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The Use of Dew-Point Temperature in Humidity Calculations

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The dew-point temperature has a number of desirable features as a means of expressing humidity. The Antoine Equation, $\log e_w = A - B(T+C)^{-1}$, where e_w is the partial pressure and T is the temperature of saturated aqueous vapor, represents the Goff-Gratch formulation quite well over the range of temperature from 0 to 140 °F. The pressure e_w, in inches of mercury, is obtained by taking the constants $A = 6.70282$, $B = 3150.515$ (°F)$^{-1}$ and $C = 391.0$ °F, calculated from values given by Dreisbach. It is shown that the dew-point DP is related to the relative humidity RH by the relation:

$$(DP+C)^{-1} = (T+C)^{-1} + B^{-1} \log (RH)^{-1}.$$

Lines of nearly constant positive slope represent constant relative humidity values on graphs of dew-point against temperature. The value of the slope decreases from unity for $RH = 100$ percent to about 0.76 for $RH = 10$ percent, corresponding to the linear equation

$$DP = [1 + 0.1471 \log (RH)^{-1}]^{-2}(T - 70) + DP_{70} \text{ where } DP_{70} = [2169 + 319 \log (RH)^{-1}]^{-1} \times 10^6 - 391.$$

Psychrometric charts showing dew-point and dry-bulb temperature as coordinates with lines representing constant relative humidity and constant wet-bulb temperature (obtained from the Ferrel Equation) are extremely useful, since given values for any two of these four variables serve to locate a point, from which the values of the other two variables can be read directly.

Key words: Antoine Equation; dew point; humidity; hygrometry; psychrometric chart; relative humidity; vapor pressure of water; wet-bulb temperature.

1. Introduction

In calculations of the humidity of air containing moisture, the dew-point temperature has a number of desirable features as a means of expressing the absolute humidity. In many instances in which the temperature of the air is changed the dew point remains relatively constant. One illustration of this is the rise of temperature when cold outdoor air in winter is heated and brought indoors without humidification. The dew point remains relatively constant also during the normal daily rise and fall of temperature of outdoor air. In fact, the usual morning weather reports could provide a number which would be much less subject to change during the day if the value of dew point were to be reported in place of the relative humidity.

The present paper stresses the advantages of using dew point in expressing humidity, derives some applicable equations, and presents illustrative charts and tables to facilitate the operation.

The results given here should be useful for engineering purposes of measurement and control of humidity in the range above about 5 percent relative humidity at pressures near a normal atmosphere, where the requirements for precision at temperatures between 0 and 140 °F, do not exceed about 0.5 percent in relative humidity or a few tenths of a degree F in temperature. These requirements are intermediate between the approximate values sometimes used in rough calculations based on readings with hair hygrometers or similar instruments and the more precise values required in research in hygrometry.

The temperature range was chosen to include the complete range of uncontrolled variation of atmospheric temperature. When a reference temperature near normal room temperature is required, a value of 70 °F has been chosen, to be at the midpoint of the range.

2. Definitions and Tabulations of Values

The present paper makes use of the definitions adopted by the Conference of Directors, International Meteorological Organization, meeting in Washington in 1947, with the revised definition of relative humidity adopted by the International Joint Committee on Psychrometric Data, meeting in Philadelphia in 1950.

These are presented in detail in the Smithsonian Meteorological Tables, Sixth Edition 1951 [1].[1] The same definitions are accepted by the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) and published in the ASHRAE Guide and Data Book [2].

An extensive study of the thermodynamic properties of moist air completed in 1945 and 1946 by Goff and Gratch [3, 4, 5] led to formulation of tables of consistent numerical values. These values have been accepted and promulgated by both the Directors of the International Meteorological Organization and the ASHRAE. They have been published in several handbooks [1, 2, 6].

