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EFFECT OF TERM OF ERROR ON WET-BULB TEMPERATURE MEASUREMENT USING ASPIRATION PSYCHROMETER

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ABSTRACT

In heating, Wet-bulb temperature in HVAC (heating, ventilation, and air conditioning) applications is crucial for building the equipment. But radiation from the surrounding surfaces caused the errors during the thermodynamic wet-bulb temperature measurement. The wet-bulb temperature of moist air is measured in the current work utilising an aspiration psychrometer designed, developed, and built to reduce the error term caused by radiation and convection heat transfer. Wet-bulb temperature is calculated in the experiments using an aspiration psychrometer at various locations throughout the year, both with and without a shield. It has been found that the error term depends on several factors, including airspeed, the characteristics of wick fabric, the distance a person may breathe between thermometers, and the heat transfer coefficient owing to radiation and convection. A minimum of seven minutes must pass during the measurement of WBT to stabilise heat and mass transfer. It has been noted that the calculated term of error is higher in the afternoon than it is in the morning and evening because of the high solar radiation. The margin of error is approximately 15% in the morning and evening and at its highest in the afternoon. This investigation has led to the conclusion that direct sunlight should be avoided when measuring WBT. It has been discovered that greater heat transfer coefficient values provide the bigger term of error for fabrics with high textile emissivity.

Keywords: Aspiration psychrometer, dry-bulb temperature, globe thermometer, thermodynamic wet-bulb temperature, radiant temperature.

1. INTRODUCTION

In order to build and rate HVACR equipment properly, wet-bulb temperature must be measured accurately. Compared to sling and aspiration psychrometers, which are used to measure air moisture content, chilled mirror dew point hygrometers are more expensive. After measuring the temperature of the dry bulb and wet bulb in HVAC applications, the relative humidity is determined using the sling and aspiration psychrometers. Two thermometers make up a sling psychrometer, also known as a whirling hygrometer. The bulb of one thermometer is used to measure the dry-bulb temperature (DBT), and the bulb of another thermometer is used to measure the wet-bulb temperature (WBT), which is measured by wrapping wet cloth around the bulb. A sling psychrometer is required to be rotated by a handle with a velocity of 2 to 3 m/s over the thermometer surfaces and during the reading it is at rest leading to errors in the temperature measurement. Thermometers are separated and protected from thermal radiation by providing a shield as studied in Wang (2000). Figure 1 shows the measurement principle of DBT and WBT for given moist air. When the moist air flowed over a wet bulb, liquid water on the surface of cotton cloth evaporated, reducing the temperature. The actual WBT is the balancing of heat and mass transfer, including radiation effect from the surrounding. The cloth absorbs the water by capillary action dropping the temperature than ambient air. It is observed that initially mass transfer is maximum and heat transfer is minimum. At equilibrium temperature, mercury is stabilized, which measures WBT of air. Thus, when forced convection is major mode of heat transfer (conduction and radiation effects are neglected), heat and mass transfer coefficient ratio is constant, resulting temperature is called as wet-bulb temperature. It is observed that for a mixture of air and water, adiabatic saturation temperature and wet-bulb temperatures are nearly same.

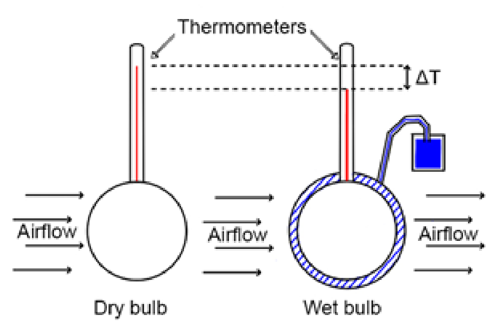

Fig. 1 Difference between DBT and WBT

An aspiration psychrometer or Assmann hygrometer consists of a battery-driven fan for generating a velocity of 2 to 8 m/s for accurate measurement of dry-bulb and wet-bulb temperature of moist air to find

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An aspiration psychrometer or Assmann hygrometer consists of a battery-driven fan, which generates air velocity of 2 to 8 m/s . It measures the accurate value of dry-bulb and wet-bulb temperature of moist air to find specific humidity and relative humidity. The distilled water is used to wet the cloth surrounding the bulb in wet-bulb temperature measurement, and the cotton wick is changed regularly for evaporation. The sensitivity of the aspiration psychrometer is low and needs a few minutes for the equilibrium state to measure WBT. The aspiration psychrometer is simple in construction, economical and consistent to fabricate, as studied in ANSI/ASHRAE (2006). The minor error in WBT measurement leads to a significant error in relative humidity in different HVAC applications such as drying, dairy, cotton and tobacco industries. It is found that WBT measurement depends on various parameters such as wind speed over the bulb of the thermometer, radiation heat transfer from the surrounding, wet bulb radius, mean radiant temperature, the emissivity of the cloth, accuracy and sensitivity of temperature sensors. The true wet-bulb temperature is different from adiabatic saturation temperature. The true wet-bulb temperature is determined by a balance between heat and mass transfer, Nellis and Klein (2009). The measured wet-bulb temperature is different from true wet-bulb temperature. The true wet-bulb temperature is equilibrium temperature when energy loss by evaporation balances the energy gain due to convection (only). In the practical measurement of wet-bulb temperature, there are different types of heat transfer to a temperature sensor which causes the measured wet-bulb temperature value to be different from that true wet-bulb temperature. These parasitic heat transfers to the temperature sensor can include radiation, lead wire/sheath conduction, and heat gain from the water source that is used to wet the sock.

