high flow rate and a large area of exposure.

Equation [2] describes the response of the instrument for a case in which the change in input involves only one gas. Where the response to a mixture of gases is required, a slightly more general expression applies. Dalton's Law states that in a mixture of gases, each behaves independently of the others. In the experiments to be described, a step change in the concentration of nitrogen and oxygen dissolved in water is simulated; the changes in equilibrium pressures are approximately in the atmospheric proportions of 80 percent nitrogen to 20 percent oxygen. The expected indicial response for this case consists of a linear superposition of the responses due to each gas separately, if it is assumed that the mixing efficiency for one gas is not affected by the presence of the other. Accordingly, instead of Equation [2], the equation describing the approach to equilibrium for a mixture of oxygen and nitrogen in atmospheric proportions after a sudden displacement from equilibrium is:

$$\begin{aligned} p &= p_0 + (P - p_0)\left(1 - .8e^{-(V/Q\beta_N\eta)t} - .2e^{-(V/Q\beta_0\eta)t}\right) \\ &= p_0 + (P - p_0)\left(1 - .8e^{-t/\tau_N} - .2e^{-t/\tau_0}\right) \end{aligned} \quad [3]$$

Here p is the instantaneous value of the total gas pressure in the gas space, P is the *total* equilibrium pressure corresponding to the new concentrations of nitrogen and oxygen in the inflow, and β_N and β_O are the solubility coefficients for nitrogen and oxygen respectively. For simplicity, the mixing efficiencies for the two gases are assumed to be equal and independent of the various pressures.* Since practically, $\beta_0 = 2\beta_N$, the response time τ_0 for oxygen may be taken to be one-half that for nitrogen. Consequently, fitting a response function of the prescribed form to experimental data involves the determination of a single parameter only. In the discussion which follows, the observed response will be characterized by giving the response time τ_N for nitrogen thus inferred.

It would be incorrect to interpret the preceding discussion as implying that the instrument can give a significant indication only when the equilibrium condition exists. Consider first the behavior where the inflowing sample contains only one dissolved gas whose concentration is changing with time. Rearrangement of terms in Equation [1] gives the instantaneous relation between the pressure P, corresponding to the instantaneous gas content of the inflowing sample, and the indicated pressure p corresponding to the instantaneous gas pressure in the chamber:

$$P = p + \tau \frac{dp}{dt} \qquad [1a]$$

Ideally, then, the instantaneous value of the gas content of the inflowing sample may be determined without delay even though its value may be fluctuating in an arbitrary manner. In practice, however, there is a limitation: Equation [1] assumes that the gas-space volume is constant. If fluctuations in gas-space volume occur, corresponding fluctuations in the gas pressure p will accompany them. Whether the extrapolation procedure indicated by Equation [1a] is made by the observer or by an automatic device incorporated in the indicating or recording instrument, spurious fluctuations proportional to the time derivative of the volume fluctuations will appear in the indication of the meter. The extent to which the lag inherent in the response may be compensated depends, therefore, upon the accuracy with which the volume of the gas space can be maintained constant. A reduction by a factor of 2 or 3 in the response time is probably the most that can be obtained with the simple type of level control contemplated for the Model Basin installation.

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*Neither of these assumptions is strictly correct; the evolution or absorption of the two gases at rates resulting in unequal net velocities of flow into or out from the liquid surface results in concentration gradients in a thin gas film adjacent to the liquid with a consequent interaction between the rates of absorption or evolution. However, because of the low solubility of oxygen and nitrogen, the gradients in the gas film may be considered negligible and the rates of absorption or evolution are determined principally by the liquid film. In the liquid, rates of diffusion of the two gases are determined near the surface by molecular diffusion and in the interior of the liquid by a combination of molecular diffusion and convection. The molecular diffusivity of oxygen in water is about 10 percent greater than that of nitrogen. The convective diffusivity, if such obtains, is of course the same for both dissolved substances. The assumed relation $(\beta\eta)_{\text{Oxygen}} = 2(\beta\eta)_{\text{Nitrogen}}$ represents, then, the limiting condition in which molecular diffusion plays a negligible role in the "mixing" as contrasted with "turbulent" diffusion occurring in the agitated upper portion of the film. The opposite extreme condition in which molecular diffusivity accounts for the major portion of the distribution of the dissolved substance within the liquid would accordingly result in the relation $(\beta\eta)_{\text{Oxygen}} \approx 2.2(\beta\eta)_{\text{Nitrogen}}$. While the former condition is believed to correspond more closely to that actually realized in the tests (except Run 1), Equation [3] should be considered as a convenient empirical form rather than as one having a strict theoretical basis.

