Calculation of the natural (unventilated) wet bulb temperature, psychrometric dry bulb temperature and Wet Bulb Globe Temperature from standard psychrometric measurements

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Abstract

A method and equations are presented to allow calculation of the natural wet bulb temperature (WBn), psychrometric dry bulb temperature (DBn) and wet bulb globe temperature (WBGT) from standard psychrometric measurements of unshielded, aspirated wet bulb temperature (WBa), unshielded, aspirated dry bulb temperature (DBa) and globe temperature (GT).

Introduction

Mine ventilation practitioners are familiar with the measurement of the ventilated (or aspirated) wet bulb temperature, the dry bulb temperature using a whirling psychrometer, wind speed using a vane or other anemometer, barometric pressure and, to a lesser extent, globe temperature. However, it is becoming increasingly common to use the wet bulb globe temperature (WBGT) as an index for measuring heat stress and as a general measure of hot environments.

The ACGIH TLV (2000) for Heat Stress defines the WBGT as:

WBGT = 0.7 x WBn + 0.3 x DB ("indoors or outdoors with no solar load") and

WBGT = 0.7 x WBn + 0.2 x DB + 0.1 x GT ("outdoors with solar load")

Both definitions require measurement of WBn.

Calculation of the WBGT requires measurement of the WBn. However, ventilation practitioners generally measure WBa, not WBn. Therefore a method of calculating WBn from WBa is required if the WBGT is to be assessed from standard psychrometric properties.

Radiant Heat Exchange

Thermal radiation is the flow of heat (apart from conduction, convection and evaporation) from a hotter surface to a cooler surface. Providing there is a temperature difference between the surfaces, there will be a radiant heat exchange irrespective of whether one or both of the surfaces are solid, liquid or gaseous.

The mean radiant temperature (MRT) is defined by ASHRAE (1997) as the uniform temperature of an imaginary black enclosure (around the sensor) that would exchange the same amount of radiant heat (with the sensor) as the actual nonuniform enclosure (around the sensor).

Therefore, even in an underground situation when the air temperature (DB) is equal to the temperature of the surrounding rock, there will still be a radiant heat exchange between the wet wick (at temperature WBn) and its surroundings, which in this case are at the DB. In other words, the air itself, being at a different temperature to the bulb, will radiate heat onto the bulb.

When the surrounding rock is at a higher (or lower) temperature than the DB, then the MRT will be higher (or lower) than the DB and there will be additional (reduced) radiant heat exchange with the bulb. For clarity in this paper, the "normal" radiant load on a bulb is assumed to be at the DB. Where the MRT is not equal to the DB, this is called the superimposed radiant load.

Thermodynamic Wet Bulb Temperature

A succinct definition of the thermodynamic or psychrometric wet bulb temperature (WBt) is given in ASHRAE as being the temperature at which water (liquid or solid), by evaporating into moist air at a given temperature and humidity ratio, can bring the air to saturation adiabatically at the same temperature (WBt) and pressure. During the adiabatic saturation process, the DB temperature of the air is reduced to the WB (which is the definition of saturation) only by evaporation of the water. Neither the WB temperature nor the water temperature changes during the process.

In practice, ventilation practitioners estimate the thermodynamic wet bulb temperature by measuring the aspirated (or ventilated) wet bulb temperature. This practice is justified on the following basis.

When a wet bulb (a thermometer bulb surrounded by a wet wick) is strongly aspirated (at least 3 m/s), the heat gains on the wick due to convection from the surrounding fluid (the air) and from any radiant heat exchange with its surroundings can be offset almost entirely by evaporation of liquid water from the wick.

Providing the wick surrounding the bulb is kept saturated, providing the water being delivered to the wick is at the wet bulb temperature itself, providing the wind speed over the bulb is sufficiently high, and providing the radiant heat exchange between the wick and its surroundings is not 'excessive' then the reading on the bulb will settle at a value that is a close approximation of WBt.

It is important to note that in a truly adiabatic saturation process, the initial difference between the DB temperature of the air and the water temperature (which is at the WB temperature) will result in radiant heat exchange between the two, but that this radiant heat flow is of no consequence as by the time the saturation process is completed, both the DB temperature and the water temperature (along with the WB temperature, which does not change during the process) are all equal, and therefore radiant heat exchange is zero. However, this is not true when the wet bulb temperature is measured using a whirling psychrometer or other aspirated device. In this case, the process does not proceed to saturation (the water from the wick never saturates the entire air mass passing over it) and therefore the radiant heat exchange between the wick and the aspirating air (due to the temperature difference between the WB and DB) results in the bulb temperature (WBa) drifting towards, but never entirely achieving, the true thermodynamic wet bulb temperature.

