THE ABSORPTION OF OXYGEN BY

WATER DROPLETS DURING CONDENSATION

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SUMMARY

It is the object of this study to gain a more detailed and systematic account of the role played by surface phenomena, i.e., surface renewal by condensation, in the absorption of oxygen by a water drop from air.

The amount of oxygen absorbed by individual drops of water after formation at the tip of a hypodermic needle has been measured. The variables studied were the humidity and oxygen concentration in the air and the exposure time of the drop.

The rate of mass transfer was observed to increase with both the humidity and oxygen concentration in the air and with the contact time. Current theories of absorption are inadequate to describe this surface phenomena, and an alternative theory should be postulated.

CHAPTER I

INTRODUCTION

The importance of sprays and scrubbing in industrial absorption processes has led in recent years to studies on the absorption of gases by the individual units of these sprays, liquid drops. In most scrubbing systems currently in use, an aqueous solution, usually water, is brought into contact with a gas and a component such as oxygen is absorbed by the liquid drop.

Earlier investigators, trying to increase the efficiencies of these scrubbers, have studied the effect of various physical parameters on the absorption of a gas by a liquid. These parameters include the composition, contact time and the solubilities of each. Little has been said, however, of the effect of surface properties on the absorption rate. Various techniques which tend to alter surface characteristics have affected this rate. Temovskaya and Belopolski [1] observed a decrease in the rate of absorption of SO_2 into water in the presence of surfactants. Matteson and Giardina [2] studied the effect of an applied surface charge in the absorption of SO_2 by a water droplet, and obtained an increase of 60% in the rate of mass transfer with a charge density of 6 Stat C/cm^2. Mark [3] has also shown that absorption rates are significantly increased in the presence of a charged surface.

Not until recently has another technique of altering the surface characteristic been under study, that of surface renewal by condensation.

Bogaevskii [4] explained that a growing drop of liquid is able, as a consequence of the condensation of vapor on its surface, to absorb more gas under certain conditions than a similar drop of similar dimensions. The explanation of this phenomenon is that the surface of the growing drop is continually renewed by the condensation of vapor on it.

It was with this in mind that a study was undertaken to design an experimental apparatus to observed the influence of this phenomenon on the rate of absorption of oxygen by a growing drop of water. This study could bring out the importance of surface renewal by condensation as the dominant factor in controlling unsteady state interphase mass transfer.

CHAPTER II

GENERAL DISCUSSION

The basis of all processes involving the absorption of a gas lies
in the fact that a liquid-gas system which is not in equilibrium tends to
approach equilibrium conditions. Thus, if a liquid is not saturated with
gas under the existing conditions absorption occurs, whereas if it is
supersaturated the reverse is true. Equilibrium or saturation represents
the ultimate state which the system tends to assume.

The mechanism of the absorption process is very complex and not
thoroughly understood, especially when turbulent flow is involved.

The basic equation for describing the absorption process by a
stationary liquid under unsteady-state conditions is Fick's Second Law of
Diffusion[†] [5]:

$$\frac{dC_A}{dt} = D_A \frac{d^2C_A}{dx^2}$$ (1)

In an attempt to simplify and describe the mass transfer process
a mass transfer coefficient, k, has been defined, reducing equation (1)
to:

[†] Symbols are defined in Appendix A, page 31.

$$N_A = k(C_A^* - C_{A\infty}) \qquad (2)$$

There are many theories which attempt to interpret and explain the properties of mass transfer coefficients. The most accepted ones are: the film theory, the penetration theory and the boundary layer theory. They are all speculations and are continually being revised. The film theory is the oldest. It assumes the existence of a stationary film with zero velocity of gas and liquid on both sides of the interface which constitutes the resistance to mass transfer. Under conditons where the liquid film resistance is controlling, as is the case for the oxygen absorption by water, the gas film resistance is neglected. The concentration of the bulk of the liquid and gas beneath this film is kept uniform by mixing while the surface is at all times in chemical equilibrium with the gas phase.

The rate of absorption per unit time per unit area is given by the expression:

$$N_A = \frac{D_A}{x_L} (C_A^* - C_{Ao}) \qquad (3)$$

It seems doubtful, however, whether the conventional picture bears a very close relation to the actual mechanism of absorption. The conditions required to maintain a stagnant film at the interface of an agitated liquid appears to be lacking, and it seems more probable that turbulence extends to the surface and that there is neither a laminar

layer nor stagnant film. This theory is the most widely taught today though the fictitious nature of the liquid film is probably widely suspected.

In 1935 Higbie [6] integrated equation (1) to give:

$$N_A = (C_A^* - C_{A0}) \left(\frac{D_A}{t} \right)^{1/2} \tag{4}$$

which is the basis of the penetration theory. Higbie emphasized that in many situations the time of exposure of a fluid to mass transport is short so equilibrium is never reached at the interface. The penetration theory is applicable only when the diffusing molecules have not completely penetrated the fluid layer in question and for short exposure times. It is best suited for falling jets of liquid and for liquid layers descending in short wetted-wall columns when rippling is absent.

The more recent boundary layer theory differs from the film and penetration theory in that allowance is made for two-dimensional velocity profiles at the interface. In the theories discussed above, the velocity at the interface will not normally be zero. But if one of the phases is a solid the fluid velocity parallel to the surface at the interface must be zero. The boundary layer next to the interface is characterized by laminar flow. For the turbulent region, exact solutions are not known because of insufficient knowledge of the turbulence, although approximations have been made by Bird, Stewart and Lightfoot [7]. In this approach, the mass transport phenomena are assumed to be similar to heat transport and the average mass transfer coefficient is defined by:

$$Sh_{av.} = \frac{K_x D}{C_A D_A} = 2.0 + 0.6 \ (Re_x)^{1/2} \ (Sc)^{1/3} \qquad (5)$$

As may be seen from these three theories presented, each viewed the problem in a different light, made different assumptions and thus arrived at different conclusions. However, none of them is adequate to describe the process under study in this research.

The absorption of one component of a gas mixture by a liquid drop, which is growing as a result of condensing vapor on its surface, is a very complex process characterized as an unsteady-state system of coupled heat and mass transfer with varying surface area.

Studies have been made to predict the behavior of this system. Danckwerts [8] developed a theory of absorption assuming the liquid surface is continually being renewed with fresh liquid. He pointed out that the Higbie theory with its constant time of exposure is a special case of what may be a more realistic picture, where the time of exposure varies. Danckwerts developed the following expression for mass transfer:

$$N_A = (C_A^* - C_{Ao}) \sqrt{D_A s} \qquad (6)$$

(see Sherwood, Pigford and Wilke [9] and Treybal [3]).

Later Groothius and Kramers [10] and then Beck and Kramers [11] developed a model which predicts mass transfer coefficients based on the continuous formation of fresh surface during growth. Angelo, Lightfoot and Howard [12] developed the surface stretch model, which gives

prediction of mass transfer coefficients which are in reasonable agreement with the predictions based on the assumption of continual surface renewal made by Groothius, et al. [10], and Beck, et al. [11], Angelo, et al. [12], reported mass transfer coefficients at least 15 times as high as predicted by boundary-layer theory. They also developed an expression for the more general situation of appreciable resistance in each phase by assuming the surface stretch model to describe the transfer process in both phases.

Lewis and Whitman [13] describe the effect of solubility on the absorption rate of a solute gas. Any factor which tends to reduce the thickness of the surface film should increase the coefficient of absorption. They showed that when liquid water was stirred the value of the mass transfer coefficient for oxygen increased about 25 times as compared to the one for which the liquid remained undisturbed. Whitman and Davis [14] compared the absorption rates for various gases of different solubilities and determined that because of its low solubility in water, oxygen absorption is controlled by liquid film diffusion.

Haslam, Hershey and Keen [15] showed that the gas film coefficient decreases somewhat with temperature because the ratio of density to viscosity for the gas decreases and therefore the gas film becomes thicker. Becker [16] studied the mechanism of absorption of moderately soluble gases when the liquid was both stirred and free from agitation. His results with stirred solutions compare favorably with those of Lewis, et al. [13]. But the results obtained when the liquid was not disturbed could not be interpreted since it was evident that stratification effects were pronounced.

Licht and Conway [17] identified three separate stages in droplet mass transfer: the drop formation time, the time of rise or fall through the continuous medium, and the drop coalescence period. They observed that the rate of absorption was greatest in the drop formation stage, and that during this stage the solute was not transferred by the ordinary process of diffusion.

Whitman, Long and Wang [18] performed experiments to determine mass transfer coefficients for a water drop formed at a capillary and falling through a tube of fixed height filled with a certain gas; they used carbon dioxide and ammonia. Whitman, et al. [18], did not attempt to determine the amount of carbon dioxide absorbed by the drop during its formation, but over the total life of the drop. They assumed that be extrapolating to zero time of formation, the absorption during fall could be calculated and hence, by subtraction from the total, the absorption during formation determined. They concluded that: (i) the rate of absorption during formation of the drop is constant; (ii) the amount of absorption during the fall of fixed length is constant and independent of time of formation; and (iii) the amount of absorption during fall is always much greater than during formation. Hatta and Baba [19], following the assumption by Whitman, et al. [18], of negligible absorption during the formation period, derived on theoretical grounds three formulas for a falling drop in carbon dioxide in accordance with three assumptions: (i) no damping of turbulence in the drop during fall; (ii) gradual damping of turbulence in the drop at the start of fall; and (iii) complete damping of turbulence in the drop at the start of the fall. They found that the third assumption on the whole agreed best

with their experimental data.

Shabalin [20], working along similar lines, ensured that each drop had attained a steady terminal velocity before entering the absorption tube and measured the absorption by drops of several sizes during fall through various distances. He found that the rate of carbon dioxide absorption per unit surface area rather surprisingly increased slightly with increase in size of the drop, but he attributed this to greater frictional resistance of the surrounding gas. He also found a considerable absorption of carbon dioxide owing to the impact of the drop on the termination of its fall at maximum speed. Johnstone and Williams [21] also investigated the absorption of gases by droplets during fall and obtained similar results.

In 1950 Dixon and Russell [22], in the belief that absorption during formation might not only be significant in itself but might also influence absorption during later stages, performed a study on the absorption of carbon dioxide by individual drops of water. They showed that, contrary to the results of previous workers, the rate of gas absorption of a drop during the period of formation may be very high, especially when the time of formation is very short. This is due to the turbulence produced within the drop by the injection of the supply jet, which reduces the resistance to diffusion at the surface of the drop. Dixon and Russell showed that the mass transfer coefficient during formation is inversely proportional to a function of the time of formation and directly proportional to the degree of turbulence.

The experimental effort discussed above has involved the study of the droplet formation period and fall upon issuing from a capillary

tip. These mechanisms may be useful in describing and characterizing sprays or jets, but they do not adequately describe fog or cloud formation. Bogaevskii [4] observed water condensate inside a copper pyrite mine contained considerably quantities of sulfur dioxide, in fact the condensate was supersaturated. He hypothesized absorption supersaturation of the water with sulfur dioxide as a consequence of the repeated absorption of this gas on growing drops of water by condensation.

Drost-Hansen [23] has characterized the process by picturing the drop surface as containing a finite number of sites where solute can become attached. When these sites become saturated, absorption would cease. But if water vapor is continually being condensed on the surface, new surface and new sites are being created at a rate dependent on the rate of condensation. It might be expected, then, that the unsteady-state condensation mechanism not only increases the rate of mass transfer, but also tends to supersaturate the growing droplet with respect to the gas in question.

In order to test experimentally these phenomena, it was necessary to design an experiment that would consider the effect of droplet growth by condensation alone. Since oxygen is a gas of moderate solubility in water, it was necessary to keep the drop suspended from the tip of a hypodermic needle in a stream of gas for a considerable time. In the first experiment, there was no condensation of vapor on the drop. Then absorption of O_2 was measured in the presence of supersaturated amounts of water vapor.

CHAPTER III

INSTRUMENTATION AND EQUIPMENT

The experimental apparatus can be divided into three parts according to their function in the experiment: the section that controls and measures the variables influencing the absorption rate; the portion relating to the quantity that is measured, that is, the oxygen absorbed by the droplet; and finally and most importantly, the component where the process takes place, the contact chamber.