Where the dissolved gas consists of more than one kind, a compromise value of τ should be used in performing the extrapolation indicated by Equation [1a]. Thus for air, a suitable value is nine-tenths of the response time τ_N.

EXPERIMENT

APPARATUS AND PROCEDURE

The earliest experimental tests of the principle outlined in the Introduction were performed with laboratory equipment arranged in the fashion shown in Figure 1. These experiments indicated the feasibility of the method and led to the version of the instrument shown in Figures 2 and 3. The glass dome enclosing the nozzle and gas space is an inverted Pyrex test tube. The mouth of the tube is sealed with litharge-and-glycerine compound into a flanged receptacle. The latter is fastened with cap screws to the lower part of the chamber, and the joint is sealed by means of an ''O''-ring. Except for the glass dome, all the parts of the chamber are made of brass. The purpose of the bulbous lower portion of the chamber is to reduce the velocity of the outgoing liquid so that gas will not be carried out in the form of entrained bubbles. It is shown in the Appendix that the presence of undissolved gas in the outflow introduces an error in the indication of the instrument. A glass sight tube sealed into the dome at the top and at the side is intended as an aid in determining the level of the liquid in the chamber under conditions of operation, where the main surface is disturbed by the falling liquid.

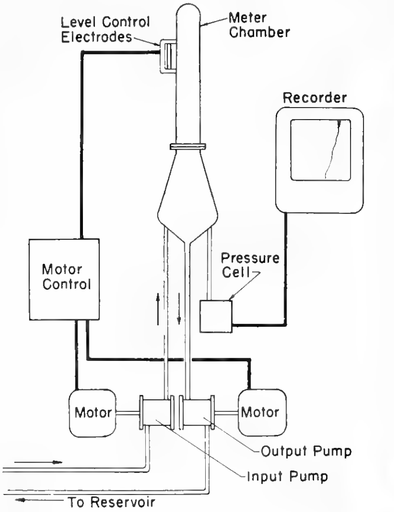

Figure 2 - Schematic Diagram Showing Installation of Air Content Meter

The automatic control was not installed at the time of the experiments described in the text.

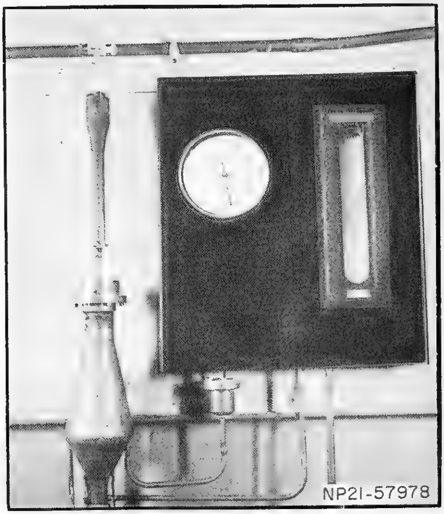

Figure 3 - Meter Chamber, Pressure Gage, and Flowmeter Installed

The installation of the meter is shown schematically in Figure 2. The reservoir for the test water is the 5000-gallon head tank of the Flow Facility. The head tank can be pressurized or evacuated. The water can be circulated through spray nozzles mounted inside the tank, and thus any desired air content can be obtained. Once established, a given air content can be maintained for hours or even days because of the large volume of water and the low diffusivity of dissolved gases. The pressure in the meter chamber was measured by means of a telemetering pressure recorder (Automatic Temperature Control Co.). The pumps are constant displacement gear pumps (Eastern Industries model GW-1) driven at reduced speed by d-c shunt motors (gearmotors).

