No. 1849

THE EVAPORATION OF A LIQUID INTO A GAS

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Non-Member

The author investigates the mechanism of the evaporation of a liquid into a gas as applied to such processes as are found in gas scrubbers, humidifiers, dehumidifiers, water coolers, air driers, etc. He establishes the formula for calculating the humidity of air from wet- and dry-bulb thermometer readings, and shows that the coefficient of heat transfer divided by the coefficient of diffusion equals the humid heat of the gas.

A LARGE amount of work has been done on the evaporation of water into air at temperatures below the boiling point. The dynamic equilibrium corresponding to the evaporation of water into air counterbalanced by the flow of heat from the air into the water is the basis of wet-bulb thermometry, the most useful method of determining the humidity of air.[2] In 1886 Desmond Fitzgerald[3] pointed out that the rate of evaporation of water into air is a function of the difference in partial pressure between the moisture in equilibrium with the evaporating water and the actual moisture content of the air in contact with it. It is true that Fitzgerald did not assume the rate of evaporation linearly proportional to this difference, but added a small correction term proportional to the square of the difference. Barrows and Babb[4] made a large number of determinations of evaporation from the surface of Maine lakes, and while their experimental determinations were subject to a large

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[2] Leslie, Nicholson's Journal, vol. 3, p. 461.
August, Pogg. Ann., vol. 5, p. 69, 1825.
Apjohn, Trans. Royal Irish Acad., vol. 17, p. 275, 1834.
Weilenmann, Meteorol. Zeit., vol. 12, pp. 268 and 368, 1877.
Maxwell, Zeit. f. Meteorol., vol. 16, p. 177, 1881.
O. D. Chowolson, Traité de Physique, vol. 3, part 3, p. 807, 1911.

[3] Journal, Am. Soc. C. E., 1886.

[4] U. S. Dept. of Interior, Washington, D. C., Water Supply Bulletin No. 279.

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percentage variation, none the less their results substantiate this proportionality. More recently Willis H. Carrier[1] has shown that the rate of water evaporation is, within experimental error, proportional to partial-pressure difference. The following is an analysis of the mechanism of such evaporation.

PRELIMINARY ASSUMPTIONS

2 For purposes of formula derivation assume a long tunnel through which unsaturated air is flowing at constant mass velocity. The walls of this tunnel are non-conductors of heat. Along the bottom of the tunnel is placed a mat or wick permanently wet with water supplied from below as evaporation takes place above. The water is furnished to this wick at every point at a temperature exactly equal to that of the water on the upper surface of the wick at that point. There is no motion of the liquid water parallel to the axis of the tunnel. The mass velocity of the air over the water is constant and sufficiently low so that heat generated by friction may be neglected.

3 The unsaturated air entering this tunnel will become humidified in passing through it owing to the evaporation of water. In consequence, the temperature of the air will fall, and if the tunnel be sufficiently long, the water and air will ultimately come to equilibrium.

NOTATION

4 In the formula to be derived, the following notation is used:

A = Area of liquid in contact with gas

H = Absolute humidity of gas, parts by weight of vapor per part by weight of vapor-free gas

h = Surface coefficient of conductivity of heat between gas and liquid, B.t.u. per unit time per unit surface area per unit temperature difference

k' = Coefficient of diffusion, parts by weight of vapor diffused per unit time per unit area per unit absolute humidity difference

k = Coefficient of diffusion, parts by weight of vapor diffused per unit time per unit area per unit vapor pressure difference

p = Partial pressure of vapor

P = Total pressure of vapor and vapor-free gas (i.e., barometer)

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[1] Am. Soc. Refrigerating Engineers, Journal, May 1916, vol. 2, no. 6, p. 25.

θ = Time
t = Temperature
r = Latent heat of vaporization
s = Humid heat[1], number of heat units necessary to change the temperature of unit weight of vapor-free gas, *plus the vapor it contains*, one degree
W = Weight of liquid evaporated.