The numerical values of vapor pressure used in the present work are those shown in Table 95 of the Smithsonian Meteorological Tables [1], which gives values of aqueous saturation vapor pressure at intervals of 0.1 °F at the standard atmospheric pressure of 29.921 inches of mercury (760.00 mm of mercury, 101,325 $N\ m^{-1}$).

Relative humidity RH is defined as the ratio of the mol-fraction of water vapor in a given volume of moist air to the mol-fraction of water vapor in the same volume of saturated moist air at the same temperature and pressure. For the ideal gas mixtures assumed here, this definition is equivalent to defining relative humidity as the ratio of the partial pressure e of water vapor in moist air to the partial saturation pressure of water vapor e_w at the temperature of the air [2]. The partial pressure of saturated water vapor is affected only slightly by the presence or absence of air [1]. At atmospheric pressure near room temperature the difference is of the order of 0.5 percent, and will be neglected in the present work.

Dew-point temperature is defined as the temperature at which the partial vapor pressure of water in moist air would be sufficient to saturate the air. In other words, the partial vapor pressure at the given temperature is equal to the partial saturation vapor pressure at the dew-point temperature.

3. Dew-Point and Relative Humidity

Let us consider first only three variables, limiting ourselves to standard atmospheric pressure and postponing for the present all discussion of wet-bulb temperatures. The variables are (dry-bulb) temperature, relative humidity, and dew point. In a search of the literature I could find no tables showing explicitly the dew point as a function of temperature and relative humidity, although small graphs with temperature in Celsius degrees have been given in the German literature [7]. Consequently table 1 has been drawn up in order to show the dew point for different temperatures at 10° intervals from 0 to 140 °F and for relative humidities at 10 percent intervals from 10 to 100 percent. Values of the saturation vapor pressure of water are shown in the second column of the table. They are taken from the Goff-Gratch formulation, as presented in the Smithsonian Meteorological Tables [1]. The units of pressure are inches of mercury, each equivalent to 3386.389 N/m^2.

Table 1 was prepared by calculating the vapor pressure as the product of the saturation vapor pressure e_w and the relative humidity RH. The dew point was then read to the nearest 0.1° from the Tables as the temperature at which this value of vapor pressure is equal to the saturation vapor pressure.

4. Antoine Equation for Vapor Pressure

Of the many empirical forms of equations for the pressure of the saturated vapor of a liquid [8] the one proposed by Antoine for water [9, 10] and later extended to other liquids [11] possesses a number of ad-

TABLE 1. *Saturated aqueous vapor pressure and dew point (°F)*

T	e_w	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
°F	*in Hg*										
0	0.04477	-44.2	-31.6	-24.1	-18.6	-14.2	-10.6	-7.5	-4.7	-2.2	0.0
10	.07080	-35.8	-23.1	-15.3	-9.5	-4.9	-1.1	+2.2	+5.1	+7.7	+10.0
20	.10960	-27.9	-14.6	-6.5	-0.4	+4.4	+8.4	11.8	14.8	17.5	20.0
30	.16631	-20.1	-6.2	+2.3	+8.6	13.6	17.8	21.4	24.6	27.4	30.0
40	.24767	-12.2	+2.2	11.1	17.6	22.9	27.3	31.0	34.3	37.3	40.0
50	.36240	-4.4	10.5	19.8	26.7	32.1	36.7	40.6	44.1	47.2	50.0
60	.52160	+3.3	18.8	28.5	35.6	41.3	46.1	50.2	53.8	57.1	60.0
70	.73916	11.0	27.1	37.2	44.6	50.5	55.5	59.8	63.6	66.9	70.0
80	1.0323	18.6	35.4	45.8	53.5	59.7	64.9	69.3	73.3	76.8	80.0
90	1.4219	26.2	43.6	54.4	62.4	68.9	74.2	78.9	83.0	86.7	90.0
100	1.9334	33.7	51.8	63.0	71.3	78.0	83.6	88.4	92.7	96.5	100.0
110	2.5968	41.2	59.9	71.5	80.2	87.1	92.9	98.0	102.4	106.4	110.0
120	3.4477	48.7	68.0	80.1	89.0	96.2	102.3	107.5	112.1	116.2	120.0
130	4.5274	56.1	76.0	88.5	97.8	105.3	111.6	117.0	121.8	126.1	130.0
140	5.8842	63.4	84.0	97.0	106.6	114.4	120.9	126.5	131.5	135.9	140.0