In order to determine more definitely the feasibility of the method and the validity of the analysis presented above, some experimental tests of the meter were conducted. These tests consisted of runs in which an initial displacement of the pressure in the gas-space was effected and the reapproach to equilibrium was monitored and recorded. Before a test run, the meter was allowed to operate until the pressure in the gas space appeared to have reached an equilibrium value. The inflow and outflow rates were carefully regulated manually so that the water level in the sight tube (and hence the volume of the gas space) remained constant. After equilibrium had been thus established, the volume of the gas space was allowed to change quickly to a new value either larger or smaller than that which had previously been maintained. The effect of this last action is to simulate a "step" change in the concentration of dissolved gas in the incoming sample since, as a result of the change in volume, the new value of the pressure in the gas space is lower or higher than the equilibrium pressure. The operation of the meter was then continued with the volume of the gas space carefully maintained at the new value and readings were taken at intervals in order to determine the manner in which the pressure returned to the equilibrium values. The flow rate was maintained as nearly constant as possible and its exact value noted and recorded with each pressure reading taken. A thermometer suspended inside the meter chamber indicated the temperature.

As testing of the meter proceeded, successive modifications were made to improve its performance. Figure 4 shows details of the arrangement of the nozzles and other components in the upper part of the chamber. For the first two runs, the gas space was unnecessarily large (Figure 4a) and the response time was excessive. A revised version is shown in the sketch of Figure 4b. A micarta core whose volume occupies the greater portion of the glass tube reduces the gas-space volume but not the surface available for exposure of the liquid. The single nozzle was replaced by a triad of nozzles to allow a higher flow rate and thus further decrease the response time. A ramp consisting of flexible plastic tubing wound in a helix about the central core was added to minimize the formation of bubbles. A later addition was the spray baffle. Its purpose was to prevent the spray from clogging the opening of the sight tube. In some of the test runs made before the installation of the baffle, erratic results were obtained because a small slug of water occupied a portion of the vertical section of the sight tube just above the dome, thus introducing errors in the adjustment of the volume of the gas space.

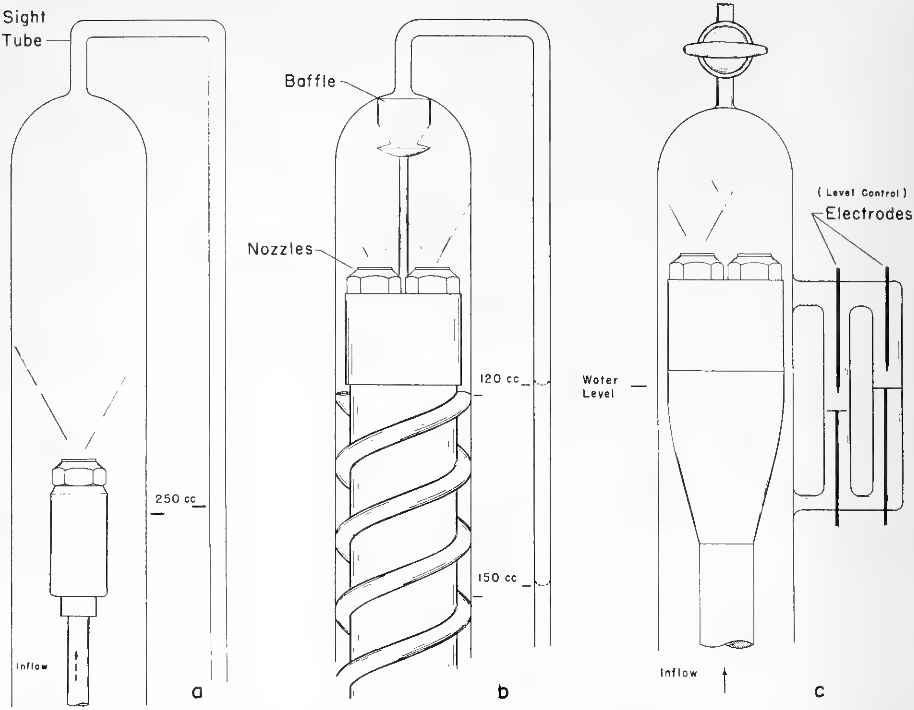

Figure 4 - Details of Three Arrangements of Meter Chamber

The inside diameter of the inverted test tube forming the glass dome is 48 millimeters.

All nozzles used were ''atomizing'' nozzles designed to produce a hollow cone spray.*

RESULTS OF EXPERIMENTS

Figure 5 shows typical results of the tests of the response characteristics of the meter. The circles represent the measured values of gas pressure in the chamber while the broken line indicates the simulated step change in the input. The solid line was obtained by fitting a curve of the form given by Equation [3] to the observed pressure readings; the response time τ_N was chosen to give the best fit. This procedure determines the value of the mixing efficiency η since V, Q, and β_N are known.