INTERACTION OF WATER WITH AIR

5 Now consider for the moment the conditions at any given point along the length of this tunnel. At this point the temperature, absolute humidity,[2] and pressure of water vapor in the air will be represented by t, H and p. Since the apparatus is continuous in its operation these conditions will remain unchanged at this particular point, but will vary from point to point along the tunnel. The corresponding quantities representing the condition of the liquid water in contact with the air at this particular point are t_w, H_w and p_w.

6 The mechanism of interaction of the water with the air is as follows: There exists over the water what is equivalent to a stationary film of air,[3] which insulates the water from the main body of the air. Through this air film heat is diffusing from the air into the water and through the same film there is diffusing, in the opposite direction, the water vapor formed by evaporation on the surface of the liquid. This evaporation cools the surface of water, and, since it is available from no other source, heat must be supplied solely by diffusion from the air. The heat of vaporization must therefore be quantitatively compensated by the heat flow

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[1] W. H. Grosvenor, Proc. Am. Inst. Chem. Engrs., vol. 1, 1908.

[2] See notation, par. 4, and bibliographical references. Humidity is expressed as ratio of vapor to dry air because this ratio is unchanged by variations in either temperature or total pressure, and because differences in humidity directly represent loss or gain of vapor in the air.

[3] The existence of a stationary liquid or gas film at the point of contact with solid surfaces and its low heat conductivity has long been appreciated. The first mention of a water film was made by Péclet in 1844 (Traité de la Chaleur-Liège, chap. 8, p. 131) and since that date many investigators have checked this idea and demonstrated the existence of the film. The most tangible conception of the gas film is represented by Langmuir (Physical Review, vol. 34, 1912, p. 421) although the film concept was not his originally. The explanation in terms of the film concept of the effect of velocity upon heat transfer is definitely stated and the part played by velocity in tearing down this film noted.

through the surface film, and the rate of evaporation is limited by the rate of diffusion of vapor through the same film.

7 From the foregoing one can immediately write the following equations:

$$-\frac{dW}{Ad\theta} = k'(p_w - p) \quad \ldots\ldots\ldots\ldots \quad [1]$$

$$\frac{dQ}{Ad\theta} = h(t - t_w) \quad \ldots\ldots\ldots\ldots \quad [2]$$

$$dQ = -r_w dW \quad \ldots\ldots\ldots\ldots \quad [3]$$

Whence

$$p_w - p = \frac{h}{k'r_w}(t - t_w) \quad \ldots\ldots\ldots\ldots \quad [4]$$

This last equation is the one normally used for calculating the humidity of air from wet- and dry-bulb thermometer readings.[1] In it, variation in r_w is neglected and the term $\frac{h}{k'r_w}$ is assumed constant. For p in millimeters of mercury and t in deg. cent., it equals 0.5. The equation implicitly assumes that the cooling of the air is differential, i.e., so small in the neighborhood of the point in question that the actual changes in temperature and humidity of the air, t and p (or H), are negligible.

Since[2]

$$p = \overset{P}{p}\frac{\frac{H}{18}}{\frac{H}{18} + \frac{1}{29}} \quad \ldots\ldots\ldots\ldots \quad [5]$$

$$t - t_w = \frac{k'r_w}{h}P\left(\frac{\frac{H_w}{18}}{\frac{H_w}{18} + \frac{1}{29}} - \frac{\frac{H}{18}}{\frac{H}{18} + \frac{1}{29}}\right) \quad \ldots\ldots \quad [6]$$

Where H is small, as is usually the case below 150 deg. fahr., $\frac{H_w}{18}$

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[1] Smithsonian Meteorological Tables, 1897, Introduction, p. xxxviii:

$$f = f_1 - 0.000367\,B(t - t_1)[1 + 0.00064(t - t_1)]$$

Physikalish-chemische Tabellen, Landolt-Bornstein, Psychrometertafel, p. 370:

$$a = m_f - \frac{1}{2}(t - f)\frac{b}{755}$$

[2] This involves the assumption, entirely valid under normal conditions, that the water vapor follows the gas laws. The deviations from the gas laws become progressively less as pressure decreases; even at saturated pressure at 150 deg. fahr. the deviation is less than 0.7 per cent. (See Steam Tables, Marks and Davis, Longmans, Green & Co., 1913.)