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[1] Figures in brackets indicate the literature references at the end of this paper.

vantages [12]. Consequently it has been extensively used in recent years. It may be written

$$\log e_w = A - B(T+C)^{-1} \qquad (1)$$

where e_w is the partial pressure and T the temperature of the saturated vapor, while A, B, and C are empirical constants.

When e_w is expressed in millimeters of mercury and T in degrees Celsius, the constants for water between 0 and 60 °C have been evaluated by Dreisbach [13a, 13b] as

$A = 8.10765$,
$B = 1750.286$, (deg C)$^{-1}$ and
$C = 235.0$ deg C.

When e_w is expressed in inches of mercury and T in degrees Fahrenheit the constants for water between 32 and 140 °C may be calculated from those just given. This calculation gives:

$A = 6.70282$,
$B = 3150.515$, (deg F)$^{-1}$ and
$C = 391.0$ deg F.

With these constants the Antoine Equation yields values of vapor pressure which, for our purposes, are in completely adequate agreement with those given in the Goff-Gratch tabulation [1, 2, 6]. The differences are less than about 0.00040 in of mercury for temperatures in the range 40 to 120 °F and less than about 0.00100 in of mercury in the ranges 0 to 40 °F and 120 to 140 °F.

If differences of this magnitude are not to be tolerated recourse must be had to equations of much greater complexity containing many more constants [1]. Computer programs have been developed to deal with this situation [14].

5. Dew Point and Relative Humidity

Since the dew point temperature DP and the relative humidity RH are defined in terms of vapor pressures, an equation involving them may be easily derived from eq (1). The vapor pressure at temperature T is $(RH)e_w$ and is equal to the saturation vapor pressure at the dew point temperature DP. Thus by applying eq (1) at the dew point temperature we obtain

$$\log (RH)e_w = A - B(DP+C)^{-1}. \qquad (2)$$

Subtracting eq (2) from eq (1) we have:

$$\log (RH)^{-1} = B[(DP+C)^{-1} - (T+C)^{-1}]$$

$$(DP+C)^{-1} = (T+C)^{-1} + B^{-1} \log (RH)^{-1}. \qquad (3)$$

This form of equation suggests a plot of $(DP+C)^{-1}$ against $(T+C)^{-1}$. When C is again taken as 391.0 °F. the lines obtained for constant relative humidity are straight and have unit slope, as predicted. From the intercepts a value of B^{-1} may be obtained.

In the present work, however, a nongraphical method has been employed to obtain B^{-1} with greater sensitivity. This involved calculating the difference of $(DP+C)^{-1}$ and $(T+C)^{-1}$ from the values of dew point as a function of temperature as given in table 1. The constant C was taken as 391.0 °F, as before. The average value of this difference for all temperatures from 0 to 140 °F for a given relative humidity was divided by $\log (RH)^{-1}$ to obtain B^{-1}.

No significant trends could be noted in this difference as a function of temperature or in the values of B^{-1} as a function of relative humidity. The mean value of B^{-1} obtained in this way was 318.6×10^{-6} (deg F)$^{-1}$. The reciprocal of the value of B in the Antoine Equation as given above by Dreisbach [13], is 317.4×10^{-6} (deg F)$^{-1}$. The agreement between these two independent values is highly satisfactory. In the remainder of this paper we shall take the value of B^{-1} as 319×10^{-6} (°F)$^{-1}$. Both the graph of eq (3) and the constancy of the individual values of B^{-1} confirm the validity of the equation in representing experimental values of dew point.