Thermodynamic wet bulb temperature (T*) is the temperature of moist air. It depends on humidity ratio (w), heat content (h) and absolute pressure (p) at a particular condition. It is equal to the ideal saturation temperature at the end of the process at constant pressure, Arora (2004). When the air with specific humidity (w), heat content (h), temperature (T) and pressure (p) is flowing over an infinite wetted surface within a perfect insulated chamber (Fig. 1), the water evaporates into water vapour and distributes into the air. The specific humidity and relative humidity increase up to the total saturation point. Figure 2 shows the concept of the ideal adiabatic saturation process.

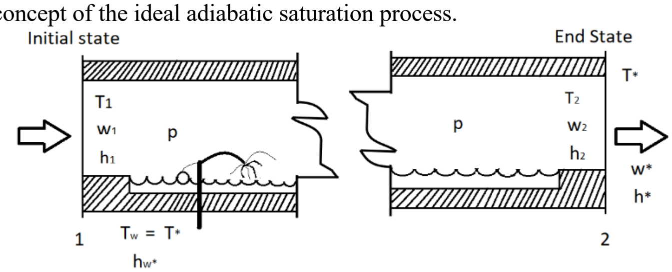

Fig. 2 Adiabatic saturation process

Steady flow enthalpy balance equation can be applied to the above open system as follows-

$$h_1 + (\omega_s^* - \omega_1)h_W^* = h_s^* \quad (1)$$

The quantity is very small and at constant wet-bulb temperature, h1 approximately equal to hs. Thus, enthalpy remains nearly the same for constant WBT. The temperature measured by wet-bulb thermometer is not similar to thermodynamic WBT, as the air leaving wet-bulb thermometer is not fully saturated, Howell (2009). Joao (2004) studied the analysis and validation of psychrometric instruments for measuring wet-bulb temperature with various instruments such as mercury in glass thermometer, PT-100 and K-thermocouple for the speed varying at 1.25 m/s to 5 m/s, found that relative humidity changes rapidly with WBT. Brenner *et al. (2011)* studied an aspirated psychrometer to measure WBT of moist air, and found that the measured WBT differs from true WBT. The true WBT is obtained when energy gained because of convection only equals the loss of evaporation. They reported the method for measuring DBT and WBT accurately by providing radiation shield and thermal sensors with an accuracy of ± 0.10 °C and compared WBT with the adiabatic saturation temperature. They revealed that the adiabatic saturation temperature is the primary measure in air conditioning. The air velocity over the sensor and radiation shield size are important in the measurement of wet-bulb temperature. They found that an air velocity of 4 m/s is the optimum velocity for the measurement of wet-bulb temperature. An air velocity of more than 4 m/s, results into reduced wick height and increases the conduction losses, whereas air velocity of less than 4 m/s, reduces heat transfer coefficients surrounding the sensor, resulted in an error in the measurement of wet-bulb temperature. Zhao and Jiang (1992) investigated the measurement of WBT and found that wind speed surrounding the sensor and radiation heat transfer affected WBT. They studied the effect of shielding and found that wet-bulb temperature is less than adiabatic saturation temperature at air velocity of 6 m/s for 6 mm to 12 mm sensor diameter. Hajidavalloo and Shakeri (2010) studied the performance of a cross-flow type of cooling tower for different wet-bulb temperatures. They showed that the rise in WBT significantly reduces the evaporation of water. They found that as DBT increases at constant WBT, rate of evaporation increases which changes the performance of cooling tower. Meliton (2014) found a relation to find WBT from DBT and relative humidity with accuracy of ± 0.55 °C. Hang and Xinhua (2017) studied ground source heat pump on the basis of WBT. Yongping (2013) established the procedure to find relative humidity from DBT and WBT within ± 4% error. Sadeghi *et al.* (2013) found thermodynamic WBT with an ambient temperature of air and vapour pressure. They found that WBT is a significant psychrometric property in ecological, metrological and agricultural applications. Chen and Chen (2017) studied humidity requirement in industries, indoor air conditions in buildings, worker's health and productivity in chemical and pharmaceutical industries. They found a psychrometer constant with the regression method to calculate relative humidity within the accuracy of ± 0.1%.