The contact chamber was a glass tube 60 centimeters in length and 3.5 centimeters in diameter. Is is shown schematically in Figure 1. This chamber was hand blown in the Georgia Tech Glass Blowing Laboratory and consisted of a straight tube with one main outlet where the droplet was collected for immediate analysis. Immediately above this outlet tube was a hypodermic needle with the tip polished flat and placed so that its tip was at the center of the contact chamber. The thermometer was placed downstream from the needle so a reading of the gas temperature could be had as near the drop as possible but without affecting the gas flow as it passes by the drop. At the entrance to the contact chamber there were a pair of baffles to insure mixing of the gas streams inside the contact chamber. The glass tube was sealed at the ends by cemented plexiglass plates. The gases were delivered to the chamber by tubing ending at Swagelock fittings which screwed into the Plexiglass plates. The chamber also contained two drains for removing the condensate. These were kept

closed during each run to prevent escape of gas.

Figure 1.   Contact Chamber.

The glass system was supported from a laboratory rack by clamps. The whole tube was wrapped with asbestos cloth to keep it insulated.

The other section of the experimental apparatus consisted of the instruments to monitor and measure the independent variables affecting the absorption rate.

The gas delivery system is shown schematically in Figure 2. The function of this system was to meter, mix and humidify the gases before delivering them to the contact chamber so the desired composition and humidity could be attained.

The gases were delivered to the contact chamber in two streams, one humid and the other dry, and both at the same temperature of 26°C. The humid stream consisted of nitrogen and/or oxygen drawn from a cylinder

Symbols:

φ Regulator   ⫴⫴⫴ Flowmeter

⊗ Valve   -ᴧᴧᴧ- Heat Exchanger

Θ Check Valve   ꓭ Pump

Figure 2. Gas Delivery System.

through a valve, a check valve, a heat exchanger, another check valve, a

rotameter and finally through the humidifier before it was delivered to

the inlet of the chamber. The humidifier was maintained at a constant

temperature by external circulation of warm water from a Haake, Model

FK2, Constant Temperature Bath. The dry stream consisted of nitrogen and/

or oxygen taken from a cylinder, through a valve, a check valve, a heat

exchanger, another check valve, through a rotameter and finally mixed and

delivered to the contact chamber. The flowmeters used were Matheson

tubes, Nos. 605, which were ideal for the flow rate used. Tygon tubing

was used for the gas line.

The gas sampling system is shown in Figure 3. The function of this

system was to take samples of the gases in the contact chamber which were

representative of the conditions existing near the droplet. The gas

stream leaving the contact chamber was split. One part was sent to the

humidity analyzer, a Cambridge System, Model 880, Thermoelectric Dew Point

Figure 3.   Gas Sampling System.

Hygrometer to give the reading for the humidity at the dew point temperature of the gas.   The other part of the stream was sent to the oxygen analyzer where a reading of the oxygen content of the gas stream was given. For this a Beckman, Model 742, Oxygen Analyzer was used.

The final system of this section is the water supply system.   The feed water used was first distilled and deionized, then it was passed through an oxygen removal ion exchange cartridge to obtain the high purity and zero oxygen desired.   The syringe was immersed in a constant temperature tank at 5°C with the needle sticking through the bottom of it. The tank was then placed in its position atop the contact chamber so the

needle would go through the hole and into the chamber (see Figure 1). Before starting an experiment, the syringe was filled with high-purity water and allowed to reach thermal equilibrium. The contact chamber was wrapped with Teflon tape to prevent condensate from forming in the stem of the needle and dripping down to the tip during the experiments. The needle was a 24 gauge rustless steel hypodermic needle with the end squared off and polished. A picture of a drop suspended on its tip showed it was spherical in shape.

The third and last part of the experimental apparatus was that which measured the oxygen dissolved in the water. For this purpose a Natelson Microgasometer, Model 650, was used. It was chosen because only a small amount of sample, 0.030 millimeter, was necessary to obtain a reading.

CHAPTER IV

PROCEDURE

In this section, the procedure used in carrying out an experimental test will be described with as much detail as possible so it could be duplicated if desired.

Prior to making a run, several preparations had to be made. The dew point hygrometer and oxygen analyzer were connected to a constant-voltage transformer and allowed to warm to equilibrium. The hot water bath was turned on and the water temperature allowed to equilibrate. While these instruments were allowed to stabilize, the standard reagents for use in the Natelson Microgasometer were prepared. They are:

1. 1.2% Potassium Ferricyanide - 1.2 grams of potassium ferricyanide are dissolved in water and made up to 100 ml.

2. 1% Saponin - 1 gram of saponin is dissolved in water and made up to 100 ml with normal saline solution (0.9% NaCl). This was prepared fresh every week.

3. Saponin Ferricyanide Mix - every day 1.5 ml of 1.2% potassium ferricyanide solution were mixed with 10 ml of 1% saponin and covered with caprylic alcohol to avoid contact with ambient air.

4. 3N Sodium Hydroxide - 12 grams of NaOH are dissolved in water and made up to 100 ml.

5. 1N Potassium Hydroxide - 5.6 grams of KOH are dissolved in

water and made up to 100 ml.

6. Sodium Hydrosulfite Solution - every day 1 gram of sodium hy-
drosulfite was placed in a 7 ml vial and covered with mineral
oil. 5 ml of 1N KOH were added.

After the preparation of these reagents, a reading of a blank was
made in the microgasometer to determine the oxygen content of the stan-
dard reagents alone.

A volume of about 100 ml of distilled and deionized water was
passed through the oxygen removal ion exchanger to remove all the oxygen
dissolved in the water. This was then analyzed with the microgasometer
to check on the oxygen content; the result was always zero.

The oxygen analyzer was calibrated with a gas of known oxygen com-
position. And finally, the syringe was filled with the high purity de-
oxygenated water and immersed in the cold water tank and allowed to reach
thermal equilibrium at 5°C.

At this point, everything was ready to start a test. The gas cyl-
inders were opened and the flow rates adjusted with the valves until the
desired reading was obtained in each rotameter. Then readings of the dew
point hygrometer, oxygen analyzer and thermometer were made. These in-
struments were monitored throughout a test for constancy. After allow-
ing a few minutes to assure steady conditions, the collecting flask was
connected to the bottom of the center outlet of the contact chamber, as
shown in Figure 1. Now a drop of water was allowed to form at the tip of
this hypodermic needle and remain suspended for the desired time. After
this time, it was allowed to drop into the collection flask. Before form-
ing the next drop, an amount of water equivalent to the one that remained

in the stem of the needle in the previous run was discarded to assure that the water temperature was at the equilibrium temperature of 5°C. After collecting a few drops, these were transferred to the microgasometer so that they would be exposed for the minimum amount of time to the air inside the collecting flask, and no oxygen would be absorbed or desorbed. To assure this, an experiment was made simulating a typical run. Here drops of water were allowed to fall from the hypodermic needle into the collecting flask at intervals and allowed to stand inside the flask for the same time as in a typical run. It was shown that no detectable amount of oxygen was absorbed by the water.

Enough drops were collected to fill the capillary tube of the microgasometer to a volume of 0.12 ml. Now the saponin ferricyanide reagent was added to release the air dissolved in the sample of water and the total pressure exerted by this air was read from the manometer in millimeters of mercury. Then NaOH, 3N, was added to absorb the carbon dioxide in the air which was released in the first step, and the pressure again read. The difference in pressure gives the partial pressure of carbon dioxide. The third and final step was to add a sodium hydrosulfite solution to absorb the oxygen in the air released in the first step. The manometer is read and the difference in pressure in this and the second step gives the partial pressure of oxygen. This, when multiplied by a given factor, gives the milligrams of oxygen dissolved in the sample of water. For additional information on the procedure and mechanism of this instrument the Natelson Microgasometer Model 650, Instruction Booklet No. 6 can be consulted.

Three samples were taken and analyzed for each time-humidity-

concentration combination. The arithmetic average cf the three readings was taken as the final result (see Appendix H). One particular set of data was collected at a specified supersaturation ratio, since this took longer to change than either the oxygen concentraticn in the gas stream or the exposure time. Therefore, at one supersaturation ratio, data were taken for one oxygen concentration in the gas at six different exposure times. Then the oxygen concentration was changed and six more runs at different exposure times were made.

In total, four supersaturation ratios -- 1.0, 1.5, 2.0 and 2.5 -- were analyzed with four oxygen concentrations in the gas -- 21, 40, 60 and 80% by volume -- and six exposure times of 15, 30, 60, 90, 120 and 180 seconds. A total of 96 data points were obtained.

CHAPTER V

RESULTS AND DISCUSSION OF RESULTS

Any errors in the data are due either to sampling and measurement errors or to systematic errors. The latter would include those arising from the absence of control of a system parameter or a failure of the validity of one of the assumptions.

A number of assumptions have been made. It has been assumed that the gases as they entered the contact chamber were very well mixed and no oxygen, temperature or humidity gradient existed inside the chamber. It was also assumed that no oxygen was absorbed while the drop was in the collecting flask, and that no significant desorption occurred as the droplet struck the bottom of the flask.

The instrument was calibrated against accurate standards to minimize errors in measurements. In using the Natelson Microgasometer precision and sensitivity were sacrificed because of the need of a small-volume sample analyzer. Readings were obtained to a precision of $\pm$ 0.2 mg/lt.

A major problem was encountered in calculating the temperature of the drop as a function of time and in explaining the results in view of this consideration. An energy balance was performed around a drop of water as described in Appendix C. A material balance is also derived in Appendix C for the drop. Two differential equations were obtained as a function of temperature and the mass of the drop. These were solved

using the Runge-Kutta method of approximation for differential equations

(see Appendix C). A computer program showing the method used and the re-

sults obtained is included in this appendix. In making this calculation,

the properties of the water and air were assumed constant at the film tem-

perature, 21°C, and at the gas temperature, 26°C, respectively.

As can be seen from the results of the program, the temperature

rises quite rapidly during the first few seconds and then slows until it

reaches an equilibrium value. The final temperature, after 3 minutes,

reached by the drop is different for each supersaturation ratio. For a

supersaturation ratio of 1.5, which is equivalent to a partial pressure

of water in the gas of 9.8918 mm Hg, the water drop reaches equilibrium

at 294.40°K. Here the drop which is initially at 278.15°K is receiving

both latent heat from the condensing vapor and sensible heat from the gas

which is at a higher temperature, 299.15°K. As the temperature of the

drop rises, its vapor pressure increases and it would reach a point where

its vapor pressure was higher than the partial pressure of water in the

gas. This occurred after approximately 28.5 seconds and at a temperature

of 293.48°K. After this time, continuous evaporation of the drop occurs

since the system has reached a thermal equilibrium where the heat loss by

evaporation is balanced by the heat gain from the gas by convection. At

higher supersaturation ratios, evaporation never occurs because the

partial pressure of water in the gas was always higher than that of the

water drop. At a supersaturation ratio of 2.5, which is equivalent to a

partial pressure of water in the gas of 16.4864 mm Hg, the drop reaches

an equilibrium temperature of 299.95°K, which is higher than that of the

gas. In this case, sensible heat is lost by convection to the gas and this is balanced by an equivalent heat gain by condensation of the vapor.

In computing this temperature it is assumed that the water has an infinite thermal conductivity, i.e., that the temperature of the drop is uniform throughout. In reality, water has a finite thermal conductivity, and the temperature at the center of the drop is less than the temperature at its surface. It was found (see Appendix D) that the temperature at the center of the drop will reach the temperature of the surface about six seconds later.

Figures 4 through 7 show the oxygen absorbed by the water drop as a function of time for different supersaturation ratios and for different oxygen contents for the air. The curves presented showed an increase in the oxygen content in the drop as time increases. At first the increase is quite rapid then it tends to reach equilibrium at a lower rate. Thus oxygen absorption is always increasing with time although the temperature of the drop is also increasing, and consequently, the saturation solubility of oxygen should decrease. This behavior is explained by the fact that the water drop has never reached saturation and, no matter if the temperature increases, the drop will continue to absorb oxygen until it reaches the saturation value at that temperature (see Appendix E).

