International Journal of Agriculture Sciences
ISSN: 0975-3710 & E-ISSN: 0975-9107, Volume 11, Issue 20, 2019, pp.-9169-9171.
Available online at https://www.bioinfopublication.org/jouarchive.php?opt=&jouid=BPJ0000217

Research Article

DIRECT CALCULATION OF WET-BULB TEMPERATURE AND DEW-POINT TEMPERATURE

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Received: October 05, 2019; Revised: October 25, 2019; Accepted: October 26, 2019; Published: October 30, 2019

Abstract: Simple and precise methods for accurate calculation of wet –bulb temperature and dew-point temperatures are presented in the paper. Input parameters required for calculation of dew-point temperature and wet-bulb temperature are dry-bulb temperature and relative humidity. In this paper, the equations for determining dew point temperature for the entire pressure range are given. The equations proposed here for saturation vapour pressure for temperature range (0ºC to 110ºC) has an average error of 0.042% only and for temperature range (0ºC to -40ºC) error of 0.108% and the same equations can be rewritten to determine the value of dew-point temperature. The mean absolute deviation in calculated values of dew-point temperature was 0.04%. The proposed method for dew-point temperature led to an average error of 0.083%as compared to that of correct values. The mean absolute deviation in calculated values of wet-bulb temperature for the entire range (-40ºC to 110ºC) was 0.031ºC. The proposed method for wet-bulb temperature led to an average error of 0.09% as compared to that of correct values.

Keywords: *Dry-bulb temperature, Wet-bulb temperature, Dew point temperature and Relative humidity*

Citation: Singh A.K., *et al*., (2019) Direct Calculation of Wet-bulb Temperature and Dew-point Temperature. International Journal of Agriculture Sciences, ISSN: 0975-3710 & E-ISSN: 0975-9107, Volume 11, Issue 20, pp.- 9169-9171.

Academic Editor / Reviewer: Dr S. G. Savalia

Introduction

It is not difficult to determine the value of relative humidity when values of dry-bulb temperature and wet-bulb temperature are given. One can use the psychrometric equation of saturation line for this purpose for any pressure, such as standard sea level pressure (101325 P_a). However, there is no easy method to calculate wet-bulb temperature for known values of dry-bulb temperature and relative humidity. The psychrometric equation cannot be used for this purpose because it has an exponential term, one linear term and even the value of psychrometric constant is not constant. The knowledge of psychrometric properties is fundamental to the design of environmental control systems for plants, crops, animals and human [1]. The equations presented in the study enable an engineer to calculate some of the psychrometric properties, if any two independent psychrometric properties of an air-water vapour mixture are known in addition to the atmospheric pressure. Values of any two psychrometric properties are required for computing other psychrometric properties. From these parameters one can easily determine other psychrometric properties such as, relative humidity, enthalpy, humidity ratio, specific volume or vapour pressure. The determination of wet-bulb temperature is somewhat difficult. Either it is solved by trial and iterative method or the secant method can be used, which is cumbersome [2]. Computational problem may occur with this method at temperatures of 100ºC and above [3]. There is, however, no easy analytical solution to get wet–bulb temperature from dry-bulb temperature and relative humidity. Hence, there is a need to develop a simple method for the determination of the wet-bulb temperature.

Equations for determination of psychometric properties

Saturation Vapour pressure

The water vapour saturation is part and parcel of psychrometric calculations. There is no dearth of formula for calculating vapour pressure. However, formulas with very high accuracy should be used. The calculation of vapour pressure should be as accurate as possible as it is used in determining many other psychrometric properties. Several formulas for different temperature ranges were evaluated to find the most suitable and accurate ones for this analysis. They are very complex and lengthy. However, vapour pressure was calculated by using the equation given by Dilley which is simple and precise [4]. His equation for computing saturation vapour pressure in Pascal required slight modification (P_a) for accurate values of vapour pressure for the temperature range (0ºC to 65ºC) and (65ºC to 110ºC) as given below:

$$P_{wsT} = 611.213\ exp\left[\frac{17.273\,T}{237.32+T}\right] \qquad 1(a)$$

(0°C < T ≤ 65.0°C) and

For temperature above 65°C, the following equation is used:

$$P_{ws\,T} = 611.679\ exp\left[\frac{17.2699\,T}{236.3435+1.01585T}\right] \qquad 2(a)$$