The temperature that is actually being measured in a whirling psychrometer should more properly be called the unshielded ventilated or unshielded aspirated wet bulb temperature (WBa). The error involved in assuming WBa is in fact WBt becomes higher as the difference between the DB and the WBt becomes greater and/or as the actual MRT surrounding the globe differs from the DB.

Thermodynamic Dry Bulb Temperature

Whilst the need to aspirate a wet bulb thermometer is generally well understood, it is often thought that there is no point in "whirling" (or aspirating) the dry bulb thermometer. In other words that the "natural" DB (DBn) is equivalent to the aspirated DB (DBa), which in turn is equal to the psychrometric or thermodynamic dry bulb temperature (DBt). Whilst this is true when there is no superimposed radiant heat load (i.e. the MRT equals the DB), it is not true when the MRT varies from the DB. In these circumstances, the DB will also be in error for the same reasons that the natural wet bulb will be in error.

This influence of thermal radiation on DB is obvious when a dry bulb thermometer is exposed to solar radiation on the surface, and is why surface thermometers used for meteorological purposes are protected from solar heat loads be being mounted in a Stevenson screen.

WBGT

The WBGT was originally derived (Parsons, 1993) by US military scientists as an approximation to the Corrected Effective Temperature (CET). CET required measurement of the aspirated wet bulb temperature, the globe temperature and wind speed. The military wished to have a heat stress index that could be measured easily in the field using a single instrument. CET therefore suffered from two problems. Firstly, neither the aspirated wet bulb temperature nor the wind speed could easily be measured in the field using small, light, mechanically simple and robust instruments. Secondly, CET required its primary factors to be combined using a complex nomogram. It was then recognised that using a natural wet bulb thermometer (i.e. a standard wet bulb thermometer, but without aspiration) would provide an indication of both the thermodynamic wet bulb temperature and the wind speed.

This then resulted in a heat stress index (WBGT) that used a relatively simple instrument that had no moving parts, was relatively small, and due to the very simple formula, could be easily assessed in the field.

Wind speed

When measuring wind speed for the purpose of calculating WBGT, then in situations where the wind speed is low, it is important to:

- Average the wind speed over a suitable time interval, typically 3 minutes,
- Ensure that the wind speed sensor is either unaffected by the direction of the wind (e.g. a suitably mounted, non-directional hot wire anemometer), or simultaneously measure the wind direction (e.g. with smoke puffs) and alter the wind speed sensor accordingly.

Method

Derivation of equations for WBn

Van der Walt and Hemp (1989) describe the steady-state heat balance and temperature on a wet thermometer. The equation is:

$$h_c\ (DB\text{-}WBn) + F_{ev}\ h_r\ (MRT\text{-}WBn) = h_c\ \lambda\ 0.7\ (e_s\text{-}e)/P \qquad \text{Eqn 1}$$

where

h_c is the convective heat transfer coefficient, $W/(m^2.K)$,

F_{ev} is the view factor for the bulb (typically 0.8, van der Walt and Hemp, 1989) with respect to its surrounding radiation field. The view factor should be combined with the emissivity of the bulb, which is typically about 0.95 (ASHRAE, 1997), with the combined view and emissivity factor being 0.74.

MRT is the mean radiant temperature, ^0C

λ is the latent heat of evaporation of water at the WBn. Whilst this will vary with WBn, any variation has only a very minor impact on the final solution and a fixed value of 2455 kJ/kg can be safely assumed.

e_s is the saturated vapour pressure at the WBn

e is the ambient vapour pressure, and

P is the barometric pressure

The units for e_s, e and P must be consistent, either kPa or Pa.

The explanation for the constant, 0.7, can be found in McPherson (1993) eqn 15A.29

In solving equation 1, it is first assumed that the DB is the DBt, i.e. corrected for any effects of radiation; this requirement is subsequently relaxed.

Calculating the MRT from the Globe temperature

Radiant heat loads were first measured using 150 mm hollow copper balls (painted matt black) with a thermometer inserted in their centre. This diameter was quite arbitrary as this size of copper ball was used for plumbing in the first part of last century and was therefore readily available to early experimenters (Kerslake, 1972).