They studied different devices to measure relative humidity with mirrors, electrical and electronics sensors and psychrometers. Estrada-Jaramillo *et al*. (2014) found that WBT with the different environment for DBT ranges from 3 °C to 35 °C with relative humidity varying from 7% to 97% for ambient pressure corresponding to local altitude. Camuffo (2019) studied measurement of DBT and WBT in forced convection with velocity changing from 3 m/s to 5 m/s. They found that fan velocity is important factor in dry conditions where relative humidity changes from 20% to 100%. They investigated that the psychrometers are accurate temperature measuring devices for ambient temperatures more than 8 °C. Ustumczuk and Giner (2011) determined relative humidity by measuring DBT and WBT, and found that for relative humidity error to be maintained below 2%, temperature measurement error must be within ± 0.2 °C. Stull (2011) developed an explicit formula for measuring wet-bulb temperature by using relative humidity and air temperature. Santini (2001) studied the drying process through the relationship between wood moisture content and wet-bulb temperature at various conditions. Sarkar (2015) published a report on variations WBT and DBT and compared it with ASHRAE published data.

From the above literature review, we have observed that very few researchers have studied the measurement errors associated with psychrometry, psychrometers and wet-bulb temperature, including thermal radiation. They studied versatile refrigeration systems with different condensers and alternative refrigerants and jet ejectors with electronic controls for measuring different temperatures, Bhatkar *et al. (2013, 2021).*

Thus, in the present research work, an aspiration psychrometer is designed, developed and manufactured along with a globe thermometer. The experiments are performed throughout the year for different conditions with and without shields using a fabricated globe

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thermometer, including the radiation effect for the specific emissivity of white cloth as 0.76.

2. DESIGN OF ASPIRATION PSYCHROMETER

In aspiration psychrometer, separate arrangement is made for both the thermometers measuring from -10 °C to 50 °C including radiation effects. In sling psychrometer, DBT and WBT are affected by the velocity due to manual rotation. Figure 3 shows actual aspiration psychrometer fabricated which contains two ordinary mercury glass thermometers.

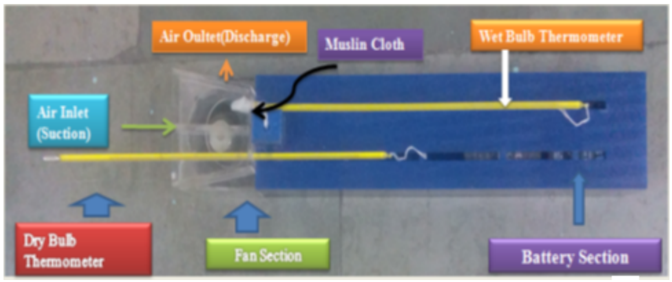

Fig. 3 Actual aspiration psychrometer

The white cloth is used to wet wick for wet-bulb thermometer from small water tank provided. The battery-driven fan is provided with 1800 rpm to provide minimum velocity of 6 m/s over wet-bulb thermometer. The shield is provided between thermometer sensors to avoid heat transfer. All the components are assembled in white acrylic sheet. The sufficient space is provided for wrapping cloth around wet-bulb sensor, which requires around 50 seconds for complete capillary action. For the measurement of thermodynamic wet-bulb temperature, hardbound paper sheet is provided in order to avoid direct sunlight. Thermometers are used with least count of ± 0.1 °C. Thus, slight change in temperature can easily be sensed by both thermometers. At thermal equilibrium condition which need minimum 4 to 5 minutes, temperature recorded by bulb of wet-bulb thermometer is wet-bulb temperature as studied in operating manual of aspiration thermometer. Table 1 shows the components used in aspiration psychrometer with their specifications.

Table 1 Range and accuracy of the equipment's used.

Part Name	*Range*	*Accuracy*
Mercury in thermometer	-10 °C to 50 °C	± 0.12 °C
Digital thermometers	-80 °C to 300 °C	± 0.006 °C
Hot wire anemometer	0.1 to 25 m/s	± 0.01 m/s
Fan	0 to 1800 m/s	± 0.1 m/s
Voltmeter	0 to 300 V	± 0.1 V
Ammeter	0 to 5 A	± 0.01 A

Following precautions are to be followed during the measurement of temperatures with aspiration psychrometer:

1. Keep psychrometer away from the human body to avoid moisture from breathing. The psychrometer can be suspended with suitable height
2. Wet-bulb temperature is dependent on fan speed and can take more time due to sluggish response of a sensor
3. There might be reading errors in psychrometer if the operator took more time due to small-scale divisions
4. The errors may be due to inadequate ventilation for wet-bulb temperature below or above 4 m/s wind speed
5. The cotton wick must be completely wet surrounding bulb of wet-bulb thermometer
6. Pure distilled water should use along with clean cotton wick for accurate reading
7. For using new cotton wick, it should be earlier boiled to eliminate unnecessary constituents to alter surface tension
8. The cotton wick should be thin for quick reading
9. As freezing temperature of water is 0 °C, capillary moment stops for wet bulb temperature measurement at 0 °C