(65°C < T ≤ 110°C)

For temperature below 0°C, the following relationship is used for computing saturation vapour pressure,

$$P_{ws\,T} = 610.78\ exp\left[\frac{21.874\,T}{265+0.9615T}\right] \qquad 3(a)$$

(0°C ≥ T ≥-40°C) and

The above equation nos. 1(a), 2(a) and 3(a)have calculate the saturation vapour pressure as a function of temperature. These equations should not be used outside the stated temperature ranges. The relationship is within 0.042 percent of the correct values for temperature range (0°C–110°C) and 0.109 percent of the values given by Wilhelm3 for the temperature range (0°C to –40°C).

Table-1 *Estimated values of T_{wb}*

(Temp. range)°C	T_{wb1}	T_{wb2}	T_{wb3}
(-30 to < -5)	T_{db}	$[T_{db}-0.3\ (T_{db}-T_{dp})]$	$[T_{db}-0.15(T_{db}-T_{dp})]$
(-5 to <30)	$T_{dp} + 0.4\ (T_{db}-T_{dp})$	$T_{dp} + 0.7\ (T_{db}-T_{dp})$	$T_{dp} + 0.55(T_{db}-T_{dp})$
(30 to 110)	T_{dp}	$T_{dp} + 0.3\ (T_{db}-T_{dp})$	$T_{dp} + 0.15\ (T_{db}-T_{dp})$

Table-2 *Determination of dew-point temperature*

T_a (°C)	P_{sTdb} (P_a)	γ (Fraction)	P_w (P_a)	T_{dp} (°C) (Calculated)	T_{dp}(°C) Table	Error (%)	Deviation
-30	37.938	0.338	12.823	-40.01	-40	0.025	0.01
20	2340.16	0.884	2068.71	-18.04	-18.03	0.005	0.01
35	5627.73	0.893	5025.55	32.97	32.97	0	0
100	101390	0.1	10139	46.22	46.08	0.304	0.14
						0.083	0.04
						Average error %)	Mean absolute deviation

Average error (%) 0.040 Mean absolute deviation

Table-3 *Determination of wet-bulb temperature*

T_{wb1}(°C)	P_{w1}(P_a)	T_{wb2}(°C)	P_{w2}(P_a)	T_{wb3}(°C)	P_{w3}(P_a)	T_{wb} (°C) Calculated	T_{wb} (°C) Table	Error (%)	Deviation(°C)
-30	37.938	-33.06	-174.4	-31.53	-68.57	-30.362	-30.37	0.026	0.008
18.79	2090.64	19.39	2212.97	19.07	2147.39	18.648	18.68	0.171	0.032
32.97	4892.16	33.58	5107.03	33.28	5000.71	33.35	33.35	0	0
46.22	6660.55	62.35	19747.5	54.28	12208	51.274	51.19	0.164	0.084
								0.09	0.031
								Av.error(%)	Mean absolute deviation

Mean absolute deviation

Dew point temperature

When the two input parameters; dry-bulb temperature (Ta) and relative humidity fraction (g) are given, the dew point temperature can be calculated by using equations 1(b),2(b) and 3(b) by putting the value of actual vapour pressure (P_w) or saturation vapour pressure at dew point temperature. First of all, the value of saturation vapour pressure at dry-bulb temperature is determined by using the equations 1(a),2(a) and 3(a) according to the temperature ranges specified therein. The saturation vapour pressure is then multiplied by relative humidity fraction to determine actual vapour pressure. The dew-point temperature can be determined by using equations [1(b),2(b) and 3(b)], which determine temperature as a function of saturation pressure, for entire saturation pressure ranges (12.838 to 143545 P_a).