Note that a copper globe of this size has a very high time constant, and only reaches equilibrium in 20 to 30 minutes. Smaller globes or globes made from lighter materials (e.g. a thin plastic bubble) reduce this time constant to one to two minutes (ASHRAE, 1977).

The temperature measured by the blackened globe is not the MRT, as the globe is also significantly affected by convective heat losses (or gains) from the surrounding fluid (the air).

ASHRAE (1997) provides an equation to calculate MRT from the black globe temperature.

$$MRT = \left[(GT + 273)^4 + \frac{1.10x10^8 WS^{0.6}}{\varepsilon D^{0.4}} (GT - DB) \right]^{1/4} - 273 \qquad \text{Eqn 2}$$

where:

GT is the globe temperature, ^{0}C

WS is the wind speed over the bulb, m/s

ε is the emissivity (0.95 for black globe), non-dimensional

D is the bulb diameter, m

DB is the thermodynamic dry bulb temperature, ^{0}C

Results and Discussion

The convective heat transfer coefficient at the bulb is required to solve Equation 1. This coefficient is very dependent on wind speed, with higher wind speeds promoting more convective heat transfer.

Whillier (1989) provides equations for hc under both forced and natural convection. These two regions are determined by the flow characteristics around the bulb.

The equation (Whillier eqn 8a) for natural convection is:

$$h_c = 1.4\,(DB - WBn)^{1/3} \qquad \text{Eqn 3}$$

The equation for forced convection is:

$$h_c = 0.2\ Re^{0.6}\ k / D \qquad \text{Eqn 4}$$

where:

k is the thermal conductivity of air (W/(m.K) = 0.028 (Whillier Table 1)

D is the diameter of the bulb, m

Re is the Reynolds number (Whillier p 476) = 67000 WS D ρ / 2 Eqn 5

and:

WS is the wind speed, m/s

ρ is the air density, kg/m^3

The radiative heat transfer coefficient is also required to solve Equation 1.

This coefficient is independent of wind speed. Whillier provides an equation (Whillier Eqn 6) for hr. Taking both the view factor (0.8 from van der Walt and Hemp (1989)) and the emissivity (0.95 from ASHRAE (1997)) into account, a slight rearrangement of Whillier's equation provides the following equation:

$$h_r = 0.8 \times 0.95 \times 4 \times 5.67 \times 10^{-8} \times ((MRT+WBn)/2 + 273.15)^3 \qquad \text{Eqn 6}$$

An iterative technique can then be used to solve for the unique value of the water on the bulb (the WBn) that will provide a heat balance on the wick.

A full listing of the program, written in Microsoft™ Excel™ Visual Basic for Applications™, is included in Appendix A. [This appendix is freely available in electronic form from the author at mvamail@mvaust.com.au].

In the above analysis, it has been assumed that the dry bulb temperature is the true thermodynamic value, DBt. If this is not the case (and it will not be if an unshielded thermometer is used when a superimposed radiant heat load is present), then the true DB can be adjusted using the method described by van der Walt and Hemp. A full listing of this program, also written in Microsoft™ Excel™ Visual Basic for Applications™, is included in Appendix A.

Using these procedures, it is then possible to:

- Calculate the effect of radiant heat loads (whether superimposed or merely the air temperature itself) on both the natural and aspirated wet bulb temperatures, and the natural and aspirated dry bulb temperatures,
- Calculate the effect of any wind speed on both the natural and aspirated wet bulb temperatures, and the natural and aspirated dry bulb temperatures,
- Convert psychrometric wet and dry bulb temperatures into values suitable for calculation of WBGT.

Figure 1 shows the difference between WBn and WBt for six different thermal environments, for wind speeds from nil to 4 m/s:

- Hot, humid with no superimposed radiant heat load (26^0 WBt, 28^0 DBt, MRT=DBt),
- Hot, dry with no superimposed radiant heat load (26^0 WBt, 34^0 DBt, MRT=DBt),

- Hot, humid with a superimposed radiant heat load (26^0 WBt, 28^0 DBt, 38^0 MRT),
- Hot, dry with a superimposed radiant heat load (26^0 WBt, 34^0 DBt, 44^0 MRT),
- Cold, dry with no superimposed radiant heat load (12^0 WBt, 16^0 DBt, 16^0 MRT),
- Cold, dry with a superimposed negative radiant heat load (12^0 WBt, 16^0 DBt, 26^0 MRT).