According to the present results, the values of the constants as given by Dreisbach for the range 32 to 140 °F appear to be valid also for the saturated vapor pressure of subcooled water in the range 0 to 32 °F.

When the dew point for a given relative humidity is plotted as a function of temperature it is found that the data can be represented by a family of almost linear curves. Figure 1 shows such a plot, where the points represent the data of table 1. The lines shown are straight lines with slopes decreasing from unity at $RH = 100\%$ to about 0.76 at $RH = 10\%$.

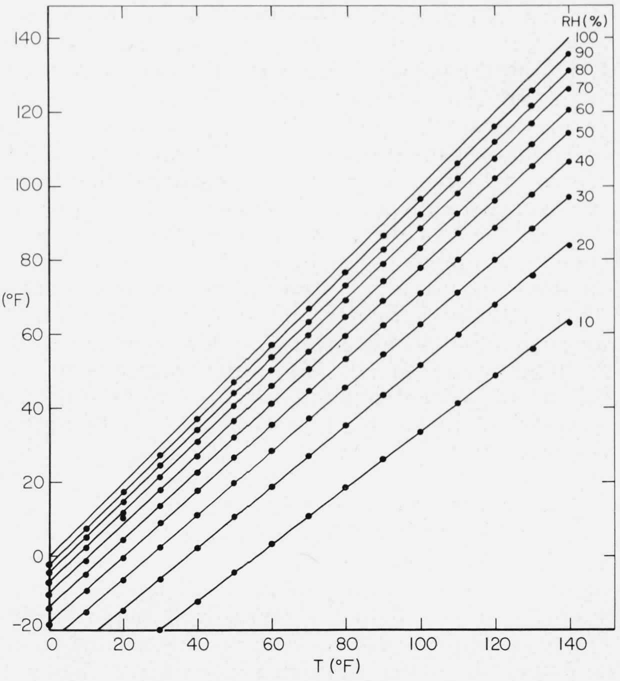

FIGURE 1. *Dew point* DP *as a function of temperature* T *at different values of relative humidity* RH.

Numerical values of the slope may be calculated from an equation obtained by differentiation of eq (3). This is:

$$d(DP)/dT = [1 + B^{-1}(T+C) \log (RH)^{-1}]^{-2}. \quad (4)$$

When the numerical values just obtained for the constants B^{-1} and C are inserted it is found that the slope for the curve corresponding to 90 percent relative humidity should be about 0.986 at 70 °F. The slope is about 0.2 percent greater than this at 0 °F and about 0.2 percent less than this at 140 °F. The predicted slope of the curve corresponding to 10 percent relative humidity should be about 0.76 at 70 °F. It should be about 4 percent greater than this at 0 °F and about 4 percent less than this at 140 °F.

In view of this close approach to linearity of DP as a function of T at constant RH it is sometimes convenient to express the relation between dew point and temperature in strictly linear form involving DP_0, the dew point at some reference temperature T_0, and a constant slope equal to the slope at T_0.

$$DP = [1 + B^{-1}(T_0 + C) \log (RH)^{-1}]^{-2}[T - T_0] + DP_0 \quad (5a)$$

where

$$DP_0 = [(T_0 + C)^{-1} + B^{-1} \log (RH)^{-1}]^{-1} - C. \quad (5b)$$

For work near room temperature it is convenient to take the reference temperature $T_0 = 70$ °F. With the constants $C = 391.0$ °F and $B^{-1} = 319 \times 10^{-6}$ (deg F)$^{-1}$ these equations become:

$$DP = [1 + 0.1471 \log (RH)^{-1}]^{-2}[T - 70] + DP_{70} \quad (6a)$$

where

$$DP_{70} = [2169 + 319 \log (RH)^{-1}]^{-1} \times 10^6 - 391. \quad (6b)$$

It should be recognized that this equation, in explicit form to yield the dew point, is an approximation. Equation (3) on the other hand depends only on the validity of the Antoine form and the proper evaluation of its constants B and C. However, calculation of values by eq (6) over the range of temperatures and humidities shown in table 1 leads to the conclusion that the differences are not significant for the degree of precision contemplated in the present work. The largest differences are found at the highest and lowest temperatures, as would be expected, and at the lowest humidities. At 0 and 140 °F for 10 percent relative humidity the approximation yields values of dew point about 1 to 2° higher than eq (3). This difference falls to about 0.5° at 40 percent humidity and is still less at higher humidities. Even at 10 percent relative humidity it is no greater than 0.6° for temperatures from 30 to 130 °F.