Table 2 summarizes the results of eleven test runs with four different combinations of nozzle size and internal arrangement. For each run, the arrangement, flow rate, gas-space

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*Spray Systems Company type ¼LN1, ¼LN2, ¼LN3 and ¼LN4. The smaller numbers designate nozzles producing a finer spray. The flow rate obtained is roughly proportional to the designating number and to the square root of pressure drop across the nozzle; it is about 120 cc/min. for a single No. 2 nozzle at 20 psi.

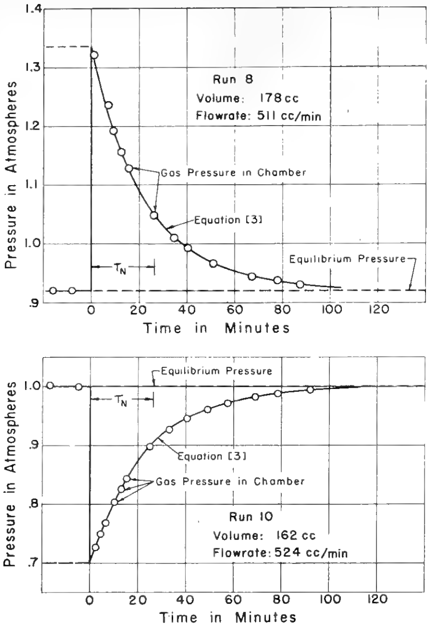

Figure 5 - Response of Meter to Sudden Change in the Concentration of Dissolved Air in the Incoming Sample

The broken line indicates the simulated step change in the air content of the inflowing sample. The circles indicate the observed gas pressure in the chamber. The solid line represents a response of the form given by Equation [3].

volume, temperature, and the solubility coefficient for nitrogen are given in the first six columns. The next two columns give the observed response time and the computed mixing efficiency. The response time given is that for nitrogen; the corresponding response time for oxygen is one-half that for nitrogen inasmuch as the solubility coefficient for oxygen is twice that of nitrogen. The initial pressure, i.e., the pressure in the gas space immediately after the simulated step in the concentration of the inflowing sample, and the equilibrium pressure are also shown in the table.

COMPARISON WITH VAN SLYKE DETERMINATIONS

In the preliminary tests of the method with the apparatus represented in Figure 1, comparisons were made with the indications given by the Van Slyke apparatus and substantial agreement between the two methods was obtained. During the tests summarized in Table 2, comparisons were made for the first two runs and for the last two. The last two columns in Table 2 show the pressure approached by the meter and the equilibrium pressure corresponding

TABLE 2

Summary of Test Runs

Run	Scheme	Flow Rate Q cc/min	Gas Volume V cc	Temperature deg. C	Coefficient of Solubility for Nitrogen β_N	Mixing Efficiency η	Response Time τ_N min	Initial Pressure p atm	Equilibrium Pressure P atmospheres	
									Indicated by Meter	Van Slyke Determination
1	Fig. 4b One nozzle, No. 3	121	254	15	0.0178	0.69	170	0.92	0.72	0.72 0.73
2	Fig 4b One nozzle, No. 1	110	250	22	0.0162	0.95	146	0.95	1.25	1.24, 1.26
3*	Fig. 4b	453	147	20	0.0166	0.68	29	1.33	1.14	
4	Three nozzles No. 2	340	191	17.5	0.0172	0.72	46	0.75	0.96	
5	No spray baffle	333	155	17.5	0.0172	0.70	39	1.18	0.96	
6	Fig. 4b	720	152	20	0.0166	0.77	16	1.28	1.13	
7	Three nozzles No. 4	594	147	20	0.0166	0.83	18	1.18	1.01	
8	No spray baffle	511	178	19	0.0167	0.80	26	1.34	0.92	
9	Fig. 4b	517	170	20	0.0165	0.64	31	0.76	0.90	
10	Three nozzles No. 4	524	162	22	0.0162	0.72	27	0.70	1.00	1.00, 1.03
11	Spray baffle	527	130	22.5	0.0162	0.71	22	1.245	1.01	1.00, 1.04

*Measurements affected by clogging of sight tube.

to the air content indicated by the Van Slyke determination.*

DISCUSSION

The data furnished by the test runs and summarized in Table 2 are not as complete as might be desired. Nevertheless, a number of conclusions deducible from the tabulated data or from observations made during the experiments permit the design of a meter chamber adequate for measurement of the air content of water employed for cavitation studies in water tunnels and similar facilities.