Note the following points:

- The considerable discrepancy between WBn and WBt as the superimposed radiant heat load increases or decreases from the DB. Note also that this discrepancy reduces as the wind speed increases. This is to be expected and is due to the face that convection and evaporation both increase as wind speed increases, which drives the temperature on the bulb to a value closer to WBt.
- That the discrepancy between WBn and WBt also increases as the gap between the WB and DB increases. This means that whereas ignoring any correction to the WBn may be acceptable in non-mechanised mines where the WB-DB gap is generally small, this will not be the case in mechanised mines where this gap is much larger, and where a significant superimposed radiant heat load may also be present.
- That a hot, humid environment with a high MRT (MRT = DB + 10^0 C) is unlikely to occur in practice, as the moisture vapour in the air absorbs thermal radiation. The DB will increase at the expense of the radiant heat transfer between the bulb and the radiation source.
- The WBn becomes slightly less (typically 0.1^0 C) that the WBt when subject to high superimposed radiant heat loads and high wind speeds. This is clearly not possible, but the error is small and probably reflects minor inaccuracies in the formulas for heat transfer coefficients.

Figure 2 shows the effect of a superimposed radiant heat load on the DBt, for wind speeds from nil to 4 m/s. Again, note that DBn is heavily influenced by a superimposed radiant heat load, but that this effect is reduced at higher wind speeds.

Reducing the effects of radiant heat load

The effects of radiant heat exchange on a DB temperature sensor can be minimised by:

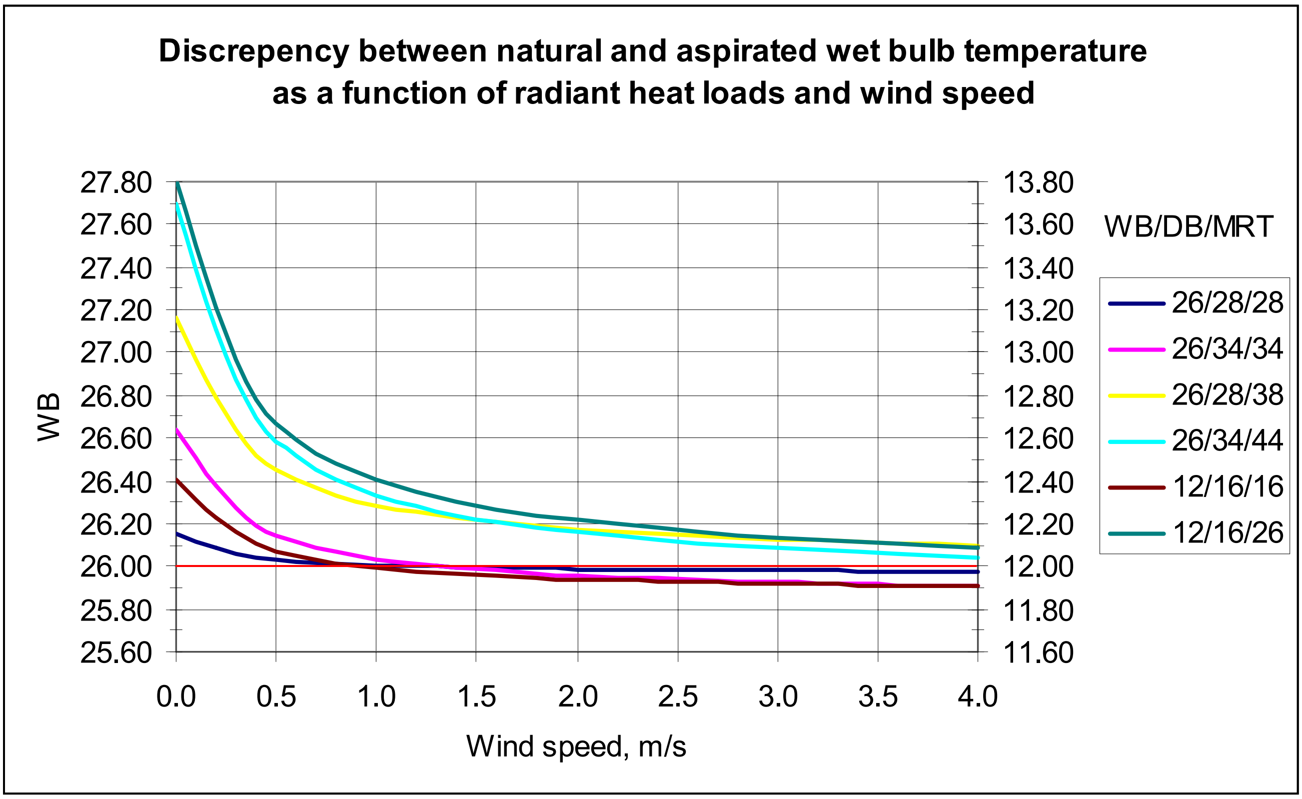
- Making the bulb as small as possible, as the convective heat transfer coefficient increases as the size decreases, while the radiant heat transfer is constant. The smaller sensor also reduces the time constant, i.e. the time for the temperature to stabilise,
- Using a radiation shield (an open, polished, aluminium cylinder) around the sensor,
- Using a sensor with a low-emittance surface, or
- Increasing the air velocity around the sensor.