and $\frac{H}{18}$ are negligible compared with $\frac{1}{29}$, and one may write, as a close approximation,

$$t - t_w = \frac{kr_w}{h}(H_w - H) \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad [7]$$

where $$k = 29k'\frac{P}{18}$$

8 It is obvious that h and k depend on the thickness of the air film and are therefore functions of the velocity of the air. It is, however, equally obvious that, if air velocity be increased sufficiently to double the one, the other will double also. The ratio of $\frac{h}{k}$ therefore remains constant, independent of velocity. This explains why the reading of a wet-bulb thermometer is uninfluenced by the velocity of air passing it, provided the velocity is sufficient so that any heat lost by radiation is negligible in comparison with that picked up by conduction.

THE RELATION $\frac{h}{k} = s$

9 Now consider the change in humidity and temperature of the air as it moves along the tunnel. Starting at the same point previously considered, the air will drop in temperature by an amount dt and increase in humidity by an amount dH. The heat given up by cooling must correspond to the heat of vaporization of the water picked up, i.e.,

$$-sdt = r_w dH \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad [8]$$

whence, assuming constancy of s and r_w,

$$H = -\frac{s}{r_w}t + \text{const.} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad [9]$$

Assuming the tunnel indefinitely long, the air will ultimately become saturated at some temperature t_e, and humidity H_e. Since these conditions represent equilibrium between the air and the water, evaporation will cease, and t_e and H_e are therefore the constant, fixed end-points of the process. Inserting these limits,

$$H_e - H = \frac{s}{r_w}(t - t_e)$$

We have now derived two formulas connecting H and t, both applying to this same process of evaporation, i.e.,

$$H_e - H = \frac{s}{r_w}(t - t_e)$$

and

$$H_w - H = \frac{h}{kr_w}(t - t_w)$$

These two expressions must therefore be identical. By the method of undetermined coefficients this can be true only provided the corresponding coefficients are equal, i.e., $\frac{s}{r_w} = \frac{h}{kr_w}$, or $s = \frac{h}{k}$; and $t_w = t_e$, a constant;[1] and $H_w = H_e$, also constant.

10 So far the discussion has been limited to water and air. Obviously, however, the same relationships must apply to any liquid and any gas with which its vapor is mixed.

11 The first of these equations, $\frac{h}{k} = s$, states that the coefficient of heat transfer divided by the coefficient of vapor diffusion through the gas film is constant, and equal to the humid heat[2] of the gas. By means of formula [4] the ratio $\frac{h}{k}$ can be calculated from the observed wet- and dry-bulb temperatures for any vapor-gas mixture of a known gas humidity. The experimental determinations of wet-bulb temperatures for

a water-air
b water-carbon dioxide
c toluol-air
d chlorbenzol-air

and calculations for $\frac{h}{k}$ given in Table 1 show that this ratio is in all cases substantially equal to the humid heat of the entering gas, which in this case was identical with the specific heat because the gas used was vapor-free.

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[1] W. H. Carrier (Journal Am. Soc. M. E., 1911, p. 1309) states as a general principle that the wet-bulb temperature of air remains constant during "adiabatic" evaporation of moisture into it. He gives, however, no proof or adequate explanation of the statement. From the above it is obvious that the statement is true only where the amount of vapor in the air is small, i.e., this relationship represents merely a limiting case. With high vapor concentration the wet-bulb temperature changes during such a process. The variation, however, is negligible for almost all engineering work.

[2] W. H. Grosvenor, Proc., Am. Inst. Chem. Engrs., vol. 1, 1908.

TABLE 1 VALUES OF $\frac{h}{k}$ FOR VARIOUS VAPOR-GAS MIXTURES

	$\frac{h}{k}$ Calculated from Experimental Results	Specific Heat of Gas
(*a*) Water-air	0.236	0.238
(*b*) Water-carbon dioxide	0.217	0.220
(*c*) Toluol-air	0.238	0.238
(*d*) Chlorbenzol-air	0.248	0.238