The straight lines in figure 1 were drawn, not to conform necessarily to the points, but rather to represent the dew point as a function of temperature as predicted by eq (6). It can be seen that the lines do conform very well to the points and that the differences are approximately those just mentioned.

When the linear approximation is not made, the values predicted by eq (3) differ by only a few tenths of a degree from those given in table 1 and thus deviate only imperceptibly from the experimental points shown in figure 1.

6. Wet-Bulb Temperature Isotherms

The lowering of temperature of a thermometer surrounded by a wick from which water is evaporating is often used to measure humidity [15]. There are numerous possibilities for error and uncertainty, but the method gives useful results when the proper precautions are taken.

Humidity is calculated from readings of wet-bulb temperature by the use of the Ferrel Equation [1, 15, 16, 17]

$$e_T = e'_{wT'} - 367 \times 10^{-6}[1 + 0.00064(T' - 32)]p(T - T') \quad (7)$$

where e_T is the partial pressure of water vapor at the dry-bulb temperature T, $e'_{wT'}$ is the partial pressure of saturated water vapor at the wet-bulb temperature T' and p is the total pressure. The quantity e_T calculated by this equation is divided by e_{wT}, the saturation vapor pressure at temperature T to obtain the relative humodity RH. From this, the dew point may be calculated by the methods given in the preceding sections of this paper. The total atmospheric pressure p appears in the Ferrel Equation, and due regard must be paid to variations in it, in calculations of humidity by this method. As in the preceding sections, the value here will be assumed to be the standard atmosphere of 29.921 in of mercury.

On a chart with dew point as ordinate and dry bulb temperature as abscissa one can show a family of curves corresponding to constant wet-bulb temperature. In figure 2 these curves have been drawn at 10° intervals. The values shown are those calculated from eq (7) in the manner just described. It will be noted that the slopes are always negative and that their absolute value increases with increase of dry-bulb temperature or with decrease of wet-bulb temperature. Several of the constant humidity lines of figure 1 are also shown in figure 2.

Dew point values as calculated from the Ferrel Equation to the nearest degree only, are tabulated directly as a function of wet- and dry-bulb temperatures in tables issued by the Weather Bureau [17]. Although the results are based on saturated vapor pressure values antedating those of Goff and Gratch [3, 4, 5], the dew points tabulated agree, to the nearest degree, with those calculated in the manner just described for the range studied in the present work.

7. Psychrometric Charts

A psychrometric chart with dew point as ordinate and temperature as abscissa, like figure 1, is very useful in humidity calculations. If wet-bulb temperatures are required, it can show superposed, as in figure 2, both the family of curves for constant wet-bulb temperature with negative slopes and the family of lines of positive slope representing constant relative humidity.