Whilst most ventilation practitioners recognise the importance of reading the WB temperature as soon as a whirling psychrometer stops moving, in situations where there is a significant superimposed radiant heat load, it can be seen that it is also important to whirl the psychrometer before reading the DB temperature.

Summary

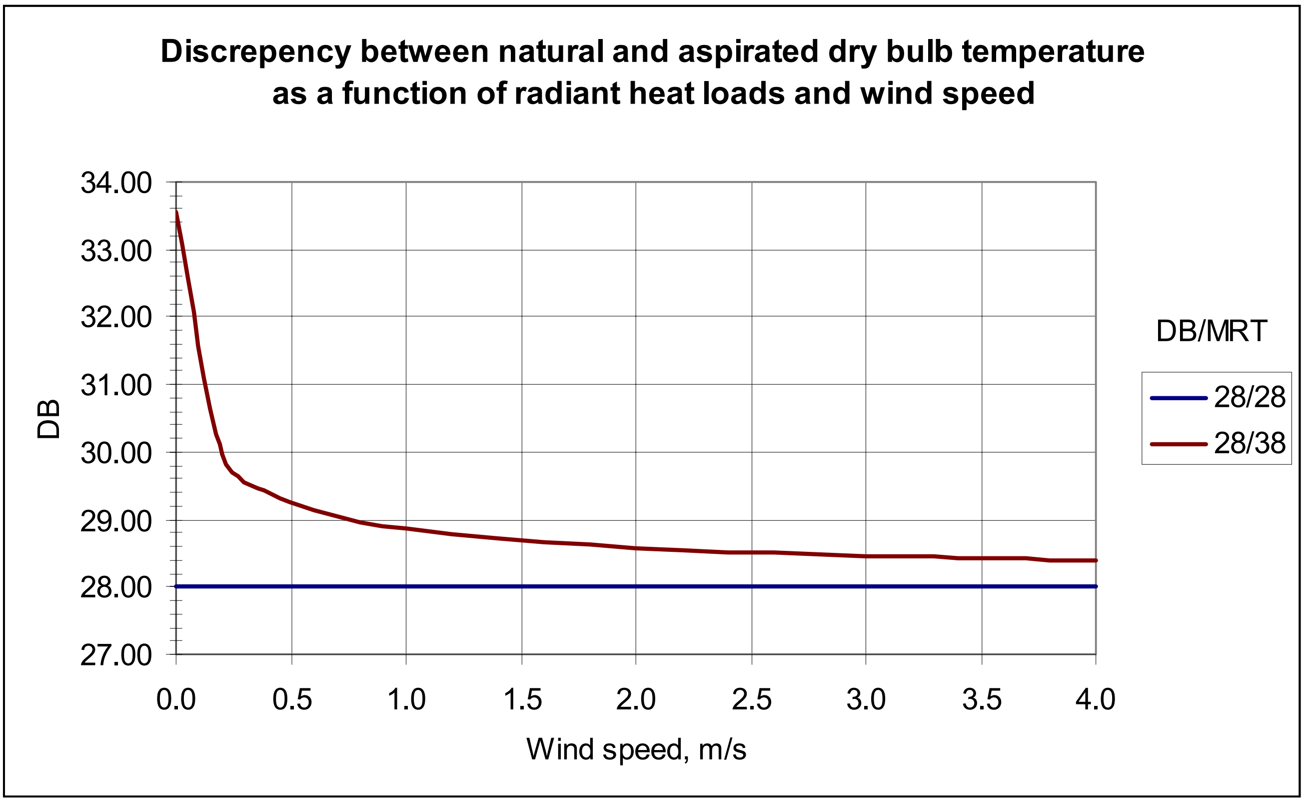
It has been shown that there can be significant differences between the natural and thermodynamic wet bulb temperature. Equations to correct both the aspirated wet bulb and natural dry bulb temperature for the effects of radiant heat load are developed. These formulations should be used when the WBGT needs to be assessed from standard psychrometric measurements. Moreover, the aspirated wet bulb temperature obtained from a whirling psychrometer should be corrected using these equations in situations where the dry bulb temperature, or the MRT, is significantly above the wet bulb temperature. It has also been demonstrated that, when significant radiant heat loads exist, the dry bulb temperature should also be obtained from a whirling psychrometer or corrected using equations in this paper.