3. MEASUREMENT OF RADIATION EFFECT DURING WET BULB TEMPERATURE

The performance of aspiration psychrometer is dependent on the radiation heat transfer. Mean radiant temperature is measured with the help of manufactured globe thermometer as shown in Fig. 4, which consists of a thermometer with mercury as manometric fluid inserted in center to measure temperature from -10 °C to 50 °C with an accuracy of ± 0.1 °C as studied by Bedfored (1934) and Modest (2003). It is found that if the globe surface temperature is more than ambient temperature, globe thermometer reads higher temperature than ambient air temperature. Radiation and convection heat transfer balance with atmosphere at equilibrium temperature. The globe thermometer is not considering the radiation direction which may lead to error in the measurement of temperatures as given in globe thermometer instruction manual.

The hollow metal globe with 125 mm in diameter is painted with black color so that it can act as a black body for absorbing maximum surrounding radiations. A rubber stopper is provided as support at the upper opening of the globe. The globe is balanced with the help of three strings. The mercury thermometer with 65 mm length is inserted into the globe to measure the correct globe temperature. The temperature is measured by a thermometer inserted into the globe after stable condition (minimum 10 minutes), which is more than the surrounding air temperature depending upon the intensity of solar radiation.

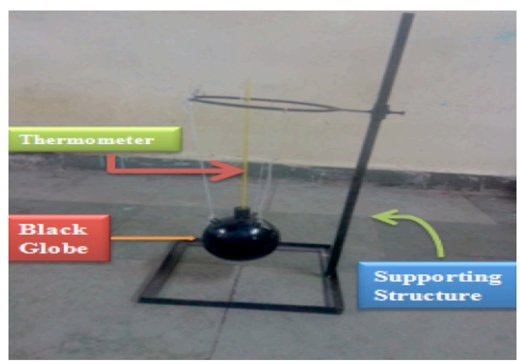

Fig. 4 Globe thermometer

4. MEASUREMENT OF WHITE CLOTH'S EMISSIVITY

Emissivity is important property in thermal radiation which decides the amount of heat transfer by radiation in the measurement of WBT. Emissivity is measure of effective surface-emitting energy with respect to blackbody. In experimental instrument for emissivity measurement, black color is coated around a circular plate to act as a black body. Another plate is wrapped with a white cloth (test plate) as shown in Fig. 5. The plates are mounted on brackets in enclosure so as to provide undisturbed natural convection. The heat input to heater is varied by separate voltage regulators provided for black and test plate. It is measured by using an ammeter and voltmeter with the help of double

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plate toggle switches. The temperature of plates and enclosure is measured by a digital temperature. The plates are interacting with the enclosure by means of convection and radiation. Heat input to both the plates is controlled in such a way that the plates will achieve the same temperature under steady state condition and change in heater input observations is due to the radiation effect with dissimilar emissivity of black and test plates as studied in instruction manual.

Under thermal equilibrium state, by applying Stefan-Boltzmann law of radiation, heat input to black body plate and test plate is given by equation (2), which shows the heat exchange by radiation between surface temperature of black plate and enclosure.

$$Qb = \sigma\, A\, \varepsilon b\, (Ts^2 - Te^2) + (\text{Convection} + \text{Conduction})\ \text{Losses} \quad (2)$$

$$Qt = \sigma\, A\, \varepsilon t\, (Ts^2 - Te^2) + (\text{Convection} + \text{Conduction})\ \text{Losses} \quad (3)$$

From Eq, (2) and (3), heat exchange by radiation between black plate and test plate with surrounding is given by:

$$Qb - Qt = \sigma\, A\, \varepsilon b\, (Ts^2 - Te^2) - \sigma\, A\, \varepsilon t\, (Ts^2 - Te^2) \quad (4)$$

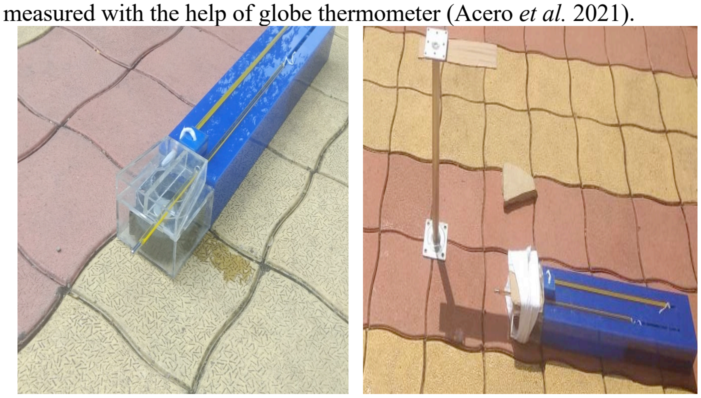
Equation (3) indicates heat transfer by radiation between test plate and enclosure. Where Qb and Qt are rate of heat transfer by radiation from black plate and test plate with the surrounding respectively, Ts and Te are surface temperature of body and enclosure, σ is Stefan Boltzmann constant, A is surface area exposed to radiation, εb and εt are emissivity of black and test body respectively. Where heat input to black plate and test plate is the product of voltage and current applied and A is the surface area including thickness of the plate. Thus, the emissivity of the cloth calculated experimentally is found to be 0.76.