In Figure 8, the oxygen absorbed by the drop is plotted against the water condensed in it. A straight line shows that the increase in the oxygen content in the drop is directly proportional to the water condensed in the drop (see Appendix F and Table 6 for calculations and tabulation of the data in Figure 8).

Comparison of the theoretical Henry's Law Constant with the

experimental value of this constant showed that the latter is 25 times greater. Consequently the water that is condensing on the drop is super-saturated with oxygen. So, it can be concluded that the rate of oxygen absorbed during condensation is greater than theories predict.

Figure 4.   Oxygen Dissolved In Water Drop Vs. Time Of
Exposure At An Oxygen Concentration In Air Of 21% By Volume.

Figure 5. Oxygen Dissolved In Water Drop Vs. Time Of
Exposure At An Oxygen Concentration In Air Of 40% By Volume.

Figure 6. Oxygen Dissolved In Water Drop Vs. Time Of
Exposure At An Oxygen Concentration In Air Of 60% By Volume.

Figure 4. Oxygen Dissolved In Water Drop Vs. Time Of
Exposure At An Oxygen Concentration In Air Of 80% By Volume.

Figure 8. Moles Of Oxygen Absorbed Per cm^2 Droplet
Vs. Moles Water Condensed Per cm^2 Droplet.

CHAPTER VI

CONCLUSIONS

From the results obtained in this research, the following conclusion can be drawn:

1. The existing theories of absorption are inadequate to describe the process of absorption of a gas by a liquid drop of water during surface renewal by condensation.

2. The rate of mass transfer of oxygen increases with oxygen concentration in the gas stream, with increasing exposure time and with increasing rate of condensation.

3. The moles of oxygen absorbed is directly proportional to the moles of water condensed in a drop.

4. Under conditions of surface renewal by condensation the rate of mass transfer is higher than theories predict.

CHAPTER VII

RECOMMENDATIONS

The need for more studies of surface phenomena, especially the effects on condensation is evident. There have been obtained promising results on the effect of humidity on the absorption of oxygen by water droplets from the air. Further studies in this area might produce valuable data for use in pollution control systems.

APPENDIX A

NOMENCLATURE

A	Surface area of drop [cm^2].
C_A	Concentration of component A [gr-mole/cm^3].
C_{Ao}	Initial concentration of component A [gr-mole/cm^3].
C_A^*	Equilibrium concentration of component A [gr-mole/cm^3].
$C_{A\infty}$	Concentration of component A in fluid stream [gr-mole/cm^3].
C_B	Concentration of water vapor in air [gr-mole/cm^3].
C_{pB}	Heat capacity of water [cal/gr-°K].
C_{pc}	Heat capacity of air [cal/gr-°K].
C_S	Oxygen saturation solubility in water [mg/lt].
D	Diameter of drop of water [cm].
D_A	Diffusivity of component A [cm^2/sec].
H	Henry's Law Constant [$^{mm\ Hg}$/mg/lt].
h_m	Heat transfer coefficient [cal/cm^2-sec-°K].
K_x	Mass transfer coefficient of water vapor in air [gr/cm^2-sec].
k_B	Thermal conductivity of water [cal/gr-°K].
k_{cf}	Thermal conductivity of air [cal/gr-°K].
k_1	Henry's Law Constant as defined in Appendix G.
k_2	Experimental value for Henry's Law Constant as defined in Appendix G.

m	Mass of the drop of water [gr].
N_A	Diffusional molar flux [gr-mole/cm^2-sec].
N_{H_2O}	Water vapor condensed [gr-mole/cm^2].
N_{O_2}	Oxygen absorbed [gr-mole/cm^2].
Nu	Nusselt Number
P	Vapor Pressure of water [mm Hg].
$P_{H_2O\infty}$	Partial pressure of water vapo in air [mm Hg].
P_{O_2}	Partial pressure of oxygen in air [mm Hg].
Pr	Prandtl Number.
P_T	Total pressure [mm Hg].
R	Radius of the drop of water [cm].
Re	Reynolds Number.
s	Rate of production of fresh surface [sec^{-1}].
Sc	Schmidt Number.
Sh	Sherwood Number.
T	Temperature of drop [°K].
t	Time [sec].
TEMPIN, T_o	Initial temperature of the drop cf water [°K].
TEMPF	Final temperature of the drop of water [°K].
TIMEIN	Initial time of exposure of the drop [sec].
T_i	Surface temperature of drop [°K].
V	Volume of drop [cm^3].
v_∞	Velocity of air stream [cm/sec].
W	Rate of condensation [gr/sec].
x	Distance from interface to bulk of fluid [cm].
x_L	Depth of laminar layer [cm].

Y_{O_2}	Mole fraction oxygen in air.
ρ_B	Density of water [gr/cm^3].
ρ_{cf}	Density of air [gr/cm^3].
μ_{cf}	Viscosity of air [gr/cm-sec].
λ	Heat of condensation of water [cal/gr].
α	Thermal Diffusivity [cm^2/sec].

APPENDIX B

DETERMINATION OF MASS TRANSFER COEFFICIENT FOR CONDENSED WATER

$$Sh = 2.0 + 0.6(Re)^{1/2} (Sc)^{1/3}$$

$$\frac{K_x}{C_B} \frac{D}{D_B} = 2.0 + 0.6 \left(\frac{\rho_{cf} \nu_\infty D}{\mu_{cf}}\right)^{1/2} \left(\frac{\mu_c}{\rho D}\right)_f^{1/3}$$

where $D = .29$ cm

$\nu_\infty = 50$ cm/sec

$\rho_{cf} = 1.210 \times 10^{-3}$ gr/cm^3

$\mu_{cf} = 1.840 \times 10^{-4}$ gr/cm-sec

$C_B = 6.40 \times 10^{-5}$ gr-mole/cm^3 [from steam tables]

$D_B = 2.5911 \times 10^{-1}$ cm^2/sec   [eq. 16.3-1 Bird, et al. [7]]

$$K_x = \frac{(2.511 \times 10^{-1})(6.40 \times 10^{-5})}{.29} \left\{ 2.0 + 0.6 \ (9.7649) \right.$$

$$\left. \left(\frac{1.84 \times 10^{-4}}{(1.21 \times 10^{-3})(2.5911 \times 10^{-1})}\right)^{1/3} \right\}$$

$$= 3.8270 \times 10^{-4} \text{ gr-mole/cm}^2\text{-sec}$$

$$= 6.8886 \times 10^{-3} \text{ gr/cm}^2\text{-sec}$$

DETERMINATION OF HEAT TRANSFER COEFFICIENT

$$Nu = 2.0 + 0.6 \, (Re)^{1/2} \, (Pr)^{1/3}$$

$$\frac{h_m D}{k_{cf}} = 2.0 + 0.6 \left(\frac{D \nu_\infty \rho_{cf}}{\mu_{cf}}\right)^{1/2} \left(\frac{C_p \mu_c}{k_c}\right)^{1/3}_f$$

where $D = 0.29$ cm

$\nu_\infty = 50$ cm/sec

$\rho_{cf} = 1.210 \times 10^{-3}$ gr/cm^3

$\mu_{cf} = 1.84 \times 10^{-4}$ gr/cm-sec

$k_{cf} = 6.111 \times 10^{-5}$ cal/sec-cm-°K

$C_{pc} = 0.24$ cal/gr-°K

$Pr = 0.723$

$$h_m = \frac{6.111 \times 10^{-5}}{0.29} \left\{ 2.0 + 0.6 \left(\frac{.29 \, (50)(1.210 \times 10^{-3})}{1.84 \times 10^{-4}}\right)^{1/2} (.723)^{1/3} \right\}$$

$$h_m = 1.53 \times 10^{-3} \text{ cal/sec-cm}^2\text{-°K}$$

APPENDIX C

ENERGY BALANCE AROUND A DROP

$$C_p \ (T - 273.15) \ \frac{dm}{dt} + m \ C_p \ \frac{dT}{dt} = h_m A \ (T\infty - T) + W\lambda$$

where
$$A = 4\pi R^2$$

$$V = 4/3\pi R^3 = m/\rho$$

$$R = \left(\frac{3m}{4\pi\rho}\right)^{1/3}$$

then
$$A = 4\pi \left(\frac{3m}{4\pi\rho}\right)^{2/3}$$

$$W = \frac{K_x A}{P_T} \left(P_{H_2O\infty} - P\right)$$

and
$$P = \exp\left(\frac{-5.535 \times 10^3}{T} + 21.15\right)$$

Substituting these values in the energy equation:

$$m\, C_p\, \frac{dT}{dt} = hm\, 4\pi \left(\frac{3m}{4\pi\rho}\right)^{2/3} (T^\infty - T) + \frac{K_x}{P_T}\, 4\pi\left(\frac{3m}{4\pi\rho}\right)^{2/3}$$

$$\left[P_{H_2O} - \exp\left(\frac{-5.535 \times 10^3}{T} + 21.15\right)\right] \left\{\lambda - C_p\ (T - 273.15)\right\}$$

$$\frac{dT}{dt} = \frac{h_m}{C_p}\frac{4\pi}{}\left(\frac{3}{4\pi\rho}\right)^{2/3}\frac{(T^\infty - T)}{m^{1/3}} + \frac{K_x}{C_p\, P_T}\frac{4\pi}{}\left(\frac{3}{4\pi\rho}\right)^{2/3}\frac{P_{H_2O\infty}}{m^{1/3}}\left\{\lambda - C_p\ (T - 273.15)\right\}$$

$$- \frac{K_x}{C_p\, P_T}\frac{4\pi}{}\left(\frac{3}{4\pi\rho}\right)^{2/3}\frac{1}{m^{1/3}}\left[\exp\left(\frac{-5.535 \times 10^3}{T} + 21.15\right)\right]\left\{\lambda - C_p\ (T - 273.15)\right\}$$

where $\lambda = 585.04$ cal/gr

$K_x = 6.8886 \times 10^{-3}$ gr/cm^2 sec

$h_m = 1.53 \times 10^{-3}$ cal/sec-cm^2-°K

$P_T = 736$ mmHg

$C_{pB} = 1$ cal/gr-°K

$T^\infty = 299.15$ °K

$\rho_B = 1$ gr/cm^3

then $\quad \frac{dT}{dt} = 2.2134 \times \frac{1}{m^{1/3}} - 7.399 \times 10^{-3}\frac{T}{m^{1/3}} + 2.648 \times 10^{-2}\frac{P_{H_2O\infty}}{m^{1/3}}$

$$-4.0574 \times 10^7 \exp\left(-\frac{5.535 \times 10^3}{T}\right)\frac{1}{m^{1/3}}$$

$$- 6.9352 \times 10^4 \exp\left(-\frac{5.535 \times 10^3}{T}\right)\frac{(T - 273.15)}{m^{1/3}}$$

$$- 4.5262 \times 10^{-5} P_{H_2O\infty}\left(\frac{(T - 273.15)}{m^{1/3}}\right)$$