12 We have therefore demonstrated that, granting substantial constancy of s and r_w, and assuming H to be small, the ratio of the coefficient of diffusion of heat to that of any vapor through the gas film on the surface of the liquid is equal to the "humid" heat of the gas. Furthermore, during "adiabatic"[1] evaporation of a liquid into a gas, the liquid being in dynamic equilibrium with the gas, the temperature of the liquid remains unchanged throughout the process and the end-point of the process is reached when the gas has cooled itself to saturation at a temperature identical with that of an ordinary wet-bulb thermometer.[2]

IMPORTANCE OF THE RELATIONSHIP $\frac{h}{k} = s$

13 The importance of the relationship $\frac{h}{k} = s$ is very great. The term s, the humid heat, may be readily calculated for any case, regardless of whether the problem is primarily one of heat transfer or of diffusion. Hence if the heat-transfer coefficient h has been experimentally determined for a certain type of apparatus operating under definite conditions, the coefficient of diffusion equals $\frac{h}{s}$, and the capacity of this same apparatus may be predicted when functioning in diffusion processes, e.g., as a gas scrubber. Conversely, if k and s are known for definite conditions, h equals ks; in other words, one can predict the performance of a given apparatus for heat transfer from data upon the same equipment functioning as a scrubber.

14 These processes of diffusion of heat and of vapor are at the basis of the performance of all such equipment as humidifiers, dehumidifiers, water coolers, gas scrubbers, air driers, light oil stripping

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[1] W. H. Carrier, Journal Am. Soc. M. E, 1912, p. 1321.

[2] Ibid.

columns, and the like. The above relationships make it possible to study the performance of such equipment on a more rational basis than hitherto and to compare the effectiveness of different types of equipment even when the data on the individual types are obtained under widely varying conditions. The Department of Chemical Engineering, Massachusetts Institute of Technology, expects to publish in the near future a series of articles showing various applications of these relations.

DISCUSSION

W. H. Carrier.. The writer is gratified to have the further confirmation of the psychrometric relationships and theories, which he endeavored to establish in his paper on Rational Psychrometric Formulae,[1] to which Professor Lewis refers. In this paper, the writer approached this subject from the standpoint of the heat balance and experimental confirmation of the identity of the wet-bulb temperature with that of adiabatic saturation.

The author approaches this from the heat flow standpoint, arriving at identical results, and giving perhaps an added confirmation of the truth of the statement, or theory, that the wet-bulb temperature is constant so long as the total heat is constant. In other words, that the wet-bulb temperature is constant during adiabatic saturation, and that the final temperature of adiabatic saturation is the same as the wet-bulb temperature, which is the temperature of the liquid, during evaporation.

In his reference to the writer's paper, the author remarks that this statement was made, but that no proof was given. The author is referred to Par. 24, page 1014, of the original paper, which reads as follows: "A statement of experimental demonstration of these four principles is given in Appendix 1, Par. 67, pages 1032–1033."

Reference should also be made to Appendix 3 of this same paper, pages 1037–1039, showing two methods of derivation of the formula, and defining the relationship between sensible and latent heat in the adiabatic change. The derivation of this re-

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[1] Trans., vol. 33, 1911, p. 1005.

lationship was fully discussed by Prof. G. A. Goodenough, pages 1041–1044.

The author further states in his note to Par. 9: " from the above it is obvious that the statement (that the wet-bulb temperature is constant during adiabatic saturation) is true only where the amount of vapor in the air is small, that is, the relationship merely represents a limiting case. With high vapor concentration, the wet-bulb temperature changes during such a process."

Assuming the correctness of the statement that the true wet-bulb temperature (i.e., disregarding small radiation error) is equivalent to the temperature of adiabatic saturation, this conclusion by the author is manifestly impossible. At the temperature of adiabatic saturation, the wet-bulb temperature, of course, is precisely the same as the temperature of adiabatic saturation, since wet- and dry-bulb temperatures and dew point are identical at this point. Also, (and this is important), if it is true that the wet-bulb temperature corresponds to the temperature of adiabatic saturation for any condition, then at any point during the process of adiabatic saturation, the wet-bulb temperature must remain the same, because it is manifestly impossible to change the temperature of final adiabatic saturation by any adiabatic process. It is then seen that Professor Lewis' statement amounts to a denial of the fact that the true wet-bulb temperature corresponds to the temperature of adiabatic saturation.