Fig. 5 Emissivity apparatus

5. MEASUREMENT OF DBT, WBT, HUMIDITY RATIO, TERM ERROR

Wet-bulb temperature (WBT) is measured when wet white cloth is wrapped on front section of wet-bulb thermometer. Hardbound paper sheet is installed on the stand in order to provide shielding from direct sunlight to dry bulb thermometer. In order to understand radiation phenomenon, both dry-bulb and wet-bulb thermometers are directly exposed to air by removing white cloth and hardbound paper. Normally, no shielding is provided in industry so the effect of radiation is included in temperature readings. After calculating dry-bulb and wet-bulb temperature with globe temperature, mean radiant temperature is calculated including radiant and convective heat transfer coefficients. The term of error is calculated to find difference between thermodynamic WBT and actual WBT. Figure 6 (a) and (b) shows aspiration psychrometer without and with shielding provided for measurement of DBT and WBT.

DBT, WBT, globe temperature, velocity over the wet-bulb thermometer along with wind velocity over bulb of globe thermometer are noted at a different time in Pune, Maharashtra, India (18.5204° N, 73.8567° E). The performance parameters such as mean radiative heat transfer coefficient (hr), mean convective heat transfer coefficient (hc), mean radiation temperature (MRT) and term of error are calculated using following equations. Mean radiation temperature is calculated from DBT measured from aspiration psychrometer and globe temperature (GT) is measured with the help of globe thermometer (Acero *et al.* 2021).



(a) Without shielding (b) With shielding

Fig. 6 Aspiration psychrometer measuring WBT and DBT

Anemometer is used to measure wind speed over globe at all four side and mean is taken as wind speed over globe thermometer, D is globe diameter and ε is emissivity of material of globe as 0.95 (Dissegna *et al.* 2021; Thorsson *et al.* 2006).

Sample calculation for 1st observation: under roof in closed room.

DBT=28.7 °C, WBT= 23.8 °C

Wet bulb depression = DBT − WBT = 28.7 °C - 23.8 °C = 4.9 °C (5)

$$MRT = \left[\left[(GT + 273.15)^4 + \frac{1.10\ \times 10^8\, V^{0.6}}{\epsilon\, D^{0.4}}(GT - DB)\right]^{0.25} - 273.15\right] \quad (6)$$

$$MRT = \left[\left[(29 + 273.15)^4 + \frac{1.10\ \times 10^8\, (0.16)^{0.6}}{(0.95)\ 0.125^{0.4}}(29 - 28.7)\right]^{0.25} - 273.15\right]$$

$$= 29.24\ °C$$

The heat transfer coefficient (HTC) in radiation (hr) is calculated with equation (7) and convection HTC is found out from equation (8). It is observed that convection and radiation HTCs are function of air speed, surface orientation, material and thermodynamic properties of fluids.

$$hr = \frac{\sigma\varepsilon(MRT^4 - T')}{MRT - T'} = \frac{5.67 \times 10^{-8}\ \times 0.76\,(29.24^4 - 23.8^4)}{29.24 - 23.8}$$
$$= 4.639\ W/m^2K \quad (7)$$

$$hc = [10.45 - V + 10 \times V^{0.5}] = [10.45 - 10.87 + 10 \times 10.87^{0.5}]$$
$$= 32.55\ W/m^2K \quad (8)$$

WBT depends on initial and final state of moist air along with heat and mass transfer at the bulb. It is found that WBT indicated with aspiration psychrometer is equal to thermodynamic WBT when equation (9) is satisfied. Where, Le is Lewis number, hc and hr be the mean convective and radiative heat transfer coefficients respectively, T is the temperature

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of uninterrupted air, T' is WBT and MRT is mean radiation temperature.
The percentage humidity ratio is calculated from equation (11).