MATERIAL BALANCE AROUND DROP

$$\frac{dm}{dt} = \frac{dw}{dt} = \frac{K_x A}{P_T}\left(\frac{P_{H_2 0} - P}{1 - \frac{P}{P_T}}\right)$$

$$= \left\{\frac{K_x}{P_T} 4\pi \left(\frac{3m}{4\pi\rho}\right)^{2/3} P_{H_2 o} - \frac{K_x}{P_T} 4\pi \left(\frac{3m}{4\pi\rho}\right)^{2/3}\right.$$

$$\left. x \exp\left(\frac{-5.535 \times 10^3}{T} + 21.15\right)\right\} \Bigg/ \left[1 - \frac{1}{P_T}\exp\left(\frac{-5.535 \times 10^3}{T} + 21.15\right)\right]$$

where $K_x = 6.8886 \times 10^{-3}$ gr/cm^2-sec

$P_T = 736$ mm Hg

$\rho_B = 1$ gr/cm^3

Then $\frac{dm}{dt} = \left\{4.5262 \times 10^{-5} P_{H_2 0} m^{2/3} - 6.9352 \times 10^4 m^{2/3} \exp\left(\frac{-5.535 \times 10^3}{T}\right.\right.$

$$\left.\left. + 21.15\right)\right\} \Bigg/ \left\{1 - \frac{1}{P_T}\exp\left(\frac{-5.535 \times 10^3}{T} + 21.15\right)\right\}$$

```
      PROGRAM MAIN(INPUT,OUTPUT,TAPE1=INPUT,TAPE2=OUTPUT)
      F(T,P,W)=2.2154/(W**(1./3.))-7.399E-03*T/(W**(1./3.))
     1+2.543E-02*P/(W**(1./3.))-4.0574E07*EXP(-5.535E03/T)/
     1(W**(1./3.))-6.9352E04*EXP(-5.535E03/T)*(T-273.15)
     1/(W**(1./3.))-4.5262E-05*P*(T-273.15)/(W**(1./3.))
      G(T,P,W)=(4.5262E-05*P*W**(2./3.)-6.9352E04*W**(2./3.)*
     1EXP(-5.535E03/T))/(1.-(EXP(-5.535E03/T+21.15))/736.)
      WRITE(2,105)
   20 READ(1,100)PH2O
      IF(PH2O.EQ.0.0)GO TO 15
      K=0
      KL=0
      READ(1,101)DELT,TEMPIN,TIMEIN,TIMEF,WIN
      INT=((TIMEF-TIMEIN)/(DELT*50.))
      TEMP=TEMPIN
      TIME=TIMEIN
      W=WIN
    1 RK11=DELT*F(TEMP,PH2O,W)
      RK21=DELT*G(TEMP,PH2O,W)
      RK12=DELT*F(TEMP+RK11/2.,PH2O,W+RK21/2.)
      RK22=DELT*G(TEMP+RK11/2.,PH2O,W+RK21/2.)
      RK13=DELT*F(TEMP+RK12/2.,PH2O,W+RK22/2.)
      RK23=DELT*G(TEMP+RK12/2.,PH2O,W+RK22/2.)
      RK14=DELT*F(TEMP+RK13,PH2O,W+RK23)
      RK24=DELT*G(TEMP+RK13,PH2O,W+RK23)
      IF(K.EQ.1)GO TO 8
      K=1
      WRITE(2,102)PH2O,TIMEF
    8 IF(JINT.GT.INT)GO TO 10
      JINT=JINT+1
      GO TO 12
   10 IF(KL.EQ.1)GO TO 11
      KL=1
      WRITE(2,103)
   11 WRITE(2,104)TIME,TEMP,W
      JINT=0
   12 IF(TIME.GE.TIMEF)GO TO 20
      TEMP=TEMP+(1./6.)*(RK11+2.*RK12+2.*RK13+RK14)
      W=W+(1./6.)*(RK21+2.*RK22+2.*RK23+RK24)
      TIME=TIME+DELT
      GO TO 1
  100 FORMAT(F7.4)
  101 FORMAT(4F10.4,F10.6)
  102 FORMAT(/1H ,T10,"H2O PARTIAL",T25,"EXPOSURE TIME",/
     11H ,T8,"PRESSURE,MMHG.",T30,"SEC",/
     11H ,T8,F10.4,T25,F10.2)
  103 FORMAT(1H ,T20,"TIME,SEC.",T35,"TEMPERATURE, DEG K.",/
     11H ,T60,"DROPLET MASS,GR.")
  104 FORMAT(1H ,T20,F8.4,T42,F8.2,T60,E15.7)
  105 FORMAT(1H1)
   15 STOP
      END
```

Table 1 .   Temperature Of Water Drop.

H_2O Partial Pressure	Exposure Time
9.8918 mm Hg	15.00 sec

Time, Sec.	Temperature Deg. K.	Droplet Mass, Gr.
.4000	278.68	.1344651E-01
.9000	279.33	.1345446E-01
1.4000	279.96	.1346219E-01
1.9000	280.57	.1346970E-01
2.4000	281.16	.1347699E-01
2.9000	281.73	.1348406E-01
3.4000	282.28	.1349091E-01
3.9000	282.81	.1349754E-01
4.4000	283.32	.1350394E-01
4.9000	283.81	.1351012E-01
5.4000	284.29	.1351608E-01
5.9000	284.75	.1352183E-01
6.4000	285.19	.1352735E-01
6.9000	285.61	.1353267E-01
7.4000	286.02	.1353777E-01
7.9000	286.41	.1354266E-01
8.4000	286.78	.1354735E-01
8.9000	287.14	.1355183E-01
9.4000	287.49	.1355612E-01
9.9000	287.82	.1256021E-01
10.4000	288.13	.1356412E-01
10.9000	288.44	.1356783E-01
11.4000	288.73	.1357137E-01
11.9000	289.00	.1357473E-01
12.4000	289.27	.1357793E-01
12.9000	289.52	.1358095E-01
13.4000	289.76	.1358381E-01
13.9000	289.99	.1358652E-01
14.4000	290.21	.1358907E-01
14.9000	290.42	.1359148E-01

Table 1. Temperature Of Water Drop (Continued).

H_2O Partial Pressure

9.8918 mm Hg

Exposure Time

30.00 sec

Time, Sec.	Temperature Deg. K.	Droplet Mass, Gr.
.5000	278.82	.1344812E-01
1.3000	279.84	.1346066E-01
2.1000	280.81	.1347264E-01
2.9000	281.73	.1348406E-01
3.7000	282.60	.1349491E-01
4.5000	283.42	.1350519E-01
5.3000	284.20	.1351491E-01
6.1000	284.92	.1352406E-01
6.9000	285.61	.1353267E-01
7.7000	286.25	.1354073E-01
8.5000	286.85	.1354826E-01
9.3000	287.42	.1355528E-01
10.1000	287.94	.1356180E-01
10.9000	288.44	.1356783E-01
11.7000	288.89	.1357341E-01
12.5000	289.32	.1357854E-01
13.3000	289.72	.1358325E-01
14.1000	290.08	.1358756E-01
14.9000	290.42	.1359148E-01
15.7000	290.74	.1359504E-01
16.5000	291.03	.1359826E-01
17.3000	291.30	.1360116E-01
18.1000	291.55	.1360375E-01
18.9000	291.79	.1360606E-01
19.7000	292.00	.1360810E-01
20.5000	292.20	.1360990E-01
21.3000	292.38	.1361146E-01
22.1000	292.54	.1361281E-01
22.9000	292.70	.1361395E-01
23.7000	292.84	.1361491E-01
24.5000	292.97	.1361570E-01
25.3000	293.09	.1361632E-01
26.1000	293.20	.1361680E-01
26.9000	293.30	.1361713E-01
27.7000	293.39	.1361735E-01
28.5000	293.48	.1361744E-01
29.3000	293.55	.1361743E-01
30.1000	293.63	.1361731E-01

Table 1. Temperature Of Water Drop (Continued).

H_2O Partial Pressure	Exposure Time
9.8918 mm Hg	60.00 sec

Time, Sec.	Temperature Deg. K.	Droplet Mass, Gr.
1.3000	279.84	.1346066E-01
2.7000	281.50	.1348126E-01
4.1000	283.02	.1350012E-01
5.5000	284.38	.1351725E-01
6.9000	285.61	.1353267E-01
8.3000	286.71	.1354643E-01
9.7000	287.69	.1355860E-01
11.1000	288.55	.1356927E-01
12.5000	289.32	.1357854E-01
13.9000	289.99	.1358652E-01
15.3000	290.59	.1359331E-01
16.7000	291.10	.1359902E-01
18.1000	291.55	.1360375E-01
19.5000	291.95	.1360762E-01
20.9000	292.29	.1361071E-01
22.3000	292.58	.1361311E-01
23.7000	292.84	.1361491E-01
25.1000	293.06	.1361618E-01
26.5000	293.25	.1361698E-01
27.9000	293.41	.1361738E-01
29.3000	293.55	.1361743E-01
30.7000	293.67	.1361717E-01
32.1000	292.78	.1361664E-01
33.5000	293.87	.1361589E-01
34.9000	293.95	.1361494E-01
36.3000	294.01	.1361383E-01
37.7000	294.07	.1361256E-01
39.1000	294.12	.1361117E-01
40.5000	294.16	.1360967E-01
41.9000	294.19	.1360808E-01
43.3000	294.22	.1360641E-01
44.7000	294.25	.1360467E-01
46.1000	294.27	.1360287E-01
47.5000	294.29	.1360103E-01
48.9000	294.31	.1359914E-01
50.3000	294.32	.1369721E-01
51.7000	294.33	.1359525E-01
53.1000	294.34	.1359327E-01
54.5000	294.35	.1359126E-01
55.9000	294.35	.1358923E-01

Table 1. Temperature Of Water Drop (Continued).

H_2O Partial Pressure   Exposure Time

9.8918 mm Hg   60.00 sec (continued)

Time, Sec.	Temperature Deg. K.	Droplet Mass, Gr.
57.3000	294.37	.1358719E-01
58.7000	294.37	.1358513E-01
60.1000	294.38	.1358306E-01

Table 1. Temperature Of Water Drop (Continued).

H_2O Partial Pressure   Exposure Time
    9.8918 mm Hg   90.00 sec

Time, Sec.	Temperature Deg. K.	Droplet Mass, Gr.
1.9000	280.57	.1346970E-01
3.9000	282.81	.1349754E-01
5.9000	284.75	.1352183E-01
7.9000	286.41	.1354266E-01
9.9000	287.82	.1356021E-01
11.9000	289.00	.1357473E-01
13.9000	289.99	.1358652E-01
15.9000	290.82	.1359588E-01
17.9000	291.49	.1350313E-01
19.9000	292.05	.1350858E-01
21.9000	292.50	.1361249E-01
23.9000	292.87	.1361512E-01
25.9000	293.17	.1361669E-01
27.9000	293.41	.1361738E-01
29.9000	293.61	.1361735E-01
31.9000	293.76	.1361673E-01
33.9000	293.80	.1361564E-01
35.9000	293.99	.1361416E-01
37.9000	294.07	.1361237E-01
39.9000	294.14	.1361033E-01
41.9000	294.19	.1360808E-01
43.9000	294.23	.1360567E-01
45.9000	294.27	.1360313E-01
47.9000	294.30	.1360049E-01
49.9000	294.32	.1359776E-01
51.9000	294.33	.1359497E-01
53.9000	294.35	.1359212E-01
55.9000	294.36	.1358923E-01
57.9000	294.37	.1358631E-01
59.9000	294.37	.1368335E-01
61.9000	294.38	.1358038E-01
63.9000	294.39	.1357739E-01
65.9000	294.39	.1357438E-01
67.9000	294.39	.1357137E-01
69.9000	294.39	.1356834E-01
71.9000	294.40	.1356531E-01
73.9000	294.40	.1356228E-01
75.9000	294.40	.1355923E-01
77.9000	294.40	.1355619E-01
7 .9000	294.40	.1355314E-01

Table 1. Temperature Of Water Drop (Continued).