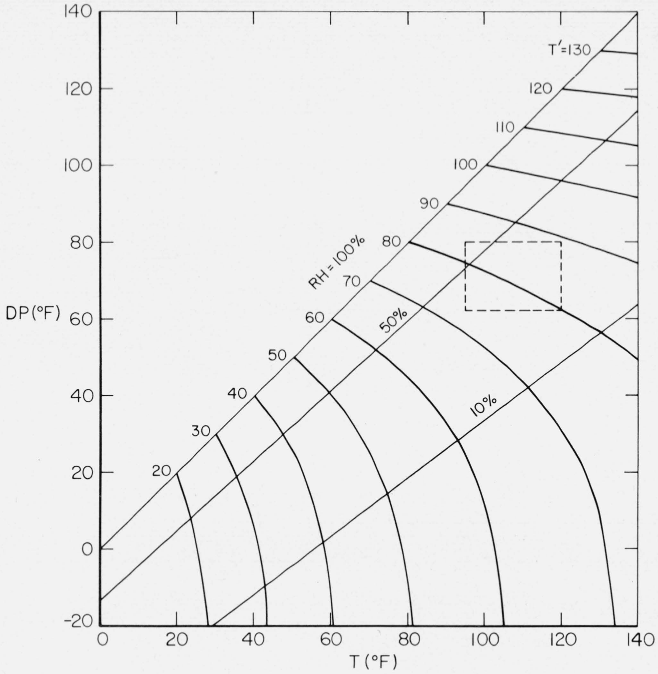

FIGURE 2. *Dew point* DP *as a function of temperature* T *at different values of wet-bulb temperature* T′.

The lines for relative humidities of 10 percent, 50 percent, and 100 percent from figure 1 are shown for comparison.

The rectangular box shows the range of values covered in figure 3.

The psychrometric charts usually available in the handbooks and other references [2, 6] are similar to these but show as ordinate the partial vapor pressure or the absolute humidity in mass per unit volume of dry air or the humidity ratio (also called mixing ratio) in mass per unit mass of dry air, rather than the dew point. In all these charts the graphs representing constant relative humidities are curves of constantly increasing slope, rather than the linear graphs shown in figures 1 and 2. Consequently, the calculation of the points, the drawing of the curves, and the visual interpolation are all considerably more difficult. However, the curves representing constant wet-bulb temperature are usually linear in contrast with those in figure 2.

As a measure of humidity the use of the dew point has another advantage over that of vapor pressure or mass per unit volume, since the conversion from British units to metric units involves only a change from temperatures in degrees Fahrenheit to temperatures in degrees Celsius. For example, figure 1 requires only a relabeling of the two coordinates in degrees Celsius to conform to the metric system; figures 2 and 3 require, in addition, only the conversion of the wet-bulb temperatures to degrees Celsius.

Our psychrometric chart shows four variables—dry bulb temperature and dew point as coordinates with relative humidity and wet-bulb temperature as lines. Given values for any two of the variables serve to define a point on the chart, from which the values of the other two variables may be read directly. Such a chart is simpler and easier to use than various nomograms which are available for humidity calculations [16].

In practical problems of humidity measurement and control the ranges of interest are usually much smaller than those shown in figures 1 and 2. Under such circumstances it is very convenient to use eqs (6) and (7) as a basis for drawing a grid consisting of lines of constant relative humidity and constant wet-bulb temperature on a psychrometric chart.

A typical example is shown in figure 3, which has been applied to the measurement and control of the humidity and temperature of the air surrounding a carbon arc. The relative humidity lines are drawn at intervals of 2 percent and the wet-bulb temperature curves at intervals of 1 °F on graph paper measuring 250 × 180 mm. Visual estimation of tenths of the intervals between curves makes possible interpolation of values to 0.2 percent relative humidity and 0.1 °F wet-bulb temperature. Each millimeter on the scales for coordinates represents tenths of degrees for dew point and dry bulb temperature.

In one application of the chart it was desired to find the wet-bulb temperature corresponding to 30 percent relative humidity at 117 °F. The chart showed the dew point to be 77.5 °F, and the corresponding wet-bulb temperature was then estimated as 87.0 °F by visual interpolation along a line through the dew point approximately normal to the two nearest wet-bulb isotherms.

In another typical application the wet-bulb temperature was observed to be 84.5 °F at a temperature of 110 °F. The dew point was then read from the chart as 76.0 °F and the relative humidity as 35.0 percent.

On another occasion it was desired to know how high the relative humidity could be at 115 °F without having condensation when the air was cooled to room temperature 77 °F. This was read from the chart as 31.4 percent, together with the corresponding wet-bulb temperature of 86.3 °F.