A pertinent question affecting the choice of the internal arrangement of the meter chamber is the relative effectiveness of the various means employed for providing contact between liquid and gas phase. Thus, if it were determined that the "mixing" takes place predominantly in the spray itself, emphasis would be directed toward the employment of finer nozzles and away from the provision of a large area of the inside walls of the chamber. Similarly, if the falling film or the helical ramp were determined as the principal area of effective mixing, optimum design would emphasize that feature. In each case the minimum gas-space volume consistent with proper function would be sought.

In all of the test runs except that indicated as Run 1, a mode of mixing of the air and water was observed which is almost certainly more effective than the combination of all those mentioned above. At and above the level at which the spray impinges upon the inside wall of

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*In converting the indication given by the Van Slyke apparatus to equilibrium pressures, it is, of course, necessary to know the relative proportions of the various gases as well as their separate coefficients of solubility. For this purpose, the relative proportions of nitrogen, oxygen, and carbon dioxide in ordinary atmospheric air and their solubility coefficients as given in Reference 5 were used.

the chamber, a cap of violently agitated foam is formed and supported by the spray. The intimate mixture and vigorous agitation maintained in this film of emulsified air and water appear to provide an extremely effective process of exposure. This conjecture is supported by the experimental results in conjunction with estimates of the extent of the exposure effected outside of the emulsified area.

The extent of the exposure of the sample water which occurs as a result of diffusion of the dissolved gas out of or into the vertical film formed as the water runs down the inside walls of the chamber can be estimated. The thickness δ of the film and the flow velocity u are given by the well-known Nusselt relations obtained by equating viscous and gravitational forces on each lamina:

$$\delta = \left[\frac{3Q\nu}{Cg}\right]^{1/3} \qquad [4]$$

$$u = \frac{3Q}{2C\delta}\left[2\frac{y}{\delta} - \frac{y^2}{\delta^2}\right] \qquad [5]$$

in which ν is the kinematic viscosity of the liquid, y is distance from the wall, and C is the width of the film. (For the experiments being considered, C, the inside circumference of the glass dome, is 15 cm.)

Let the coordinate x represent distance measured in the flow direction, i.e., downward, from the top of the film. Then if $\rho(x, y)$ represents the *excess* concentration of dissolved gas in the film, the equation describing the steady-state distribution resulting from convection in the x-direction and diffusion in the y-direction is[10]

$$u\,\frac{\partial \rho}{\partial x} - D\,\frac{\partial^2 \rho}{\partial y^2} = 0 \qquad [6]$$

Here D is the diffusivity of the dissolved gas.

The mixing efficiency η' which would result if the exposure of the sample were restricted to that which results from diffusion out of such a laminar* film of vertical height x is the fraction of excess (or deficit) of dissolved gas which is removed as the film falls a distance x. If the dissolved gas is assumed to be uniformly distributed at the top of the film, e.g., $\rho(0, y) = \rho_0$, the fraction which has been removed in vertical distance x is then given by

$$\eta' = 1 - \frac{C}{\rho_0 Q}\int_0^{\delta} u\,\rho\,(x, y)\,dy \qquad [7]$$

since the total rate at which the dissolved gas enters the top of the film is $\rho_0 Q$, and the rate

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*Experience has shown[11] that laminar flow obtains if a Reynolds number $4Q/C\nu$ is smaller than 1000. This condition is well satisfied even for the highest flow rates employed in the present experiments.

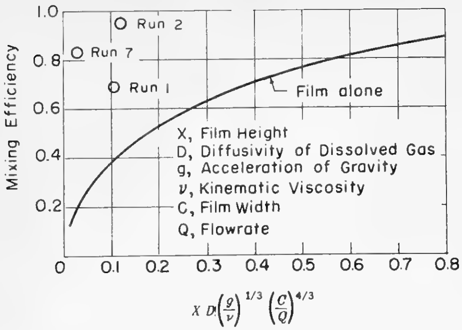

Figure 6 - Comparison of Observed Mixing Efficiency with Mixing Efficiency Estimated for Vertical Film Alone

The solid line indicates the estimated mixing efficiency for an arrangement in which the exposure of the sample water is confined to that provided by the vertical film which runs down the inside wall of the meter chamber. The circles indicate observed mixing efficiencies. This comparison indicates that the exposure provided by the vertical film is insignificant in the design tested.

at which dissolved gas is conveyed past the section at x is the width C multiplied by the integral in Equation [7].