It is not possible to answer this question by any mathematical analysis, except through certain assumptions, as for example, those made in the author's paper, with reference to the action of the interchange of heat at the surface film. It can, however, be demonstrated experimentally, and the writer has given the method of such a demonstration in Appendix 1, Trans. A.S.M.E., Vol. 33, 1911. Further experiments are at present being conducted at Cornell University, employing methods of great precision and covering a wide range of temperatures and humidities, and all the data so far obtained confirm this identity within the range of experimental error (that is, about 0.05 deg. fahr., regardless of the moisture content.

Furthermore, if there were any variation in the wet-bulb temperature, the greatest variation would not occur, as the author remarks, at high moisture content, but at high temperatures and low moisture content. If we assume this to be correct with low moisture content, as, for example, at zero moisture content, then mathematically and physically it must follow that it is true for all other values. This was mathematically demonstrated in Appendix 3, pages 1037–1039, of the writer's paper. The mathematical and physical proof was thoroughly discussed on pages 1041–1044, by so eminent an authority on this subject as Prof. G. A. Goodenough of the University of Illinois, and the conclusions which the writer reached were definitely verified, so that it must either be proved that the true wet-bulb temperature identity with the temperature of saturation does not hold at low moisture content, regardless of temperature, or else it must be proved that the physical and mathematical proof given by the writer and Professor Goodenough, for the equation of the adiabatic saturation line, is not correct.

The writer's paper on the Theory of Evaporation in connection with Compartment Driers, presented to the American Chemical Society[1] may also be cited as a reference. In this it was shown that the rate of heat transfer by evaporation, as determined by the difference in vapor pressures, is approximately equivalent to the heat transfer corresponding to the difference in the wet- and dry-bulb temperatures, or, in other words, that the latent heat transfer is approximately proportional to the sensible heat transfer, so far as rate is concerned, one being proportional to the difference in vapor pressures, and the other proportional to the difference in temperatures; these differences being related through any of the various psychrometric formulae.

This, however, does not detract in any way from the ingenious and admirable method presented by Professor Lewis. There is one point in his demonstration, however, which is not quite conclusive, apart from experimental evidence, and that is the assumption that the rate of latent heat and moisture diffusion follows the same law with respect to change in air velocity, as does the law of sensible heat transfer, with corresponding changes of velocity. No matter what method of attack is employed we return to the experimental evidence that the wet-bulb temperature is identical with the temperature of adiabatic satura-

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[1] *Journal Industrial and Engineering Chemistry*, vol. 13, no. 5, May 1921.

tion, and that the rate of heat transfer is substantially proportional to temperature difference, and, also, that they both vary approximately according to the same law, over certain ranges of velocity. Present data would seem to indicate that the rate of moisture " diffusion " for a given vapor pressure difference has a certain minimum at zero velocity, and increases in direct ratio with increase of velocity, while all experimental evidence that we have at present would indicate that the rate of sensible heat transfer does so only approximately, but falls off gradually as the velocity increases. The experimental evidence on evaporation cannot be said, however, to be conclusive in this respect, at present, and is apparently contradicted by experiments with the wet- and dry-bulb " Kata-thermometer," which have shown, with the bulb dry, that the heat transfer occurs in proportion to the difference in sensible heat between the air and that of the film, at all velocities, while with the wet " Kata-thermometer," the rate of heat transfer occurs in exact proportion to the difference of total heat, that is, sensible and latent, between that of the circulating air and that of the surface film. The latter experiment would indicate that convection and radiation occur in uniform proportions for all velocities. These experiments were conducted with both vapor pressures and temperatures considerably above those of the surrounding air, and over a wide range of variations in temperature and velocity, so that they seemed to be quite conclusive on this point. These experiments were made at the Research Laboratory of the American Society of Heating and Ventilating Engineers in Pittsburgh, and are discussed in a paper by O. W. Armspach, *Journal* A.S.H.&V.E., January 1922.