Table 2 Readings with hard paper shielding (Thermodynamic Condition) at different conditions

Location No.	*Time*	*DBT (With shield) (°C)*	*WBT (Without Shield) (°C)*	*Wet Bulb Depression (°C)*	*MRT (°C)*	*Velocity* (m/s)	*hr (W/m*²K)	*hc (W/m*²K)	*TOE*
1	4.30 PM	28.7	23.8	4.9	29.24	10.87	4.638	32.55	0.1582
2	5.05 PM	30.6	22.9	7.7	38.09	8.22	4.828	30.90	0.3084
3	2.15 PM	32.4	24.8	7.6	48.30	10.48	5.127	32.34	0.4902
4	4.00 PM	30.9	24.7	6.2	33.82	16.05	4.768	34.46	0.2036
5	3.45 PM	36.5	25.9	10.6	52.80	12.41	5.270	33.41	0.4003
6	3.10 PM	32.9	21.7	11.2	49.92	18.95	5.094	35.03	0.3665
7	3.30 PM	30.1	23.8	6.3	62.25	19.10	5.4682	35.05	0.8953
8	9.45 AM	25.7	23.4	2.3	27.69	17.11	4.593	34.70	0.2471
9	3.15 PM	27.9	24.8	3.1	37.25	16.15	4.853	34.48	0.5655
10	5.02 PM	29.7	24.6	5.1	30.59	13.27	4.689	33.60	0.1641
11	1.00 PM	24.9	22.1	2.8	27.84	11.63	4.567	32.92	0.2847
12	6.00 PM	27	23.9	3.1	27.63	12.14	4.605	33.15	0.1673
13	12.45PM	30.5	23.1	7.4	33.21	19.91	4.716	35.16	0.1832
14	11.00AM	34.5	25.1	9.4	44.45	12.10	5.037	33.13	0.3130
15	3.30 PM	38.2	25.3	12.9	60.26	15.36	5.452	34.28	0.4310
16	11.40AM	25.7	23.2	2.5	26.81	16.69	4.568	34.61	0.1908
17	9.30 PM	26.5	24.2	2.3	26.84	10.54	4.5925	32.37	0.1631
18	9.00 AM	27.2	22	5.2	41.91	15.67	4.900	34.36	0.5462
19	3.00 PM	30.3	22.7	7.6	42.35	8.48	4.928	31.09	0.4099
20	10.50 PM	26.8	24.2	2.6	26.97	10.54	4.595	32.37	0.1513

Table 3 Readings without hard paper sheet (open to radiations)

Location No.	*Time*	*DBT (With shield) (°C)*	*WBT (Without Shield) (°C)*	*Wet Bulb Depression (°C)*	*MRT (°C)*	*Velocity* (m/s)	*hr (W/m*²K)	*hc (W/m*²K)	*TOE*
1	4.30 PM	28.8	23.9	4.9	29.16	10.87	4.639	32.54	0.1530
2	5.05 PM	30.9	23.1	7.8	37.92	8.22	4.829	30.90	0.2969
3	2.15 PM	34.2	25.3	8.9	47.23	10.48	5.112	32.34	0.3896
4	4.00 PM	31	24.8	6.2	33.68	16.05	4.767	34.46	0.1981
5	3.45 PM	37.4	26.7	10.7	51.94	12.77	5.267	33.41	0.3719
6	3.10 PM	33.8	22.2	11.6	48.65	18.95	5.073	35.03	0.3302
7	3.30 PM	31.2	24.7	6.5	60.20	19.10	5.435	35.05	0.7646
8	9.45AM	26.1	23.8	2.3	26.95	17.11	4.585	34.70	0.1813
9	3.15 PM	28.7	25.3	3.4	36.00	16.15	4.834	34.48	0.4414
10	5.02 PM	29.8	24.8	5	30.47	13.27	4.691	33.60	0.1584
11	1.00 PM	25.1	22.4	2.7	27.65	11.63	4.569	32.92	0.2701
12	6.00 PM	27.1	24	3.1	27.52	12.14	4.603	33.15	0.1578
13	12.45PM	30.9	23.4	7.5	32.41	19.91	4.704	35.16	0.1607
14	11.00AM	35.8	25.6	10.2	43.19	12.10	5.018	33.13	0.2611
15	3.30 PM	39	26.2	12.8	59.39	15.36	5.451	34.28	0.4123
16	11.40AM	25.9	23.4	2.5	26.45	16.69	4.565	34.61	0.1613
17	9.30 PM	26.6	24.3	2.3	26.77	10.54	4.593	32.37	0.1531
18	9.00 AM	28.1	23.5	4.6	40.72	15.67	4.907	34.36	0.5345
19	3.00 PM	31.8	23.6	8.2	41.45	8.48	4.927	31.09	0.3451
20	10.50 PM	26.6	24.2	2.4	27.11	10.54	4.598	32.37	0.172

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$$Le^{0.6667}\left[1+\frac{hr(MRT-T')}{hc(T-T')}\right]=1 \qquad (9)$$