Equation [6] may be integrated by methods too detailed to be included here. With the aid of Equations [4], [5], and [7], the essential result is shown in the form of the graph of Figure 6 which allows the estimated mixing efficiency to be determined directly from the flow rate, chamber dimensions, and properties of the fluids. Conversely, the film height which would be necessary to result in a given mixing efficiency by exposure in the film alone may be determined. The observed mixing efficiencies for three representative conditions are plotted and may be compared with the mixing efficiencies which would have been obtained for the same flow rate and film height if the exposure provided by the film had been the only means of mixing. It is apparent that an insignificant part of the observed exposure is attributable to the film.

A significant difference in mixing efficiency appears between comparable tests with a relatively fine nozzle (Runs 3, 4, and 5) and with a coarse nozzle (Runs 6, 7, and 8). The difference is in the opposite direction from that which is to be expected if the mixing process depends primarily upon the fineness of the spray. It is believed that the difference in favor of the coarser nozzle is due to the fact that, for a given flow rate, the vertex angle of the conical spray pattern is smaller for the coarser nozzle and that, consequently, a more extensive area of emulsion is formed.

The results of Runs 9, 10, and 11, for which the spray baffle had been installed, show a significant decrease in the mixing efficiency from the values obtained for the three runs immediately previous. The reason for this was apparent: a considerable portion of the flow drained from the top of the chamber down the support of the spray baffle, thus reducing the volume of water supported and agitated by the spray in the form of an emulsion.

DESCRIPTION OF FINAL DESIGN

In accordance with observations made during the experiments and with conclusions indicated above, the version of the meter chamber illustrated in Figure 4c was designed.

As a measure for reducing the response time, provision of a large wall area was abandoned in favor of minimizing the gas-space volume. This choice follows the conclusion indicated above that the extent of exposure provided by the vertical falling film is relatively unimportant.

The connection of the sight tube to the side of the chamber instead of to the top eliminates the need for the spray baffle.

The internal core tapers to a smaller diameter immediately below the intended level of the liquid surface. The resulting lowering of the velocity of outflow facilitates the rapid return of entrained bubbles to the surface. The lower bulbous portion is retained as an additional precaution.

A stopcock connected to the upper part of the chamber is useful for venting the gas space for the purpose of establishing nearly the equilibrium pressure before starting. This is desirable because, even with the method of compensation described above, the instrument begins to give accurate indications only after the equilibrium condition has been approximated and the time required for this is small if the starting condition roughly approximates the equilibrium condition. An additional reason for the provision of such a means for venting is the possibility that some relatively insoluble gas might be carried into the gas space in undissolved state and accumulate there, thus producing an erroneously high reading for a considerable period thereafter. This, of course, is hardly possible where the body of liquid is exposed only to atmospheric air, as in the present application.

From the observed performance of the arrangements tested, e.g., Runs 7 and 8, the following operating characteristics may be expected for the meter chamber designed according to the sketch, Figure 4c:

Flow rate: 600 cc/min with 3 No. 4 nozzles
Air-space volume: 110 cc
Mixing efficiency: 0.75
Response time (Nitrogen, 20°C): 15 min. (uncompensated)

These characteristics are suitable for indicating the air content of the water used in a hydrodynamic facility such as the flow facility or a large water tunnel. If a shorter response time is required, or if the presence of undissolved air in the inflow requires a higher value of the mixing efficiency, a different compromise in design is desirable. Thus, an increase in the flow rate will reduce the response time, though at some detriment to mixing efficiency, whereas the use of finer spray nozzles might improve the mixing efficiency but require a higher nozzle pressure. Similarly, a reduction in the dimensions of the meter chamber would reduce the response time but with attendant difficulties associated with control of the flow rate and gas-space volume. It appears that no absolute limit exists with regard to an approach to a mixing efficiency of unity or increase in 'the rapidity of response but that practical considerations such as those indicated will dictate the optimum compromise for a given application.