H_2O Partial Pressure   Exposure Time

   9.8918 mm Hg   90.00 sec (continued)

Time, Sec.	Temperature Deg. K.	Droplet Mass, Gr.
81.9000	294.40	.1355009E-01
83.9000	294.40	.1354704E-01
85.9000	294.40	.1354399E-01
87.9000	294.40	.1354094E-01
89.9000	294.40	.1353789E-01

Table 1. Temperature Of Water Drop (Continued)

H_2O Partial Pressure   Exposure Time

9.8918 mm Hg   120.00 sec

Time, Sec.	Temperature Deg. K.	Droplet Mass, Gr.
2.3000	281.04	.1347555E-01
4.9000	283.81	.1351012E-01
7.5000	286.10	.1353876E-01
10.1000	187.94	.1356180E-01
12.7000	289.42	.1357976E-01
15.3000	290.59	.1359331E-01
17.9000	291.49	.1360313E-01
20.5000	292.20	.1360990E-01
23.1000	292.73	.1361421E-01
25.7000	293.14	.1361658E-01
28.3000	293.46	.1361743E-01
30.9000	293.69	.1361711E-01
33.5000	293.87	.1361589E-01
36.1000	294.00	.1361400E-01
38.7000	294.10	.1361158E-01
41.3000	294.18	.1360877E-01
43.9000	294.23	.1360567E-01
46.5000	294.28	.1360235E-01
49.1000	294.31	.1359886E-01
51.7000	294.33	.1359525E-01
54.3000	294.35	.1359155E-01
56.9000	294.36	.1358777E-01
59.5000	294.37	.1358395E-01
62.1000	294.38	.1358008E-01
64.7000	294.39	.1357619E-01
67.3000	294.39	.1357227E-01
69.9000	294.39	.1356834E-01
72.5000	294.40	.1356440E-01
75.1000	294.40	.1356045E-01
77.7000	294.40	.1355649E-01
80.3000	294.40	.1355253E-01
82.9000	294.40	.1354857E-01
85.5000	294.40	.1354460E-01
88.1000	294.40	.1354064E-01
90.7000	294.40	.1353667E-01
93.3000	294.40	.1353270E-01
95.9000	294.40	.1352873E-01
98.5000	294.40	.1352476E-01
101.1000	294.40	.1352079E-01
103.7000	294.40	.1351683E-01

Table 1.   Temperature Of Water Drop (Continued)

H_2O Partial Pressure   Exposure Time
        9.8918 mm Hg   120.00 sec (continued)

Time, Sec.	Temperature Deg. K.	Droplet Mass, Gr.
106.3000	294.40	.1351286E-01
108.9000	294.40	.1350889E-01
111.5000	294.40	.1350493E-01
114.1000	294.40	.1350096E-01
116.7000	294.40	.1349700E-01
119.3000	294.40	.1349303E-01

Table 1. Temperature Of Water Drop (Continued)

H$_2$O Partial Pressure   Exposure Time

    9.8918 mm Hg   180.00 sec

Time, Sec.	Temperature Deg. K.	Droplet Mass, Gr.
2.9000	281.73	.1348406E-01
6.7000	285.44	.1353057E-01
10.5000	288.19	.1356487E-01
14.3000	290.17	.1358857E-01
18.1000	291.55	.1360375E-01
21.9000	292.50	.1361249E-01
25.7000	293.14	.1361658E-01
29.5000	293.57	.1361741E-01
33.3000	293.86	.1361601E-01
37.1000	294.04	.1361312E-01
40.9000	294.17	.1360923E-01
44.7000	294.25	.1360467E-01
48.5000	294.30	.1359968E-01
52.3000	294.34	.1359440E-01
56.1000	294.36	.1358894E-01
59.9000	294.37	.1358335E-01
63.7000	294.38	.1357769E-01
67.5000	294.39	.1357197E-01
71.3000	294.40	.1356622E-01
75.1000	294.40	.1356045E-01
78.9000	294.40	.1355467E-01
82.7000	294.40	.1354888E-01
86.5000	294.40	.1354308E-01
90.3000	294.40	.1353728E-01
94.1000	294.40	.1353148E-01
97.9000	294.40	.1352568E-01
101.7000	294.40	.1351988E-01
105.5000	294.40	.1351408E-01
109.3000	294.40	.1350828E-01
113.1000	294.40	.1350249E-01
116.9000	294.40	.1349669E-01
120.7000	294.40	.1349090E-01
124.5000	294.40	.1348511E-01
128.3000	294.40	.1347932E-01
132.1000	294.40	.1347353E-01
135.9000	294.40	.1346774E-01
139.7000	294.40	.1346195E-01
143.5000	294.40	.1345617E-01
147.3000	294.40	.1345039E-01
151.1000	294.40	.1344461E-01

Table 1. Temperature Of Water Drop (Continued)

H_2O Partial Pressure

9.8918 mm Hg

Exposure Time

180.00 sec (continued)

Time, Sec.	Temperature Deg. K.	Droplet Mass, Gr.
154.9000	294.40	.1343883E-01
158.7000	294.40	.1343305E-01
162.5000	294.40	.1342728E-01
166.3000	294.40	.1342150E-01
170.1000	294.40	.1341573E-01
173.9000	294.40	.1340996E-01
177.7000	294.40	.1340419E-01

Table 1.   Temperature Of Water Drop (Continued).

H$_2$O Partial Pressure   Exposure Time

   13.1891 mm Hg   15.00 sec

Time, Sec.	Temperature Deg. K.	Droplet Mass, Gr.
0.0000	278.15	.1344000E-01
0.5000	279.00	.1345233E-01
1.0000	279.81	.1346439E-01
1.5000	280.61	.1347617E-01
2.0000	281.37	.1348767E-01
2.5000	282.11	.1349888E-01
3.0000	282.82	.1350980E-01
3.5000	283.51	.1352043E-01
4.0000	284.17	.1353076E-01
4.5000	284.81	.1354078E-01
5.0000	285.42	.1355051E-01
5.5000	286.01	.1355995E-01
6.0000	286.58	.1356908E-01
6.5000	287.12	.1357791E-01
7.0000	287.64	.1358645E-01
7.5000	288.14	.1359470E-01
8.0000	288.62	.1360266E-01
8.5000	289.07	.1361033E-01
9.0000	289.51	.1361773E-01
9.5000	289.92	.1362485E-01
10.0000	290.32	.1363170E-01
10.5000	290.70	.1363829E-01
11.0000	291.06	.1364462E-01
11.5000	291.40	.1365070E-01
12.0000	291.73	.1365654E-01
12.5000	292.04	.1366214E-01
13.0000	292.33	.1366751E-01
13.5000	292.61	.1367267E-01
14.0000	292.88	.1367761E-01
14.5000	293.13	.1368234E-01
15.0000	293.37	.1368687E-01

Table 1. Temperature Of Water Drop (Continued).

H_2O Partial Pressure   Exposure Time

    13.1891 mm Hg   30.00 sec

Time, Sec.	Temperature Deg. K.	Droplet Mass, Gr.
.6000	279.16	.1345476E-01
1.4000	280.45	.1347384E-01
2.2000	281.67	.1349219E-01
3.0000	282.82	.1350980E-01
3.8000	283.91	.1352666E-01
4.6000	284.94	.1354275E-01
5.4000	285.90	.1355808E-01
6.2000	286.80	.1357265E-01
7.0000	287.64	.1358645E-01
7.8000	288.43	.1359951E-01
8.6000	289.16	.1361183E-01
9.4000	289.84	.1362344E-01
10.2000	290.47	.1363436E-01
11.0000	291.06	.1364462E-01
11.8000	291.60	.1365423E-01
12.6000	292.10	.1366323E-01
13.4000	292.56	.1367165E-01
14.2000	292.98	.1367952E-01
15.0000	293.37	.1368687E-01
15.8000	293.73	.1369374E-01
16.6000	294.05	.1370014E-01
17.4000	294.35	.1370612E-01
18.2000	294.63	.1371170E-01
19.0000	294.88	.1371691E-01
19.8000	295.10	.1372178E-01
20.6000	295.31	.1372633E-01
21.4000	295.50	.1373059E-01
22.2000	295.67	.1373458E-01
23.0000	295.83	.1373832E-01
23.8000	295.97	.1374183E-01
24.6000	296.10	.1374514E-01
25.4000	296.22	.1374825E-01
26.2000	296.33	.1375119E-01
27.0000	296.42	.1375397E-01
27.8000	296.51	.1375660E-01
28.6000	296.59	.1375910E-01
29.4000	296.66	.1376148E-01

Table 1. Temperature Of Water Drop (Continued)

H_2O Partial Pressure   Exposure Time

    13.1891 mm Hg   60.00 sec

Time, Sec.	Temperature Deg. K.	Droplet Mass, Gr.
.6000	279.16	.1345476E-01
2.0000	281.37	.1348767E-01
3.4000	283.38	.1351833E-01
4.8000	285.18	.1354666E-01
6.2000	286.80	.1357265E-01
7.6000	288.24	.1359631E-01
9.0000	289.51	.1361773E-01
10.4000	290.63	.1363699E-01
11.8000	291.60	.1365423E-01
13.2000	292.45	.1366960E-01
14.6000	293.18	.1368326E-01
16.0000	293.81	.1369538E-01
17.4000	294.35	.1370612E-01
18.8000	294.82	.1371564E-01
20.2000	295.21	.1372410E-01
21.6000	295.54	.1373161E-01
23.0000	295.83	.1373832E-01
24.4000	296.07	.1374433E-01
25.8000	296.27	.1374974E-01
27.2000	296.45	.1375464E-01
28.6000	296.59	.1375910E-01
30.0000	296.71	.1376320E-01
31.4000	296.81	.1376697E-01
32.8000	296.90	.1377048E-01
34.2000	296.97	.1377377E-01
35.6000	297.03	.1377687E-01
37.0000	297.09	.1377980E-01
38.4000	297.13	.1378260E-01
39.8000	297.16	.1378529E-01
41.2000	297.19	.1378789E-01
42.6000	297.22	.1379040E-01
44.0000	297.24	.1379285E-01
45.4000	297.26	.1379524E-01
46.8000	297.27	.1379758E-01
48.2000	297.29	.1379988E-01
49.6000	297.30	.1380215E-01
51.0000	297.30	.1380439E-01
52.4000	297.31	.1380661E-01
53.8000	297.32	.1380881E-01
55.2000	297.32	.1381100E-01

Table 1. Temperature Of Water Drop (Continued)

H_2O Partial Pressure   Exposure Time

13.1891 mm Hg   60.00 sec (continued)

Time, Sec	Temperature Deg. K.	Droplet Mass, Gr.
56.6000	297.33	.1381317E-01
58.0000	297.33	.1381532E-01
59.4000	297.33	.1381747E-01

Table 1. Temperature Of Water Drop (Continued)

H_2O Partial Pressure   Exposure Time

    13.1891 mm Hg   90.00 sec

Time, Sec.	Temperature Deg. K.	Droplet Mass, Gr.
1.2000	280.13	.1346914E-01
3.2000	283.10	.1351409E-01
5.2000	285.66	.1355432E-01
7.2000	287.84	.1358979E-01
9.2000	289.68	.1362061E-01
11.2000	291.20	.1364708E-01
13.2000	292.45	.1366960E-01
15.2000	293.46	.1368863E-01
17.2000	294.28	.1370467E-01
19.2000	294.93	.1371816E-01
21.2000	295.45	.1372955E-01
23.2000	295.87	.1373922E-01
25.2000	296.19	.1374749E-01
27.2000	296.45	.1375464E-01
29.2000	296.64	.1376090E-01
31.2000	296.64	.1376645E-01
33.2000	296.80	.1377144E-01
35.2000	296.92	.1377600E-01
37.2000	297.02	.1378021E-01
39.2000	297.09	.1378415E-01
41.2000	297.15	.1378789E-01
43.2000	297.19	.1379145E-01
45.2000	297.23	.1379490E-01
47.2000	297.26	.1379824E-01
49.2000	297.28	.1380151E-01
51.2000	297.29	.1380471E-01
53.2000	297.31	.1380787E-01
55.2000	297.32	.1381100E-01
57.2000	297.32	.1381409E-01
59.2000	297.33	.1381717E-01
61.2000	297.33	.1382023E-01
63.2000	297.34	.1382327E-01
65.2000	297.34	.1382631E-01
67.2000	297.34	.1382933E-01
69.2000	297.35	.1383236E-01
71.2000	297.35	.1383735E-01
73.2000	297.35	.1383839E-01
75.2000	297.35	.1384040E-01
77.2000	297.35	.1384441E-01
79.2000	297.35	.1385043E-01

Table 1. Temperature Of Water Drop (Continued)

H_2O Partial Pressure   Exposure Time

   13.1891 mm Hg   90.00 sec (continued)

Time, Sec.	Temperature Deg. K.	Droplet Mass, Gr.
83.2000	297.35	.1385343E-01
85.2000	297.35	.1385644E-01
87.2000	297.35	.1385945E-01
89.2000	297.35	.1386245E-01

Table 1. Temperature Of Water Drop (Continued)