The term of error (TOE) is calculated by using equation (10)

$$TOE=\left[\frac{hr(MRT-T')}{hc\ (T-T')}\right]=\frac{4.639(29.24-23.8)}{32.55\ (28.7-23.8)}=0.153 \qquad (10)$$

$$\begin{aligned}Humidity\ ratio\ \%\ error &= \frac{W2-W1}{W2}\times 100\\ &= \frac{0.01804987868-0.017925954618}{0.01804987868}\times 100\\ &= 0.68\% \qquad (11)\end{aligned}$$

Table 2 and Table 3 shows experimental observations conducted using aspiration psychrometer with and without shield respectively. Lewis studied the significance of heat and mass transfer coefficients in different mixture composition and found that equation (9) is satisfied for Lewis number equal to unity for mixture of air and water vapor at low mass transfer rate only. Thus, it is indicated that WBT and adiabatic saturation temperatures are in close proximity for Lewis number of unity. The simultaneous heat and mass transfer from wet-bulb is given by Lewi's relation, which states the difference between adiabatic saturation temperature and thermodynamic WBT with small correction factor applied to WBT to measure thermodynamic WBT.

A shield sheet is located in such a way that it can only restrict direct sun light. The experiments are performed for various locations mentioned in chronological order in Tables (2) and Table (3) with and without shield as (1) under roof in closed room (2) near to opposite side of radiating wall (sun already passed over wall with distance from wall is 900 mm) under the clear sky in open area (3) in closed room of concrete roof (4) with condition of near to radiating wall (5) with condition of near to solar panel at roof of building (6) with condition of under full sunlight (7) With condition of cloudy condition under big tree, (8) with condition of under humid condition before raining, (9) with condition in closed room at evening (10) with condition in cloudy condition with open sky (11) with condition of outside cloudy condition in closed room (12) with condition of under shadow of big tree (13) with condition of under open sky with sunlight (14) Reading with condition of near radiating wall (15) with condition of under cloudy condition, (16) with condition of under impact of radiations from electrical appliances (17) in morning (18) under open sky with sunlight, (19) afternoon with full sunlight (20) at night under cloudy atmosphere. All the experiments are performed with and without shielding with aspiration psychrometer. Wet-bulb depression, mean radiation temperature, heat transfer coefficient due to radiation, convection and term of error are calculated and tabulated in Table 2 and Table 3 with and without shield. Thus, term of error is calculated for every psychrometer temperature reading for all experimental conditions which indicated error in temperature between adiabatic and wet-bulb temperature due to convection and radiation HTCs. Following results are discussed from above experimental observations:

5.1 Day/Night Time vs. term of error

It is found from the experimental observation that the radiation intensity increases from morning 9.45 am to afternoon up to 3.30 pm and then decreases on a clear sky day. Thus, term of error is dependent on the intensity of sun from morning to evening. Figure 7 shows term of error varying with respect to time calculated from equation 10. Maximum term of error is observed to be 0.78 at 3.30 pm due to the effect of MRT, convection and radiation heat transfer coefficients and WBT.

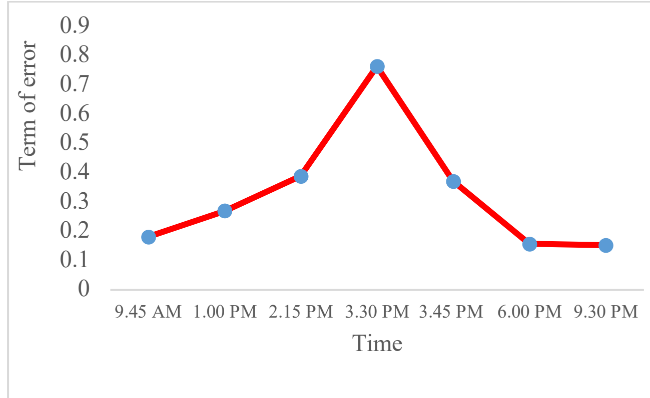

Fig. 7 Time vs. term of error

5.2 Mean radiant temperature vs. term of error

Mean radiant temperature is the uniform temperature of hypothetical enclosure where heat transfer by radiation from a human body is same as radiant heat transfer in actual non-uniform enclosure. The mean radiant temperature is useful in meteorological governing human energy balance with strong influence on thermos-physiological indices such as Physiological Equivalent Temperature (PET) and Predicted Mean Vote (PMV). MRT is calculated from 300 K to 330 K using equation (6). From Fig. 8, it is found that at higher mean radiant temperature, term of error is more. At higher MRT, more heat exchange with the surrounding environment observed that lead to more term of error in WBT measurement.