For practical use, it is desirable that the meter provide a continuous indication while unattended. For this purpose a servomechanism arranged to maintain constant gas-space volume is necessary. A simple control system designed for the Model Basin installation provides two-point control of the water level in the sight tube. Electrical contacts made between the water and metal electrodes fused into the sight tube actuate, through relays, a motor-driven rheostat differentially controlling the fields of the two motors driving the inlet and outlet pumps. The servo system has not been tested at this writing so that no experimental data concerning the adjustments required for satisfactory operation are available, but no extreme difficulties in this regard are anticipated.

SUMMARY

The air-content meter described in this report determines the concentration of dissolved air in water by measuring the air pressure which is in equilibrium with the water. In this way the meter can be used to indicate directly the degree of saturation of the water, relative to any arbitrary air pressure. If it is desired to express the air content in terms of volume or weight concentration, these quantities can be calculated from the measured equilibrium pressure by using well-known tables.

The meter operates continuously and can be used to provide a continuous indication of air content. However, the meter is limited in the rapidity with which it can follow a change in air content. For the present design, the response time is about 15 minutes but, by a method of compensation discussed in the text, it may be reduced effectually to about 5 minutes. This response is obtained with the sample water flowing at 600 cubic centimeters per minute. For applications where faster response is necessary, modifications in design have been suggested.

Comparison of the indications given by the continuously operating meter with those of the more conventional Van Slyke apparatus show good agreement over the restricted range of air content considered.

APPENDIX

EFFECT OF UNDISSOLVED GAS

The presence of undissolved gas bubbles in either the inflow or outflow can be shown to be detrimental to the accuracy of indication. It is convenient to express the concentration of undissolved gas in terms of the equilibrium pressure which would correspond to its concentration if it were dissolved. Let the equilibrium pressure corresponding to the *undissolved* gas in the inflow be denoted by P_1 and that corresponding to the *total* gas in the inflow be P, so that $(P - P_1)$ is the equilibrium pressure corresponding to the *dissolved* gas in the inflow. Also let P_2 be the equilibrium pressure corresponding to the undissolved gas in the outflow. Then the rate of change of the pressure p in the gas space may be determined as follows:

It may be assumed that the undissolved gas in the inflow is wholly released into the gas space regardless of the mixing efficiency and the existing pressure, whereas the dissolved portion is brought toward equilibrium with the existing pressure p at a rate dependent upon the mixing efficiency.* The rate of change of the pressure p ascribable to the difference between the concentration of the dissolved gas in the inflow and in the outflow is then given by an expression similar to that appearing in Equation [1], namely,

$$\frac{Q\beta\eta}{V}(P - P_1 - p)$$

whereas the contribution to the rate at which p changes due to the undissolved gas is

$$\frac{Q\beta}{V}(P_1 - P_2)$$

Adding these two contributions gives

$$\frac{dp}{dt} = \frac{Q\beta\eta}{V}(P - P_1 - p) + \frac{Q\beta}{V}(P_1 - P_2) \qquad [6]$$

The equilibrium condition $dp/dt = 0$ requires that $\eta(P - P_1 - p) + (P_1 - P_2) = 0$ or

$$p = P + \left(\frac{1}{\eta} - 1\right) P_1 - \frac{P_2}{\eta} \qquad [7]$$

Since the total gas content corresponds to a pressure P, the terms on the right side of [7] involving P_1 and P_2 represent the errors arising from undissolved gas in the inflow and in the outflow respectively. It may be observed that while the error due to undissolved gas in the inflow vanishes as the mixing efficiency approaches unity, that due to the same condition in the outflow does not. It is desirable, therefore, to make the mixing efficiency as large as practical and, in addition, to eliminate the convection of significant amounts of undissolved

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*This statement is really a definition of "undissolved gas" combined with the assumption that the gas in the inflow, however, actually dispersed, may be considered to consist of two phases only, dissolved gas and undissolved gas, each of which behaves as indicated in the above treatment.

gas in the outflow. In the instrument described in the text, a bulbous enlargement of the lower portion of the meter chamber is provided in order to reduce the velocity of outflow and so minimize the downward convection of any minute bubbles which may have persisted in the outflow.

The property of the instrument indicated above suggests the possibility of discriminating between dissolved and undissolved gas in the inflow if this were desirable. This could be effected, for example, by simultaneous operation of two meter chambers in one of which the mixing efficiency is maintained purposely at some known low value.

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