H_2O Partial Pressure   Exposure Time

13.891 mm Hg   120.00 sec

Time, Sec.	Temperature Deg. K.	Droplet Mass, Gr.
1.6000	280.76	.1347849E-01
4.2000	284.43	.1353480E-01
6.8000	287.44	.1358307E-01
9.4000	289.84	.1362344E-01
12.0000	291.73	.1365654E-01
14.6000	293.18	.1368326E-01
17.2000	294.28	.1370467E-01
19.8000	295.10	.1372178E-01
22.4000	295.71	.1373554E-01
25.0000	296.16	.1374672E-01
27.6000	296.49	.1375596E-01
30.2000	296.73	.1376375E-01
32.8000	296.90	.1377048E-01
35.4000	297.03	.1377643E-01
38.0000	297.12	.1378182E-01
40.6000	297.18	.1378678E-01
43.2000	297.23	.1379145E-01
45.8000	297.26	.1379591E-01
48.4000	297.29	.1380021E-01
51.0000	297.30	.1380439E-01
53.6000	297.32	.1380850E-01
56.2000	297.33	.1381255E-01
58.8000	297.33	.1381655E-01
61.4000	297.34	.1382053E-01
64.0000	297.34	.1382449E-01
66.6000	297.34	.1382843E-01
69.2000	297.35	.1383236E-01
71.8000	297.35	.1383628E-01
74.4000	297.35	.1384020E-01
77.0000	297.35	.1384411E-01
79.6000	297.35	.1384802E-01
82.2000	297.35	.1385193E-01
84.8000	297.35	.1385584E-01
87.4000	297.35	.1385975E-01
90.0000	297.35	.1386366E-01
92.6000	297.35	.1386737E-01
95.2000	297.35	.1387147E-01
97.8000	297.35	.1387538E-01
100.4000	297.35	.1387929E-01
103.0000	297.35	.1388320E-01

Table 1. Temperature Of Water Drop (Continued)

H$_2$0 Partial Pressure

13.8918 mm Hg

Exposure Time

120.00 sec (continued)

Time, Sec	Temperature Deg. K.	Droplet Mass, Gr.
105.6000	297.35	.1388712E-01
108.2000	297.35	.1389103E-01
110.8000	297.35	.1380494E-01
113.4000	297.35	.1389885E-01
116.0000	297.35	.1390277E-01
118.6000	297.35	.1390668E-01

Table 1. Temperature Of Water Drop (Continued)

H$_2$O Partial Pressure   Exposure Time

     13.1891 mm Hg   180.00 sec

Time, Sec	Temperature Deg. K.	Droplet Mass, Gr.
2.2000	281.67	.1349219E-01
6.0000	286.58	.1356908E-01
9.8000	290.16	.1362899E-01
13.6000	292.67	.1367367E-01
17.4000	294.35	.1370612E-01
21.2000	295.45	.1372955E-01
25.0000	296.16	.1374672E-01
28.8000	296.61	.1375971E-01
32.6000	296.89	.1377000E-01
36.4000	297.06	.1377856E-01
40.2000	297.17	.1378604E-01
44.0000	297.24	.1379285E-01
47.8000	297.28	.1379923E-01
51.6000	297.31	.1380535E-01
55.4000	297.32	.1381131E-01
59.2000	297.33	.1381717E-01
63.0000	297.34	.1382297E-01
66.8000	297.35	.1382873E-01
70.6000	297.35	.1383447E-01
74.4000	297.35	.1384020E-01
78.2000	297.35	.1384591E-01
82.0000	297.35	.1385163E-01
85.8000	297.35	.1385734E-01
89.6000	297.35	.1386306E-01
93.4000	297.35	.1386877E-01
97.2000	297.35	.1387448E-01
101.0000	297.35	.1388020E-01
104.8000	297.35	.1388591E-01
108.6000	297.35	.1389163E-01
112.4000	297.35	.1389735E-01
116.2000	297.35	.1390307E-01
120.0000	297.35	.1390879E-01
123.8000	297.35	.1391451E-01
127.6000	297.35	.1392024E-01
131.4000	297.35	.1392596E-01
135.2000	297.35	.1393169E-01
139.0000	297.35	.1393742E-01
142.8000	297.35	.1394315E-01
146.6000	297.35	.1394888E-01
150.4000	297.35	.1395462E-01

Table 1.   Temperature Of Water Drop (Continued)

H_2O Partial Pressure   Exposure Time

13.8918 mm Hg   180.00 sec (continued)

Time, Sec.	Temperature Deg. K.	Droplet Mass, Gr.
154.2000	297.35	.1396035E-01
158.0000	297.35	.1396609E-01
161.8000	297.35	.1397183E-01
165.6000	297.35	.1397757E-01
169.4000	297.35	.1398331E-01
173.2000	297.35	.1398906E-01
177.0000	297.35	.1399480E-01

Table 1. Temperature Of Water Drop (Continued)

H$_2$0 Partial Pressure   Exposure Time

16.4864 mm Hg   15.00 sec

Time, Sec.	Temperature Deg. K.	Droplet Mass, Gr.
0.0000	278.15	.1344000E-01
0.5000	279.17	.1345654E-01
1.0000	280.17	.1347276E-01
1.5000	281.12	.1348864E-01
2.0000	282.05	.1350417E-01
2.5000	282.94	.1351934E-01
3.0000	283.80	.1353415E-01
3.5000	284.63	.1354858E-01
4.0000	285.42	.1356263E-01
4.5000	286.19	.1357630E-01
5.0000	286.92	.1358959E-01
5.5000	287.63	.1360248E-01
6.0000	288.30	.1361499E-01
6.5000	288.94	.1362711E-01
7.0000	289.56	.1363884E-01
7.5000	290.14	.1365018E-01
8.0000	290.70	.1366114E-01
8.5000	291.24	.1367173E-01
9.0000	291.74	.1368195E-01
9.5000	292.22	.1369181E-01
10.0000	292.68	.1370131E-01
10.5000	293.12	.1371046E-01
11.0000	293.53	.1371928E-01
11.5000	293.92	.1372777E-01
12.0000	294.28	.1373594E-01
12.5000	294.63	.1374380E-01
13.0000	294.96	.1375137E-01
13.5000	295.27	.1375865E-01
14.0000	295.56	.1376566E-01
14.5000	295.84	.1377240E-01
15.0000	296.10	.1377889E-01

Table 1. Temperature Of Water Drop (Continued)

H$_2$0 Partial Pressure   Exposure Time

    16.4864 mm Hg   30.00 sec

Time, Sec.	Temperature Deg. K.	Droplet Mass, Gr.
.6000	279.38	.1345981E-01
1.4000	280.93	.1348549E-01
2.2000	282.41	.1351028E-01
3.0000	283.80	.1353415E-01
3.8000	285.11	.1355706E-01
4.6000	286.34	.1357899E-01
5.4000	287.49	.1359994E-01
6.2000	288.56	.1361988E-01
7.0000	289.56	.1363884E-01
7.8000	290.48	.1365680E-01
8.6000	291.34	.1367380E-01
9.4000	292.13	.1368986E-01
10.2000	292.86	.1370501E-01
11.0000	293.53	.1371928E-01
11.8000	294.14	.1373271E-01
12.6000	294.70	.1374534E-01
13.4000	295.21	.1375722E-01
14.2000	295.68	.1376839E-01
15.0000	296.10	.1377889E-01
15.8000	296.48	.1378877E-01
16.6000	296.83	.1379808E-01
17.4000	297.15	.1380686E-01
18.2000	297.43	.1381515E-01
19.0000	297.69	.1382298E-01
19.8000	297.92	.1383041E-01
20.6000	298.13	.1383746E-01
21.4000	298.32	.1384416E-01
22.2000	298.49	.1385055E-01
23.0000	298.64	.1385665E-01
23.8000	298.78	.1386250E-01
24.6000	298.90	.1386811E-01
25.4000	299.01	.1387352E-01
26.2000	299.11	.1387873E-01
27.0000	299.20	.1388377E-01
27.8000	299.28	.1388866E-01
28.6000	299.35	.1389341E-01
29.4000	299.41	.1389803E-01

Table 1.   Temperature Of Water Drop (Continued)

H$_2$O Partial Pressure   Exposure Time

    16.4864 mm Hg   60.00 sec

Time, Sec.	Temperature Deg. K.	Droplet Mass, Gr.
.6000	279.38	.1345981E-01
2.0000	282.05	.1350417E-01
3.4000	284.47	.1354572E-01
4.8000	286.63	.1358432E-01
6.2000	288.56	.1361988E-01
7.6000	290.26	.1365240E-01
9.0000	291.74	.1368195E-01
10.4000	293.03	.1370866E-01
11.8000	294.14	.1373271E-01
13.2000	295.09	.1375432E-01
14.6000	295.89	.1377372E-01
16.0000	296.57	.1379115E-01
17.4000	297.15	.1380686E-01
18.8000	297.63	.1382107E-01
20.2000	298.03	.1383398E-01
21.6000	298.36	.1384578E-01
23.0000	298.64	.1385665E-01
24.4000	298.87	.1386673E-01
25.8000	299.06	.1387615E-01
27.2000	299.22	.1388501E-01
28.6000	299.35	.1389341E-01
30.0000	299.45	.1390142E-01
31.4000	299.54	.1390912E-01
32.8000	299.61	.1391656E-01
34.2000	299.67	.1392377E-01
35.6000	299.72	.1393081E-01
37.0000	299.76	.1393771E-01
38.4000	299.79	.1394448E-01
39.8000	299.82	.1395116E-01
41.2000	299.84	.1395775E-01
42.6000	299.86	.1396427E-01
44.0000	299.88	.1397075E-01
45.4000	299.89	.1397718E-01
46.8000	299.90	.1398357E-01
48.2000	299.91	.1398993E-01
49.6000	299.91	.1399627E-01
51.0000	299.92	.1400259E-01
52.4000	299.92	.1400890E-01
53.8000	299.93	.1401519E-01

Table 1. Temperature Of Water Drop (Continued)

H$_2$0 Partial Pressure   Exposure Time

    16.4864 mm Hg   60.00 sec (continued)

Time, Sec.	Temperature Deg. K.	Droplet Mass, Gr.
55.2000	299.93	.1402147E-01
56.6000	299.93	.1402775E-01
58.0000	299.94	.1403402E-01
59.4000	299.94	.1404028E-01

Table 1. Temperature Of Water Drop (Continued)

H_2O Partial Pressure   Exposure Time

    16.4864 mm Hg   90.00 sec

Time, Sec.	Temperature Deg. K.	Droplet Mass, Gr.
1.2000	280.55	.1347915E-01
3.2000	284.14	.1353996E-01
5.2000	287.21	.1349479E-01
7.2000	289.80	.1364342E-01
9.2000	291.94	.1368594E-01
11.2000	293.68	.1372271E-01
13.2000	295.09	.1375432E-01
15.2000	296.20	.1378142E-01
17.2000	297.07	.1380471E-01
19.2000	297.75	.1382488E-01
21.2000	298.27	.1384251E-01
23.2000	298.68	.1385814E-01
25.2000	298.98	.1387219E-01
27.2000	299.22	.1388501E-01
29.2000	299.39	.1389688E-01
31.2000	299.53	.1390804E-01
33.2000	299.63	.1391864E-01
35.2000	299.71	.1392882E-01
37.2000	299.77	.1393868E-01
39.2000	299.81	.1394831E-01
41.2000	299.84	.1395775E-01
43.2000	299.87	.1395705E-01
45.2000	299.89	.1397626E-01
47.2000	299.90	.1398539E-01
49.2000	299.91	.1399446E-01
51.2000	299.92	.1400349E-01
53.2000	299.93	.1401249E-01
55.2000	299.93	.1402147E-01
57.2000	299.93	.1403044E-01
59.2000	299.94	.1403939E-01
61.2000	299.94	.1404833E-01
63.2000	299.94	.1405727E-01
65.2000	299.94	.1406621E-01
67.2000	299.94	.1407515E-01
69.2000	299.94	.1408408E-01
71.2000	299.94	.1409302E-01
73.2000	299.94	.1410196E-01
75.2000	299.94	.1411090E-01
77.2000	299.94	.1411985E-01
79.2000	299.94	.1412880E-01