In his analysis of the process occurring in the interchange of heat, the author speaks of the heat as being transferred through the gas film to the water. On this assumption there would, of necessity, be a difference in temperature between the film and the water. Otherwise heat transfer could not occur. We would then be forced to the assumption that this film was not saturated, or else if it were saturated, that the temperature of the water on the bulb was below that of adiabatic saturation in the film. As a matter of fact, it seems probable that when the temperature of the water on the bulb has reached its minimum, there is a condition of stability reached in which no heat is transferred, either to or from the water on the bulb, (except a small amount from radiation), and that by the purely convection process, the particle of air impinging into the film becoming saturated and giving up its corresponding sensible heat simultaneously at the film surface.

There is other evidence which apparently disproves this to a certain extent. At very low velocities there is apparently heat conducted through the film to the bulb in excess of the rate at which the moisture is diffused, for it has been shown by the writer that the radiation error increases rapidly as the velocity decreases. In still air this discrepancy is about 17 per cent. (See Radiation Error in Wet Bulb of Sling Psychrometer, Rational Psychrometric Formulae, Trans. A.S.M.E., Vol. 33, pp. 1025). This error between the theoretical and actual depression at low velocities is considerably greater than anything that can be accounted for by pure radiation alone. Therefore it must be due to conduction, which indicates that the rate of heat transmission is greater than the rate of vapor diffusion at low velocities, and that these rates gradually approach the same value as the velocity is increased.

The author's use of the term "diffusion" seems to differ somewhat from the ordinary conception of that expression. Under artificially produced velocities, the interchange of heat and moisture occurs through a process of *forced mechanical mixture,* rather than what is ordinarily understood by the term "diffusion," which, in the case of a vapor, is more analogous to the conduction of heat in still air. The laws of gas diffusion or mixture and the corresponding convection of heat can only be determined empirically by experiment, in which there is considerable opportunity for slight experimental errors, and for considerably divergent results through slight variations in experimental method, so that any psychrometric relationship based upon the comparison of these experimental rates must always be considered only as approximate, and useful for engineering purposes only, rather than of scientific value.

For industrial engineering purposes, at any except very low velocities, the approximate relationship given by the author may be said to hold with sufficient accuracy. For scientific work, however, the other variables, such as radiation and transmission, must be taken into account, as must also the variation of the psychrometric coefficient with the wet-bulb temperature. The formulae given in the author's paper for determination of the vapor pressure in wet- and dry-bulb temperature readings are not accurate, as they neglect this factor, and assume the vapor pressure differences proportional to the depression, while the experimental work done by the Weather Bureau (Annual Report, Ch. Signal Officer, 1886, Appendix 24, pp. 233-259) shows conclusively that the relation $\frac{e'-e}{t-t'}$ varies with the wet-bulb temperature. The same thing is also shown by the mathematical and physical deduction of the writer.[1]

The author also compares the values of h/k as calculated from experiments made upon the temperature of evaporation, with the specific heat of the gases. Attention should be called to the fact that the apparent close agreement between the experimental values of h/k and the specific heat of the gases is misleading. In the first place the experimental data upon which are based the values of h/k are neither shown nor quoted. Determination of the specific heat by the evaporative method is not at all an easy task, and requires very special equipment and very accurate instruments for determination and control of conditions, in order to eliminate the radiation and conduction errors and to determine values with the degree of exactness given by the author. In the second place, the value used by the author for the specific heat of air (0.238) is now considered obsolete. Probably a more accurate value was that given first by W. F. G. Swann, *Phil. Trans. Royal Soc.*, series A., vol. 210, pp. 199–238, 1909, which was used by the writer in 1911, because it conformed almost exactly with the experimental determinations as shown by the data of the U. S. Weather Bureau, of wet-bulb and dew-point temperature relationships. This value is

$$C_{pa} = 0.24112 + 0.000009t \text{ deg. fahr.}$$

A still later experimental value was determined in 1913 at the Reichsanstalt by the thorough investigations of Holborn and Jakob (*Zeitschrift des Vereines Deutscher Ingenieure,* vol. 58, p. 1436), which gives the mean value of C_{pa} as 0.2415 between the

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[1] Trans. vol. 33, 1911, pp. 1023–1024, also Theory of Atmospheric Evaporation with Special Reference to Compartment Dryers, *Journal of Industrial and Engineering Chemistry,* vol. 13, no. 5, equation 6.