The equation 1(a) can be rewritten for computing temperature as a function of saturation vapour pressure as given below,

$$T = \left[\frac{237.32\ln\left(\frac{Pws}{611.213}\right)}{17.273-\ln\left(\frac{Pws}{611.213}\right)}\right] \qquad 1(b)$$

(611.213 P_a ≤ P_{ws}T or P_w ≤ 25064.53 P_a)

The equation 2(a) can be rewritten for computing temperature as a function of vapour pressure as given below,

$$T = \left[\frac{236.3435\ ln\left(\frac{Pws}{611.679}\right)}{17.2699-1.01585\ ln\left(\frac{Pws}{611.679}\right)}\right] \qquad 2(b)$$

(25064.53 P_a<P_{ws}T or P_w ≤ 143447 P_a)

The equation 3(a) can be rewritten for computing temperature as a function of vapour pressure as given below,

$$T = \left[\frac{265\ ln\left(\frac{Pws}{610.78}\right)}{21.874-0.9615\ ln\left(\frac{Pws}{610.78}\right)}\right] \qquad 3(b)$$

(610.78 P_a ≥ P_{ws}T or P_w ≥ 12.838 P_a)

To calculate the value of T_{dp} for T_{db} as -30°C and γ as 0.338, actual vapour pressure is calculated as 12.823 P_a. For this value of P_w, we shall use the equation 3(c) and the calculated value of T_{dp} is is -40.0°C. Similarly, for T_{db} as 20°C and γ as 0.884 actual vapour pressure is calculated as 2068.705 P_a. For this value of P_w equation 3(a) is used and the calculated value of T_{dp} is is -18.02°C. For T_{db} as 35°C and γ as 0.893, actual vapour pressure (P_w) is calculated as 5925.549 P_a. For this value of P_w, we shall use the equation 3(a) and the calculated value of T_{dp} is is 32.97°C. For known values of T_{db} as 100°C and γ as 0.100 actual vapour pressure (P_w= γ x T_{db}) is calculated as 10139 P_a. For this value of P_w, we shall use the equation 3(a) and the calculated value of T_{dp} is 46.22°C.

Wet-bulb temperature

The wet-bulb temperature can be estimated from the following well known psychrometric relation:

$$P_w = P_sT_{wb} - B\ (T_{db}-T_{wb}) \qquad (4)$$

B is given by Dr Carrier equation as 66 P_a°C^{-1}, P_w is saturation vapour pressure at dew-point temperature, P_s T_{wb} is saturation vapour pressure at wet-bulb temperature and (T_{db}-T_w) is wet-bulb depression. Using the [Table-5], the effort was put in to reach in the close vicinity of wet-bulb temperature. It is generally observed that wet-bulb temperature moves towards T_{db} for T_{db} ranging from -5 to -30°C, towards T_{dp} for T_{db} ranging from 30 to 110°C and it keeps moving in the middle of T_{db} and T_{dp} for the temperature range of -5 to 30°C.The [Table-5] is based on this assumption. With the help of [Table-1], we determine the three values of estimated wet-bulb temperatures,T_{wb1}, T_{wb2} and T_{wb3} and values of P_sT_{wb1}, P_sT_{wb2} and P_sT_{wb3} using equations (1a) or 1(b) or 1(c) and then actual vapour pressures (P_{w1}, P_{w2} and P_{w3}) are determined from equation (4a,, 4b and 4c) by putting the values of P_st_{wb1}, P_st_{wb2}, P_st_{wb3}, T_{wb1} T_{wb2} and Tw_{b3} as given below; and given in [Table-3].

$$P_{w1} = P_sT_{wb1} - B\ (T_{db}-T_{wb}) \qquad (4a)$$

$$P_{w2} = P_sT_{wb2} - B\ (T_{db}-T_{wb}) \qquad (4b)$$

$$P_{w3} = P_sT_{wb3} - B\ (T_{db}-T_{wb}) \qquad (4c)$$

Then we determine the accurate value of wet-bulb temperature using one of the following equations. If P_w falls between P_{w2} and P_{w3}, use equation 5(a). If value of P_w falls between P_{w1} and P_{w3}, use equation 5(b). If P_w falls between P_{w1} and P_{w2}, use equation 5(c).

$$T_{wb} = \frac{[((P_{w2} - P_w)T_{wb3} + T_{wb2}(P_w - P_{w3})]}{(P_{w2} - P_{w3})} \quad 5(a)$$

Or,

$$T_{wb} = \frac{[((P_{w1} - P_w)T_{wb3} + T_{wb1}(P_w - P_{w3})]}{(P_{w1} - P_{w3})} \quad 5(b)$$

or

$$T_{wb} = \frac{[((P_{w1} - P_w)T_{wb2} + T_{wb1}(P_w - P_{w2})]}{(P_{w1} - P_{w2})} \quad 5(c)$$