Table 1. Temperature Of Water Drop (Continued)

H_2O Partial Pressure

16.4864 mm Hg

Exposure Time

90.00 sec (Continued)

Time, Sec	Temperature Deg. K.	Droplet Mass, Gr.
81.2000	299.94	.1413775E-01
83.2000	299.94	.1414670E-01
85.2000	299.94	.1415566E-01
87.2000	299.94	.1416462E-01
89.2000	299.94	.1417358E-01

Table 1. Temperature Of Water Drop (Continued)

H$_2$0 Partial Pressure

16.4864 mm Hg

Exposure Time

120.00 sec

Time, Sec.	Temperature Deg. K.	Droplet Mass, Gr.
1.6000	281.31	.1349177E-01
4.2000	285.73	.1356815E-01
6.8000	289.32	.1363419E-01
9.4000	292.13	.1368986E-01
12.0000	294.28	.1373594E-01
14.6000	295.89	.1377372E-01
17.2000	297.07	.1380471E-01
19.8000	297.92	.1383041E-01
22.4000	298 53	.1385210E-01
25.0000	298.96	.1387084E-01
27.6000	299.26	.1388745E-01
30.2000	299.47	.1390254E-01
32.8000	299.61	.1391656E-01
35.4000	299.71	.1392982E-01
38.0000	299.79	.1394256E-01
40.6000	299.83	.1395493E-01
43.2000	299.87	.1396705E-01
45.8000	299.89	.1397901E-01
48.4000	299.91	.1399084E-01
51.0000	299.92	.1400259E-01
53.6000	299.93	.1401429E-01
56.2000	299.93	.1402596E-01
58.8000	299.94	.1403760E-01
61.4000	299.94	.1404923E-01
64.0000	299.94	.1406085E-01
66.6000	299.94	.1407247E-01
69.2000	299.94	.1408408E-01
71.8000	299.94	.1409570E-01
74.4000	299.94	.1410733E-01
77.0000	299.94	.1411895E-01
79.6000	299.94	.1413059E-01
82.2000	299.94	.1414222E-01
84.8000	299.94	.1415387E-01
87.4000	299.94	.1416551E-01
90.0000	299.94	.1417717E-01
92.6000	299.94	.1418883E-01
95.2000	299.94	.1420050E-01
97.8000	299.95	.1421217E-01
100.4000	299.95	.1422385E-01
103.0000	299.95	.1423554E-01

Table 1. Temperature Of Water Drop (Continued)

H$_2$0 Partial Pressure   Exposure Time

16.4864 mm Hg   120.00 sec (continued)

Time, Sec.	Temperature Deg. K.	Droplet Mass, Gr.
105.6000	299.95	.1424723E-01
108.2000	299.95	.1425893E-01
110.8000	299.95	.1427063E-01
113.4000	299.95	.1428234E-01
116.0000	299.95	.1429406E-01
118.6000	299.95	.1430579E-01

Table 1. Temperature Of Water Drop (Continued)

H$_2$0 Partial Pressure.   Exposure Time

16.4864 mm Hg   180.00 sec

Time, Sec.	Temperature Deg. K.	Droplet Mass, Gr.
2.2000	282.41	.1351028 E-01
6.0000	288.30	.1361499 E-01
9.8000	292.50	.1369755 E-01
13.6000	295.33	.1376007 E-01
17.4000	297.15	.1380686 E-01
21.2000	298.27	.1384251 E-01
25.0000	298.96	.1387084 E-01
28.8000	299.36	.1389457 E-01
32.6000	299.60	.1391551 E-01
36.4000	299.75	.1393477 E-01
40.2000	299.83	.1395305 E-01
44.0000	299.88	.1397075 E-01
47.8000	299.91	.1398812 E-01
51.6000	299.92	.1400530 E-01
55.4000	299.93	.1402237 E-01
59.2000	299.94	.1403939 E-01
63.0000	299.94	.1405638 E-01
66.8000	299.94	.1407336 E-01
70.6000	299.94	.1409034 E-01
74.4000	299.94	.1410733 E-01
78.2000	299.94	.1412432 E-01
82.0000	299.94	.1414133 E-01
85.8000	299.94	.1415835 E-01
89.6000	299.94	.1417538 E-01
93.4000	299.94	.1419242 E-01
97.2000	299.94	.1420948 E-01
101.0000	299.95	.1422655 E-01
104.8000	299.95	.1424363 E-01
108.6000	299.95	.1426073 E-01
112.4000	299.95	.1427784 E-01
116.2000	299.95	.1429496 E-01
120.0000	299.95	.1431210 E-01
123.8000	299.95	.1432926 E-01
127.6000	299.95	.1434642 E-01
131.4000	299.95	.1436360 E-01
135.2000	299.95	.1438079 E-01
139.0000	299.95	.1439800 E-01
142.8000	299.95	.1441522 E-01
146.6000	299.95	.1443246 E-01
159.4000	299.95	.1444970 E-01

Table 1. Temperature Of Water Drop (Continued)

H$_2$O Partial Pressure   Exposure Time

    16.4864 mm Hg   180.00 sec (continued)

Time, Sec.	Temperature Deg. K.	Droplet Mass, Gr.
154.2000	299.95	.1446697E-01
158.0000	299.95	.1448424E-01
161.8000	299.95	.1450153E-01
165.6000	299.95	.1451883E-01
169.4000	299.95	.1453615E-01
173.2000	299.95	.1455348E-01
177.0000	299.95	.1457083E-01

APPENDIX D

DETERMINATION OF THE ERROR INCURRED
IN ASSUMING A UNIFORM DROP TEMPERATURE

$$\alpha = \frac{k_B}{C_{p\infty}\rho_B}$$

where

$$k_B = 1.43 \times 10^{-3} \text{ cal/sec cm } °K$$

$$C_{pB} = 1 \text{ cal/gr-}°K$$

$$\rho_B = 1 \text{ gr/cm}^3$$

then

$$\alpha = 1.43 \times 10^{-3} \text{ cm}^2/\text{sec}$$

using Figure 11.1-3, Bird, et al., [7], making the ordinate, $\left[\dfrac{T_c - T_o}{T_i - T_o}\right]$ as close as possible to 1.0 since this would mean that T_c, the temperature at the center is close to T_i, the temperature at the surface.

For

$$\left[\frac{T_c - T_o}{T_i - T_o}\right] = 0.97 \rightarrow \frac{\alpha t}{R^2} = 0.4$$

Solving for "t'"" $\qquad t = \dfrac{0.4(.145)^2}{1.43 \times 10^3} = 5.88 \text{ sec}$

This means that the temperature at the center of the drop will reach the temperature of the surface 5.88 seconds later. This doesn't present much of an error since after around 15 seconds the temperature of the surface is not varying too much so the temperature at the center is very nearly equal that at the surface.

APPENDIX E

DETERMINATION OF OXYGEN SATURATION
SOLUBILITY IN WATER

When water is in equilibrium with ambient air, the saturation con-
centration of oxygen in water is given by:

$$C_s = 10,087.530 - 129.62761T + 0.62758425T^2$$

$$-(1.354821 \times 10^{-3}) T^3 + (1.09878 \times 10^{-6}) T^4$$

Substitution into this equation for the temperature of the drop at
different times would give the oxygen saturation in water at different
times.   (See Table 2 below.)

Table 2 .   Oxygen Saturation Solubility In Water
In Equilibrium With Air at 21% Oxygen.

Time (sec)	Temp. (°K)	Supersaturation Ratio	Oxygen Saturation (mg/lt)
0	278.15	2.5	13.2
15	290.46	2.5	8.8
30	293.62	2.5	8.5
60	294.37	2.5	8.4
90	294.40	2.5	8.4
120	294.40	2.5	8.4
180	294.40	2.5	8.4

Table 2. Oxygen Saturation Solubility In Water
In Equilibrium With Air at 21% Oxygen (Continued).

Time (sec)	Temp. (°K)	Supersaturation Ratio	Oxygen Saturation (mg/1t)
0	278.15	2.0	13.2
15	293.37	2.0	9.2
30	296.71	2.0	8.9
60	297.33	2.0	8.8
90	297.35	2.0	8.8
120	297.35	2.0	8.8
180	297.35	2.0	8.8
0	278.15	1.5	13.2
15	296.10	1.5	9.6
30	299.94	1.5	9.4
60	299.95	1.5	9.3
90	299.95	1.5	9.3
120	299.95	1.5	9.3
180	299.95	1.5	9.3

If the oxygen content of the air varies, the oxygen saturation concentration changes according to Henry's Law.

$$P_{O_2} = H\,C_s$$

Calculation of Henry's Law Constant from the results obtained in Table 5 leads to the saturation concentration, C_s, at a specific oxygen partial pressures in the air (see Table 3 to 5 on the following pages

for results).

Table 3. Oxygen Saturation Solubility In Water
In Equilibrium With Air At 40% Oxygen.

Time (sec)	Temp. (°K)	Henry's Constant (mmHg/mg/1t)	Supersaturation Ratio	Oxygen Saturation (mg/1t)
0	278.15	11.71	2.5	25.14
15	290.46	17.56	2.5	16.77
30	293.62	18.18	2.5	16.19
60	294.37	18.40	2.5	16.0
90	294.40	18.40	2.5	16.0
120	294.40	18.40	2.5	16.0
180	294.40	18.40	2.5	16.0
0	278.15	11.71	2.0	25.14
15	293.37	16.80	2.0	17.52
30	295.71	17.37	2.0	16.95
60	297.33	17.56	2.0	16.77
90	297.35	17.56	2.0	16.77
120	297.35	17.56	2.0	16.77
180	297.35	17.56	2.0	16.77
0	278.15	11.71	1.5	25.14
15	296.10	16.10	1.5	18.29
30	299.94	16.44	1.5	17.91
60	299.95	16.62	1.5	17.71
90	299.95	16.62	1.5	17.71
120	299.95	16.62	1.5	17.71
180	299.95	16.62	1.5	17.71

Table 4. Oxygen Saturation Solubility In Water
In Equilibrium With Air At 60% Oxygen.

Time (sec)	Temp. (°K)	Henry's Constant (mmHg/mg/1t)	Supersaturation Ratio	Oxygen Saturation (mg/1t)
0	278.15	11.71	2.5	37.71
15	290.46	17.56	2.5	25.15
30	293.62	18.18	2.5	24.29
60	204.37	18.40	2.5	24.00
90	294.40	18.40	2.5	24.00
120	294.40	18.40	2.5	24.00
180	294.40	18.40	2.5	24.00
0	278.15	11.71	2.0	37.71
15	293.37	16.80	2.0	26.29
30	296.71	17.37	2.0	25.42
60	297.33	17.56	2.0	25.15
90	297.35	17.56	2.0	25.15
120	297.35	17.56	2.0	25.15
180	297.35	17.56	2.0	25.15
0	278.15	11.71	1.5	37.71
15	296.10	16.10	1.5	27.43
30	299.94	16.44	1.5	26.86
60	299.95	16.62	1.5	26.57
90	299.95	16.62	1.5	26.57
120	299.95	16.62	1.5	26.57
180	299.95	16.62	1.5	26.57

Table 5. Oxygen Saturation Solubility In Water
In Equilibrium With Air at 80% Oxygen.