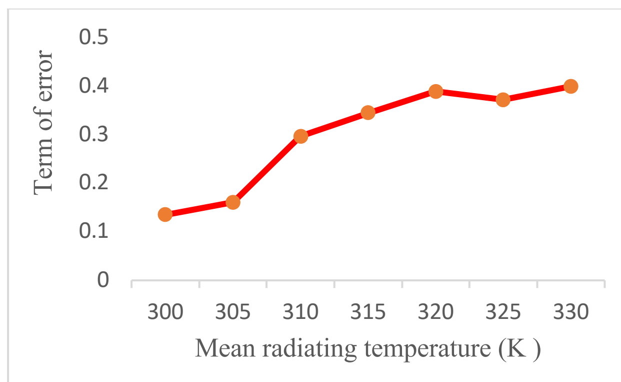

Fig. 8 Mean radiating temperature vs. term of error

5.3 Radiant heat transfer coefficient vs. term of error

Radiative heat transfer coefficient indicates heat transfer between the gray bodies and diffuse surfaces. Radiant heat transfer coefficient is calculated using equation (7) for mean radiant temperature and wet-bulb temperature. As the radiation heat transfer by radiation increases, coefficient of radiation increases along with term of error as shown in Fig. 9 that lead to error multiplication in the measurement of wet-bulb temperature.

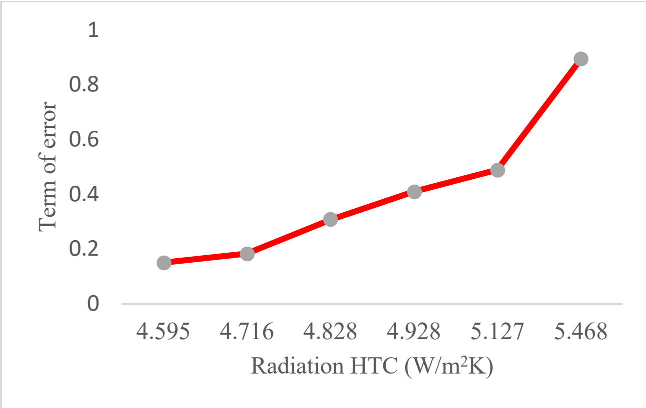

Fig. 9 Radiation HTC vs. term of error

5.4 WBT (With and without shield) vs. humidity ratio % error

Figure 10 shows the difference between the WBT (without shield) and WBT (with shield) vs. humidity ratio % error. As the WBT without shield is always greater than WBT with shield, humidity ratio % error always increases due to radiation effects that lead to error in wet-bulb temperature measurement.

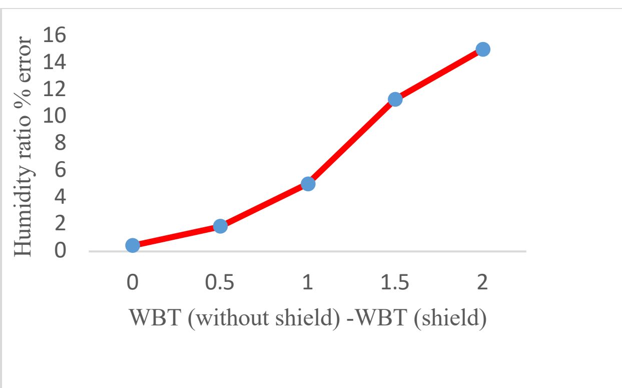

Fig. 10 Difference between WBT without and with shield vs. humidity ratio % error

6. CONCLUSIONS

The experiments are performed using aspiration psychrometer to calculate wet-bulb temperature at various locations at different times throughout the year with and without shield. During the measurement of WBT to stabilize heat and mass transfer, a minimum of seven minutes is required. In afternoon time compared to morning and evening, calculated term of error is more due to high solar radiation. The term of error in the morning and evening is around 15%, while in afternoon, it is maximum equal to 41%. Thus, during WBT measurement, direct sunlight must be avoided. It is found that for high cloth emissivity, higher heat transfer coefficient values lead to high term of error. A minimum of 4 m/s suction air velocity is required to evaporate water vapor over the bulb of the thermometer. The proper wetting of the bulb is necessary for calculation of WBT. When the thermometer bulb is too much wetted, it will measure water temperature inside the wick, whereas for less wetted cloth, it will measure dry-bulb temperature. It is found that aspiration psychrometer is simple, inexpensive, accurate and easy to use for different conditions.

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NOMENCLATURE

A	Surface area of plate [m^2]
D	Bulb diameter [m]
DB	Dry bulb temperature [K]
GT	Globe temperature [K]
h	Enthalpy [kJ/kg]
hc	Convective heat transfer coefficient [W/m^2K]
hr	Radiative heat transfer coefficient [W/m^2K]
MRT	Mean radiating temperature [K]
Q	Radiation heat transfer [W]
T'	Wet bulb temperature [K]
V	Velocity of air [m/s]
W	Humidity ratio [kg of w. v. /kg of dry air]
Suffices	
b	Black body
s	Saturated/steady state/surface
t	Test plate
e	Enclosure
w	Water
ε	Emissivity
σ	Stefan Boltzmann constant [W/m^2K^4]
Le	Lewis number

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