limits of 68 and 212 deg. fahr., therefore almost exactly confirming the values obtained earlier by Swann, so that this value at present should be used rather than the old value of 0.2375, obtained by Regnault, which is apparently the value used by the author. If the present accepted value is used, then the comparison between the values of specific heat as given is not nearly so close. Furthermore, the only published data on evaporative temperatures corresponding to different vapor pressures and air temperatures are those given by the U. S. Weather Bureau. Their data also agree with this value rather than the lower one, although there are probably discrepancies in the U. S. Weather Bureau data, which must be taken into account. These probable errors in the U. S. Weather Bureau data seem very largely to neutralize each other, insofar as the effect on specific heat is concerned. There is one experimental error in their determinations of the dew points which gives somewhat higher values than the actual. The possibility of this error was pointed out by the writer (TRANS. A.S.M.E. vol. 33, 1911, Par. 11 and 12, p. 1010). Offsetting this there is apparently an error in the specific weight of vapor in mixture with air. Dalton's law does not seem to hold with accuracy for mixtures of gases and vapors. The possibility of this error was pointed out by the writer in his closure page 1052, TRANS. A.S.M.E. vol. 33, 1911.

Experiments are now being conducted under the writer's supervision at Cornell University, which will show the sources and amounts of these errors. Therefore present data on the weight of any vapor per cubic foot in a mixture of air or gas cannot be used with entire assurance. The source of this error may be clearly shown by theoretical thermodynamic calculations, as well as by experiments. On account of these errors in accepted data, no conclusions with reference to the agreement of experimental values of h/k and data on specific heat do not seem warranted. The only conclusion from experimental data that is warranted is the substantial identity of the wet-bulb temperature with the temperature of evaporation, except for a slight radiation and conduction error at high velocities.

THE AUTHOR. The major point made by Mr. Carrier is his disagreement with the conclusion reached by the author that the true wet-bulb temperature does not quantitatively correspond to the temperature of adiabatic saturation. It is true that " it is not possible to answer this question by any mathematical analysis," and also true that the vapor pressure of water at ordinary temperatures is so slight that the difference between the observed wet-bulb temperature and the point of adiabatic saturation is less than the experimental error. This laboratory is endeavoring to secure dependable experimental data on the point, using liquids of higher vapor pressure. Until such data are obtained discussion of this particular point will not prove conclusive.

Mr. Carrier states " it seems probable that when the temperature of the water on the bulb has reached its minimum, there is a condition of stability reached, in which no heat is transferred, either to or from the water on the bulb, (except a small amount from radiation.)." Observation shows two facts, first, that under these conditions the water on the bulb is evaporating, and second, that during this evaporation the temperature of the bulb remains substantially constant. Where then does the heat of evaporation of the water come from?

As regards experimental methods used by the author, the liquid was placed in a Dewar bulb and air or CO_2 dried by chemical absorption forced through it. The bulb was immersed in a liquid bath artificially maintained at the same temperature as the liquid within the bulb, so that radiation losses to the outside were thereby eliminated. The amount of contact of the gas with the liquid was controlled by varying the depth of the latter and by the use of solid filling material in the bulb. The only serious source of error encountered was the cooling of the entering gas by heat conduction along the tube through which it entered before it came into contact with the liquid. To reduce this error the tube glass was vacuum jacketed. With these precautions the wet-bulb reading was found independent of air velocity and of amount of contact with the liquid in the cases reported but not for liquids of high vapor pressure. We believe this latter discrepancy is partly caused by lack of constancy of the wet-bulb temperature, but the experimental data are not yet sufficiently refined to prove it.

It will be noted that the average of the calculated values for the specific heat of air is 0.241. This checks better with the modern data than with the Reghault figure, contrary to the statement of Mr. Carrier.

Further confirmation of the relationship $h/k = s$ and illustrations of its engineering usefulness will be found in an article by Whitman and Keats[1] and in one to appear later in this journal by Professor Robinson.

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[1] Rates of Absorption and Heat Transfer between Gases and Liquids, *Jour. Ind. Eng. Chem.*, vol. 14, 1922, p. 186.