For calculating the value of wet-bulb temperature three values of T_{wb} are estimated (T_{wb1}, T_{wb2} and T_{wb3} depending on which range T_{db} falls in [Table-1]. Then the values of P_{w1}, P_{w2}, P_{w3} and P_w ($\gamma x P_s T_{db}$) are calculated. It is evident from [Table-2] and [Table-3] that for T_{db} as -30°C and γ as 0.338, the value of P_w falls between P_{w1} and P_{w3} and therefore equation 5(b) is used. For known values of T_{db} as 20°C and γ as 0.884, the value of P_w falls between P_{w1} and P_{w3} and therefore equation 5(b) is used. For the input parameters; Tdb as 35°C and γ as 0.893, the value of P_w (5035.538) falls between P_{w2} and P_{w3} and therefore equation 5(a) is used for calculating T_{wb}. For given values of T_{db} as 100°C and γ as 0.1, the value of P_w(10139) falls between P_{w1} and P_{w3} and therefore equation 5(b) is used.

Accuracy and Limitations

The accuracy of the calculated values of dew point temperature depends on the limits of temperature and vapour pressure. Within the limits specified, the equations 1(b), 2(b) and 3(b) compute the accurate values of dew point temperature, the average error being only 0.619 percent over the entire temperature range (-40°C to 90.01°C). As far as water vapour saturation pressure is concerned, equation 3(a) has the accuracy of 0.031 percent of the correct values of saturation vapour pressure for the temperature range (0°C to 65°C) and 0.042 percent for the temperature range (0°C to 110°C) The errors go on accumulating, if we go for still higher temperatures. Similarly, for the temperature below freezing (0°C– 40°C), equation 3(a) gives the values of saturation vapour pressure within 0.108 percent of the values given by Wilhelm [3]. There are other formulas available in the literature for calculating saturation vapour pressure IAPWS [5], ASHRAE [6], Perry [7], Wexler and Greenspan [8] etc. which are more accurate than that used here [Table-2], but they are very complex and lengthy. In addition, those formulas cannot be used for determining the values of dew-point temperature, whereas the relationships used here (equations 1(a), 2(a) and 3(a)) for determining water vapour saturation pressure were rewritten as (1(b), 2(b) and 3(b)) for determining the values of dew-point temperature. These equations give very accurate values of both water vapour saturation pressure (average error 0.042 percent) and dew-point temperature (average error 0.619 percent).

Summary

The paper presents three equations for calculation of saturation vapour pressure in three different temperature ranges (0°C to-40°C),(0°C to 65°C) and (65°C to 110°C).The equations to calculate dew point temperature as a function of actual vapour pressure are also given. The relationships proposed here are valid for the temperatures ranging from -40°C to 110°C. Outside the stated limits, the equations need to be reformulated. The paper provides a simple method to calculate wet-bulb temperature, one of the most important thermodynamic properties of air-water mixture, by direct calculations.

Application of research: The psychrometric properties are very important for calculating crop evapotranspiration and one also useful in drying of fruits and vegetables.

Research Category: Psychrometric properties

Abbreviations:

Temperature, °C	T
Relative humidity, fraction	g
Partial pressure, Pa	P
Psychrometric constant	B

Acknowledgement / Funding: Authors are thankful to ICAR-Central Arid Zone and Research Institute, Jodhpur, 342 003, Rajasthan, India

***Principal Investigator or Chairperson of research: Dr A.K. Singh**
Institute: ICAR-Central Arid Zone and Research Institute, Jodhpur, 342 003, Rajasthan, India
Research project name or number: Research station trials

Author Contributions: All authors equally contributed

Author statement: All authors read, reviewed, agreed and approved the final manuscript. Note-All authors agreed that- Written informed consent was obtained from all participants prior to publish / enrolment

Study area / Sample Collection: CAZRI, Jodhpur, 342 003

Cultivar / Variety / Breed name: Nil

Conflict of Interest: None declared

Ethical approval: This article does not contain any studies with human participants or animals performed by any of the authors.
Ethical Committee Approval Number: Nil

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