Time (sec)	Temp. (°K)	Henry's Constant (mmHg/mg/1t)	Supersaturation Ratio	Oxygen Saturation (mg/1t)
0	278.15	11.71	2.5	50.28
15	290.46	17.56	2.5	33.53
30	293.62	18.18	2.5	32.39
60	294.37	18.40	2.5	32.00
90	294.40	18.40	2.5	32.00
120	294.40	18.40	2.5	32.00
180	294.40	18.40	2.5	32.00
0	278.15	11.71	2.0	50.28
15	293.37	16.80	2.0	35.05
30	296.71	17.37	2.0	33.90
60	297.33	17.56	2.0	33.53
90	297.35	17.56	2.0	33.53
120	297.35	17.56	2.0	33.53
180	297.35	17.56	2.0	33.53
0	278.15	11.71	1.5	50.28
15	296.10	16.10	1.5	36.57
30	299.94	16.40	1.5	35.90
60	299.95	16.44	1.5	35.82
90	299.95	16.62	1.5	35.43
120	299.94	16.62	1.5	35.43
180	299.95	16.62	1.5	35.43

APPENDIX F

DETERMINATION OF MOLES OF WATER
CONDENSED ON DROPLET SURFACE PER CM^2 DROPLET

From the results in the computer program, the total mass of the
drop is obtained, then subtracting this from the initial mass and dividing
by the molecular weight and the surface area gives:

$$\text{Moles of } H_2O \text{ Condensed} = \frac{m - 0.01344}{18A} \qquad (F.1)$$

where
$$A = 4\pi R^2$$

$$V = \frac{m}{\rho_B} = \frac{4}{3} \pi R^3$$

then
$$\frac{m_B}{\rho} = \frac{AR}{3}$$

$$A = \frac{3m_B}{R\rho}$$

and
$$R = \left(\frac{3m}{4\pi \rho_B}\right)^{1/3}$$

Substituting in Equation F.1:

$$\text{Moles of } H_2O \text{ Condensed} = \frac{(m - .01344)}{54m} \, \rho_B \left(\frac{3m}{4\pi\rho_B}\right)^{1/3}$$

where $\rho = 1.0 \text{ gr/cm}^3$

Values of the moles of water condensed per cm^2 of droplet are given in Table 6.

Table 6. Water Condensed In Drop.

Time (sec)	Supersaturation Ratio	Oxygen in Air (% by Vol.)	Oxygen Absorbed (gr-mole/cm^2)	H_2O Condensed (gr-mole/cm^2)
15	1.5	21	6.94×10^{-9}	3.06×10^{-5}
15	1.5	40	1.06×10^{-8}	3.06×10^{-5}
15	1.5	60	1.30×10^{-8}	3.06×10^{-5}
15	1.5	80	1.48×10^{-8}	3.06×10^{-5}
15	2.0	21	1.21×10^{-8}	4.96×10^{-5}
15	2.0	40	1.62×10^{-8}	4.96×10^{-5}
15	2.0	60	1.90×10^{-8}	4.96×10^{-5}
15	2.0	80	2.23×10^{-8}	4.96×10^{-5}
30	2.0	21	1.77×10^{-8}	6.47×10^{-5}
30	2.0	40	2.23×10^{-8}	6.47×10^{-5}
30	2.0	60	2.65×10^{-8}	6.47×10^{-5}
30	2.0	80	3.11×10^{-8}	6.47×10^{-5}
60	2.0	21	2.23×10^{-8}	7.55×10^{-5}
60	2.0	40	2.93×10^{-8}	7.55×10^{-5}
60	2.0	60	3.54×10^{-8}	7.55×10^{-5}
60	2.0	80	4.00×10^{-8}	7.55×10^{-5}
90	2.0	21	2.47×10^{-8}	8.43×10^{-5}
90	2.0	40	3.31×10^{-8}	8.43×10^{-5}
90	2.0	60	4.14×10^{-8}	8.43×10^{-5}
90	2.0	80	4.52×10^{-8}	8.43×10^{-5}

Table 6. Water Condensed In Drop (Continued).

Time (sec)	Supersaturation Ratio	Oxygen in Air (% by Vol.)	Oxygen Absorbed (gr-mole/cm^2)	H_2O Condensed (gr-mole/cm^2)
120	2.0	21	2.70×10^{-8}	9.31×10^{-5}
120	2.0	40	3.59×10^{-8}	9.31×10^{-5}
120	2.0	60	4.48×10^{-8}	9.31×10^{-5}
120	2.0	80	5.04×10^{-8}	9.31×10^{-5}
180	2.0	21	2.90×10^{-8}	1.11×10^{-4}
180	2.0	40	4.02×10^{-8}	1.11×10^{-4}
180	2.0	60	4.91×10^{-8}	1.11×10^{-4}
180	2.0	80	5.61×10^{-8}	1.11×10^{-4}
15	2.5	21	1.86×10^{-8}	6.78×10^{-5}
15	2.5	40	2.23×10^{-8}	6.78×10^{-5}
15	2.5	60	2.84×10^{-8}	6.78×10^{-5}
15	2.5	80	3.30×10^{-8}	6.78×10^{-5}
30	2.5	21	2.61×10^{-8}	9.17×10^{-5}
30	2.5	40	3.22×10^{-8}	9.17×10^{-5}
30	2.5	60	3.96×10^{-8}	9.17×10^{-5}
30	2.5	80	4.52×10^{-8}	9.17×10^{-5}
60	2.5	21	3.41×10^{-8}	1.19×10^{-4}
60	2.5	40	4.26×10^{-8}	1.19×10^{-4}
60	2.5	60	5.33×10^{-8}	1.19×10^{-4}
60	2.5	80	6.03×10^{-8}	1.19×10^{-4}
90	2.5	21	3.66×10^{-8}	1.45×10^{-4}
90	2.5	40	5.30×10^{-8}	1.45×10^{-4}
90	2.5	60	6.11×10^{-8}	1.45×10^{-4}
90	2.5	80	7.46×10^{-8}	1.45×10^{-4}

Table 6.   Water Condensed In Drop (Continued).

Time (sec)	Supersaturation Ratio	Oxygen in Air (% by Vol.)	Oxygen Absorbed (gr-mole/cm^2)	H$_2$0 Condensed (gr-mole/cm^2)
120	2.5	21	3.91×10^{-8}	1.70×10^{-4}
120	2.5	40	5.74×10^{-8}	1.70×10^{-4}
120	2.5	60	6.97×10^{-8}	1.70×10^{-4}
120	2.5	80	7.48×10^{-8}	1.70×10^{-4}
180	2.5	21	4.31×10^{-8}	2.21×10^{-4}
180	2.5	40	6.25×10^{-8}	2.21×10^{-4}
180	2.5	60	7.67×10^{-8}	2.21×10^{-4}
180	2.5	80	8.34×10^{-8}	2.21×10^{-4}

APPENDIX G

DETERMINATION OF HENRY'S LAW
CONSTANT FROM EXPERIMENT

A stepwise regression analysis is conducted using the data in Figure 8. (See Table 7.)

$$\frac{d(N_{O_2})}{dt} = kY_{O_2}^{\ n} \frac{d(N_{H_2O})}{dt}$$

After integration

$$N_{O_2} = kY_{O_2}^{\ n} N_{H_2O}$$

$$\frac{N_{O_2}}{N_{H_2O}} = kY_{O_2}^{\ n}$$

Table 7. Experimental Value Of Henry's Law
Constant As Defined In Appendix G

$\dfrac{N_{O_2}}{N_{H_2O}}$	Y_{O_2}	k_2	n
2.75×10^{-4}	0.21	5.4×10^{-4}	0.43
3.62×10^{-4}	0.40	5.4×10^{-4}	0.43
4.31×10^{-4}	0.60	5.4×10^{-4}	0.43
4.88×10^{-4}	0.80	5.4×10^{-4}	0.43

Henry's Law Constant is given by

$$Y_{0_2} P_T = H C_s$$

$$Y_{0_2} \frac{P_T}{H} = 1.77 \times 10^6 \; k_1 \; Y_{0_2} = C_s$$

$$k_1 = \frac{C_s}{1.77 \times 10^6 \; Y_{0_2}}$$

Values of C_s are given in Tables 2 to 5 for different values of Y_{0_2}.

$$\text{For } Y_{0_2} = 0.40$$

$$C_s = 16.5 \text{ mg/1t}$$

Substitution
$$k_1 = \frac{16.5}{1.77 \times 10^6 \; Y_{0_2}} = 2.33 \times 10^{-5}$$

Comparing both the experimental value, k_2, with the theoretical value, k_1:

$$\frac{k_2}{K_1} = \frac{5.4 \times 10^{-4}}{2.33 \times 10^{-5}} = 23.2$$

APPENDIX H

EXPERIMENTAL DATA

Table 8. Experimental Data.

Time (sec)	Air Temp. (°C)	Supersaturation Ratio	Oxygen in Air (% by Vol.)	Oxygen Absorbed (mg/lt)
15	26	1.0	21	1.0
30	26	1.0	21	1.6
60	26	1.0	21	2.8
90	26	1.0	21	3.1
120	26	1.0	21	3.4
180	26	1.0	21	3.6
15	26	1.0	40	1.4
30	26	1.0	40	2.3
60	26	1.0	40	3.7
90	26	1.0	40	4.2
120	26	1.0	40	4.6
180	26	1.0	40	4.9
15	26	1.0	60	1.8
30	26	1.0	60	2.9
60	26	1.0	60	4.1
90	26	1.0	60	4.7
120	26	1.0	60	5.1
180	26	1.0	60	5.4

Table 8.   Experimental Data (Continued).

Time (sec)	Air Temp. (°C)	Supersaturation Ratio	Oxygen in Air (% by Vol.)	Oxygen Absorbed (mg/lt)
15	26	1.0	80	2.0
30	26	1.0	80	3.4
60	26	1.0	80	4.4
90	26	1.0	80	5.2
120	26	1.0	80	5.6
180	26	1.0	80	6.0
15	26	1.5	21	1.5
30	26	1.5	21	2.6
60	26	1.5	21	3.8
90	26	1.5	21	4.1
120	26	1.5	21	4.3
180	26	1.5	21	4.6
15	26	1.5	40	2.3
30	26	1.5	40	3.1
60	26	1.5	40	4.8
90	26	1.5	40	5.5
120	26	1.5	40	6.1
180	26	1.5	40	6.6
15	26	1.5	60	2.8
30	26	1.5	60	3.9
60	26	1.5	60	5.2
90	26	1.5	60	5.9
120	26	1.5	60	6.5
180	26	1.5	60	6.9

Table 8. Experimental Data (Continued).

Time (sec)	Air Temp. (°C)	Supersaturation Ratio	Oxygen in Air (% by Vol.)	Oxygen Absorbed (mg/1t)
15	26	1.5	80	3.2
30	26	1.5	80	4.3
60	26	1.5	80	5.7
90	26	1.5	80	6.4
120	26	1.5	80	7.1
180	26	1.5	80	7.8
15	26	2.0	21	2.6
30	26	2.0	21	3.8
60	26	2.0	21	4.8
90	26	2.0	21	5.3
120	26	2.0	21	5.8
180	26	2.0	21	6.2
15	26	2.0	40	3.5
30	26	2.0	40	4.8
60	26	2.0	40	6.3
90	26	2.0	40	7.1
120	26	2.0	40	7.7
180	26	2.0	40	8.6
15	26	2.0	60	4.1
30	26	2.0	60	5.7
60	26	2.0	60	7.6
90	26	2.0	60	8.9
120	26	2.0	60	9.6
180	26	2.0	60	10.5

Table 8. Experimental Data (Continued).

Time (sec)	Air Temp. (°C)	Supersaturation Ratio	Oxygen in Air (% by Vol.)	Oxygen Absorbed (mg/lt)
15	26	2.0	80	4.8
30	26	2.0	80	6.7
60	26	2.0	80	8.6
90	26	2.0	80	9.7
120	26	2.0	80	10.8
180	26	2.0	80	12.0
15	26	2.5	21	4.0
30	26	2.5	21	5.6
60	26	2.5	21	7.3
90	26	2.5	21	7.8
120	26	2.5	21	8.3
180	26	2.5	21	9.1
15	26	2.5	40	4.8
30	26	2.5	40	6.9
60	26	2.5	40	9.1
90	26	2.5	40	11.3
120	26	2.5	40	12.2
180	26	2.5	40	13.2
15	26	2.5	60	6.1
30	26	2.5	60	8.5
60	26	2.5	60	11.4
90	26	2.5	60	13.0
120	26	2.5	60	14.8
180	26	2.5	60	16.2

Table 8.   Experimental Data (Continued).

Time (sec)	Air Temp. (°C)	Supersaturation Ratio	Oxygen in Air (% by Vol.)	Oxygen Absorbed (mg/lt)
15	26	2.5	80	7.1
30	26	2.5	80	9.7
60	26	2.5	80	12.9
90	26	2.5	80	14.8
120	26	2.5	80	15.9
180	26	2.5	80	17.6

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