Figure 1



Brake D J. Calculation of the natural (unventilated) wet bulb temperature, psychrometric dry bulb temperature and Wet Bulb Globe Temperature from standard psychrometric measurements. J Mine Vent Soc of Sth Africa. Oct-Dec 2001

Figure 2


Discrepency between natural and aspirated dry bulb temperature
as a function of radiant heat loads and wind speed
34.00
33.00
32.00
31.00
30.00
29.00
28.00
27.00
DB
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Wind speed, m/s
DB/MRT
28/28
28/38

References:

American Conference of Government Industrial Hygienists: Thermal Stress. In: TLVs and BEIs: Threshold limit values for chemical substances and physical agents and biological exposure indices, pp. 180-188. ACGIH, Cincinnati, OH (2000).

American Society of Heating, Refrigeration and Air-conditioning Engineers: ASHRAE Fundamentals (SI edition), pp. 14.26. ASHRAE, Atlanta, GA (1997).

Kerslake, D M, 1972. The Stress of Hot Environments. Cambridge: Cambridge University Press, p 67.

McPherson, M J, 1993. Subsurface Ventilation and Environmental Engineering. (Chapman and Hall)

Parsons K C, 1993. Human Thermal Environments. Taylor & Francis, p 174.

Van der Walt, N T and Hemp, R, 1989. Thermometry and Temperature measurements in *Environmental Engineering in South African Mines*. Chp 17. The Mine Ventilation Society of South Africa.

Whillier, A, 1989. Heat Transfer in *Environmental Engineering in South African Mines*. Chp 19. The Mine Ventilation Society of South Africa.