Finally, a fourth problem involved determining the temperature to which one must heat air with a dew point of 70 °F in order to reduce its relative humidity to 30 percent. The value was read to be 108.5 °F, with a corresponding wet-bulb temperature of 80.7 °F.

In all four problems the values of the desired qunatities were found by locating a single point on the chart, and the whole operation was completed in a much shorter time than when alternative methods were used.

8. Summary and Conclusions

The Antoine Equation has been shown to represent with good accuracy the values of the saturated vapor pressure of water over the range 0 to 140 °F, as formulated by Goff and Gratch and promulgated by meteorological and air-conditioning organizations. The dew point DP is related to the temperature T and relative humidity RH by the following equation:

$$(DP+C)^{-1}=(T+C)^{-1}+B^{-1}\log(RH)^{-1}$$

where B^{-1} and C, constants in the Antoine Equation, have the values 319×10^{-6} (°F)$^{-1}$ and 391 (°F) respectively. The dew point DP may also be calculated with

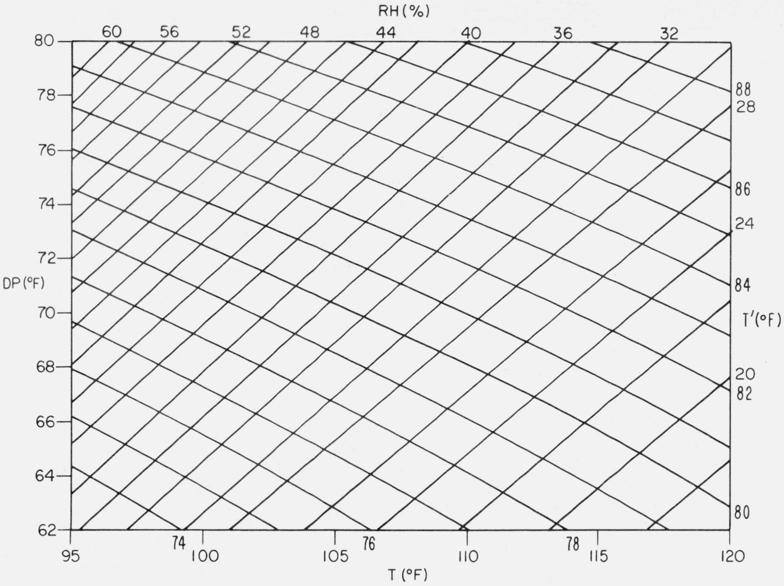

FIGURE 3. *Typical psychrometric chart of dew point* DP *and temperature* T *used in humidity calculations.*

The range of values covered is that of the rectangular box shown in figure 2.
Lines of positive slope correspond to constant relative humidity ($RH=18$ to 60%).
Lines of negative slope correspond to constant wet-bulb temperature ($T'=74$ to 88 °F).

satisfactory accuracy from the linear equation

$$DP=[1+0.1471\log(RH)^{-1}]^{-2}(T-70)+DP_{70}$$

where

$$DP_{70}=[2169+319\log(RH)^{-1}]^{-1}\times 10^{6}-391.$$

It is convenient and useful to plot the dew point of moist air as a function of the temperature of the air. Points corresponding to constant relative humidity are well represented by lines of constant positive slope with the value of the slope decreasing from unity at 100 percent relative humidity to about 0.76 at 10 percent relative humidity. On the same chart showing dew point as ordinate and temperature as abscissa, points corresponding to constant wet-bulb temperature appear on lines of variable negative slope. The absolute value of this slope increases with increase of (dry-bulb) temperature and with decrease of wet-bulb temperature. Psychrometric charts showing dry-bulb temperature and dew point as coordinates with relative humidity and wet-bulb temperature as lines are extremely useful in humidity calculations, since given values for any two of these four variables serve to locate a point, from which the values of the other two variables can be read directly.

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