Appendix: Functions to calculate NWB and associated parameters from standard psychrometric parameters

```
Function fPsyNaturalWB(WBa, DB, BaroP, Windspeed, Optional MRT)  ' deg C
'   Converts a ventilated or "aspirated" WB (WBa) into a "natural" or unventilated WB
'   Assumes the DB is the true thermodynamic DB, i.e. the air temperature and is unaffected
'       by radiation. If this is not so, then the DB should be adjusted to remove the thermal
'       radiation effects before calling this procedure.
'   If the wick is shielded from radiation, then the MRT should be the same as the DB
'   Assumes the wick of the natural WB sensor is fully wet
'   All temperatures are degrees C, wind speed in m/s relative to the bulb
'   The method of solution is generally as per Env in SA Mines (BB), pp 427-429
'   Supplemented with some information from Subsurface Vent & Env Eng (McP)
Const AccuracyReqd = 0.02   ' This is the acceptable difference in heat gain and heat loss on the wick, W/m2
Const LatentHeatEvapWater = 2455000 ' J/kg The latent heat of evap of water, average value
Const CombinedViewEmissivityFactor = 0.8 * 0.95 ' Combined view (0.8) and emissivity (0.95) factor of slender wick/thermometer
'   The view factor is from EESAM p 427; the emissivity factor is from McP p 539
Const AbsZero = 273.15  ' To convert deg C to K
Const StefanBoltzmannConst = 0.0000000567   ' W/(m2.K)
Const BulbDia = 0.004   ' assumes WBn sensor is 4 mm diameter
Const AirThermalConductivity = 0.028  ' W/(m.K): BB p 470 Table 1
Dim WBn_guess  ' the current "guesstimate" of the natural WB
Dim HeatDiff    ' the "error" between the heat gain from convection and the
'               heat loss from evaporation at the WBn_guess, W/m2
Dim Counter ' This is used to ensure an infinite loop is trapped, if it were ever to occur
```

```
Dim AmbientVapPress ' the ambient vapour pressure in kPa
Dim HeatGainOnWick, HeatLossFromWick    ' W/m2
Dim Slope   ' Ratio, non-dimensional
Dim ConvHeatTferCoeff, RadHeatTferCoeff  ' W/(m2.K)
Dim EvapHeatTferCoeff       ' W/(m2.Pa)
Dim MoistCont   ' kg/kg dry air
Dim SpecificVol ' m3/kg dry air
Dim AirDensity  ' kg "vair"/m3 "vair"
On Error GoTo ErrorHandler  ' If a runtime error occurs, trap it
'   Note that the WBn must lie at some point between the WBa and the DB
'   The WBn is typically no more than about 1 to 2 deg C above the WBa
'   The difference between the DB (which will be above both the WBa and WBn) and the WBn
'       will be the driving force for convective heat transfer (which will therefore be a heat gain on the wick).
'   The difference between the ambient vapour pressure and the saturated vapour pressure at the WBn
'       will be the driving force for evaporative heat transfer (which will therefore be a heat loss on the wick).
'   The WBn is initially unknown, but note that at equilibrium, the heat gain
'       from convection must equal the heat loss from evaporation
'   Check for invalid data (other checks can be added)
If IsMissing(MRT) Then MRT = DB ' If MRT is omitted, then assume same as DB
If WBa > DB Or Windspeed < 0 Or (BaroP < 80 Or BaroP > 130) Then _
   GoTo ErrorHandler
'   If the wind speed is nil, then increase it to 0.1 m/s to avoid problems
If Windspeed < 0.1 Then Windspeed = 0.1
BaroP = BaroP * 1000 ' convert kPa to Pa
```

```
'  Calculate the vapour pressure in the ambient air
AmbientVapPress = fPsyVapPressLessAcc(WBa, DB, BaroP)   ' Pa
'  Calculate the air density, kg/m3 using 'less accurate eqns': BB p 455, Note BB is kPa
MoistCont = 0.622 * AmbientVapPress / (BaroP - AmbientVapPress)
SpecificVol = 0.287 * (AbsZero + DB) / ((BaroP - AmbientVapPress) / 1000)
AirDensity = (1 + MoistCont) / SpecificVol
'  Select an initial guess for the WBn as being 2 deg C above the WBa
'     or the DB, whichever is the lower
WBn_guess = Application.Min(WBa + 2, DB)
'  Convective heat transfer eqn from BB p 427, 478 and 480
'  Note that heat gain to the wick is treated as positive
'  Use whichever heat transfer coefficient is larger, natural or forced.
'  Note that natural convection has no wind speed term and is quite low.
ConvHeatTferCoeff = Application.Max(1.4 * (DB - WBn_guess) ^ (1 / 3), _
   0.2 * (67000 * Windspeed * BulbDia * AirDensity / 1.2) ^ 0.6 * AirThermalConductivity / BulbDia)
'  Radiative heat transfer eqn from BB p 473
'  Note that heat gain to the wick is treated as positive
RadHeatTferCoeff = CombinedViewEmissivityFactor * 4 * StefanBoltzmannConst * _
      ((WBn_guess + MRT) / 2 + AbsZero) ^ 3
'  Evaporative heat transfer eqn from BB p 427. Refer also McP eqn 15A.29 p 581
'  Note that heat loss from the wick is treated as positive
EvapHeatTferCoeff = 0.0007 * ConvHeatTferCoeff * LatentHeatEvapWater / BaroP  ' 0.00063
'  Calculate the difference between convective and radiative heat gain at the WBa and the WBn_guess
'  Since the WBa is always lower than WBn_guess, which in turn is lower than DB,
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```
'       this diff in convective heat gain will always be positive.
'   For radiation, the MRT can be higher or lower than the WBn_guess, however, it normally is higher.
HeatGainOnWick = (ConvHeatTferCoeff * (DB - WBa) - ConvHeatTferCoeff * (DB - WBn_guess)) _
        + (RadHeatTferCoeff * (MRT - WBa) - RadHeatTferCoeff * (MRT - WBn_guess))
'   Calculate the difference between evap heat loss at the WBa and the WBn_guess
'   Since the WBa is always lower than WBn_guess, which in turn is lower than DB,
'       and since the vapour pressure increases as the WB increases, if the DB and BaroP remain constant,
'       this diff in evaporative heat loss (not gain) will always be positive
HeatLossFromWick = EvapHeatTferCoeff * (fPsyVapPressLessAcc(WBn_guess, WBn_guess, BaroP) - AmbientVapPress) - _
    EvapHeatTferCoeff * (fPsyVapPressLessAcc(WBa, WBa, BaroP) - AmbientVapPress)
'   Calculate the "slope", "gain" or "proportionality constant" for the
'   SensibleHeatGain v EvapHeatloss curve in the region near the WBa.
'   In effect, this is the net heat gain per unit change in the temperature of the wick
'   It is not a true constant as the curve isn't quite a straight line,
'       but both are close approximations to a straight line.
'   This "slope" is only used to speed up the iteration and does not affect
'       the accuracy of the final solution.
Slope = HeatGainOnWick / HeatLossFromWick
'   Now iterate until a value of WBn_guess is found at which a heat balance occurs
Do
    HeatDiff = ConvHeatTferCoeff * (DB - WBn_guess) _
        + RadHeatTferCoeff * (MRT - WBn_guess) _
        - EvapHeatTferCoeff * (fPsyVapPressLessAcc(WBn_guess, WBn_guess, BaroP) - AmbientVapPress)
'   Proportionally adjust the WB by the HeatDiff x Slope / ConvHeatTferCoeff
```

```
    WBn_guess = WBn_guess + HeatDiff * Slope / (ConvHeatTferCoeff + RadHeatTferCoeff)
    Counter = Counter + 1
Loop While Abs(HeatDiff) > AccuracyReqd And Counter < 100
If Counter >= 100 Then GoTo ErrorHandler   ' if no solution in 100 iterations
fPsyNaturalWB = WBn_guess
Exit Function
ErrorHandler:
    fPsyNaturalWB = -1 ' return -1 if there is a problem
End Function
```

```
Private Function fPsyVapPressLessAcc(WB, DB, BaroP) ' in Pa
'   Uses eqn from EESAM p 455 eqn 1
'   Not as accurate as other formulations, but 0.1% of the more accurate eqns over range
'       of 0 deg to 60 deg C
'   WB, DB in deg C, BaroP in Pa
Const A = 0.000644
Dim Pws
Pws = 0.6105 * Exp(17.27 * WB / (237.3 + WB)) ' kPa
fPsyVapPressLessAcc = (Pws - (A * (BaroP / 1000) * (DB - WB))) * 1000 ' in Pa
End Function
```

```
Function fPsyDBwithRadLoad(DB, MRT, Windspeed)
'   refer BB p 427
Const CombinedViewEmissivityFactor = 0.8 * 0.95 ' Combined view (0.8) and emissivity (0.95) factor of slender wick/thermometer
'   The view factor is from EESAM p 427; the emissivity factor is from McP p 539
Const BulbDia = 0.004   ' assumes WBn sensor is 4 mm diameter
Const AirThermalConductivity = 0.028  ' W/(m.K): BB p 470 Table 1
Const AirDensity = 1.2 ' kg "vair"/m3 "vair"
Const StefanBoltzmannConst = 0.0000000567   ' W/(m2.K)
Const AbsZero = 273.15  ' To convert deg C to K
Dim ConvHeatTferCoeff, RadHeatTferCoeff  ' W/(m2.K)
'   Convective heat transfer eqn from BB p 427, 478 and 480
'   Note that heat gain to the wick is treated as positive
'   Use whichever heat transfer coefficient is larger, natural or forced.
'   Note that natural convection has no wind speed term and is quite low.
ConvHeatTferCoeff = Application.Max(1.4 * (MRT - DB) ^ (1 / 3), _
   0.2 * (67000 * Windspeed * BulbDia * AirDensity / 1.2) ^ 0.6 * AirThermalConductivity / BulbDia)
'   Radiative heat transfer eqn from BB p 473
'   Note that heat gain to the wick is treated as positive
RadHeatTferCoeff = CombinedViewEmissivityFactor * 4 * StefanBoltzmannConst * _
      ((MRT + DB) / 2 + AbsZero) ^ 3
fPsyDBwithRadLoad = DB + 1 / (1 + ConvHeatTferCoeff / _
   (CombinedViewEmissivityFactor * RadHeatTferCoeff)) * (MRT - DB)
End Function
```