Adiabatic saturation and thermodynamic wet bulb temperature

Adiabatic saturation temperature is defined as that temperature at which water, by evaporating into air, can bring the air to saturation at the same temperature adiabatically. An adiabatic saturator is a device using which one can measure theoretically the adiabatic saturation temperature of air.

As shown in Fig.2.1 an adiabatic saturator is a device in which air flows through an infinitely long duct containing water. As the air comes in contact with water in the duct, there will be heat and mass transfer between water and air. If the duct is infinitely long, then at the exit, there would exist perfect equilibrium between air and water at steady state. Air at the exit would be fully saturated and its temperature is equal to that of water temperature. The device is adiabatic as the walls of the chamber are thermally insulated. In order to continue the process, make-up water has to be provided to compensate for the amount of water evaporated into the air. The temperature of the make-up water is controlled so that it is the same as that in the duct.

After the adiabatic saturator has achieved a steady-state condition, the temperature indicated by the thermometer immersed in the water is the *thermodynamic wet-bulb temperature*. The thermodynamic wet bulb temperature will be less than the entering air DBT but greater than the dew point temperature.

Certain combinations of air conditions will result in a given sump temperature, and this can be defined by writing the energy balance equation for the adiabatic saturator. Based on a unit mass flow rate of dry air, this is given by:

$$h_1 = h_2 - (W_2 - W_1)h_f \qquad \text{.................................. (2.21)}$$

where h_f is the enthalpy of saturated liquid at the sump or thermodynamic wet-bulb temperature, h_1 and h_2 are the enthalpies of air at the inlet and exit of the adiabatic saturator, and W_1 and W_2 are the humidity ratio of air at the inlet and exit of the adiabatic saturator, respectively.

It is to be observed that the thermodynamic wet-bulb temperature is a thermodynamic property, and is independent of the path taken by air. Assuming the humid specific heat to be constant, from the enthalpy balance, the thermodynamic wet-bulb temperature can be written as:

$$t_2 = t_1 - \frac{h_{fg,2}}{c_{pm}}(w_2 - w_1) \qquad \text{.................................. (2.22)}$$

where $h_{fg,2}$ is the latent heat of vaporization at the saturated condition 2. Thus measuring the dry bulb (t_1) and wet bulb temperature (t_2) one can find the inlet humidity ratio (W_1) from the above expression as the outlet saturated humidity ratio (W_2) and latent heat heat of vaporizations are functions of t_2 alone (at fixed barometric pressure).

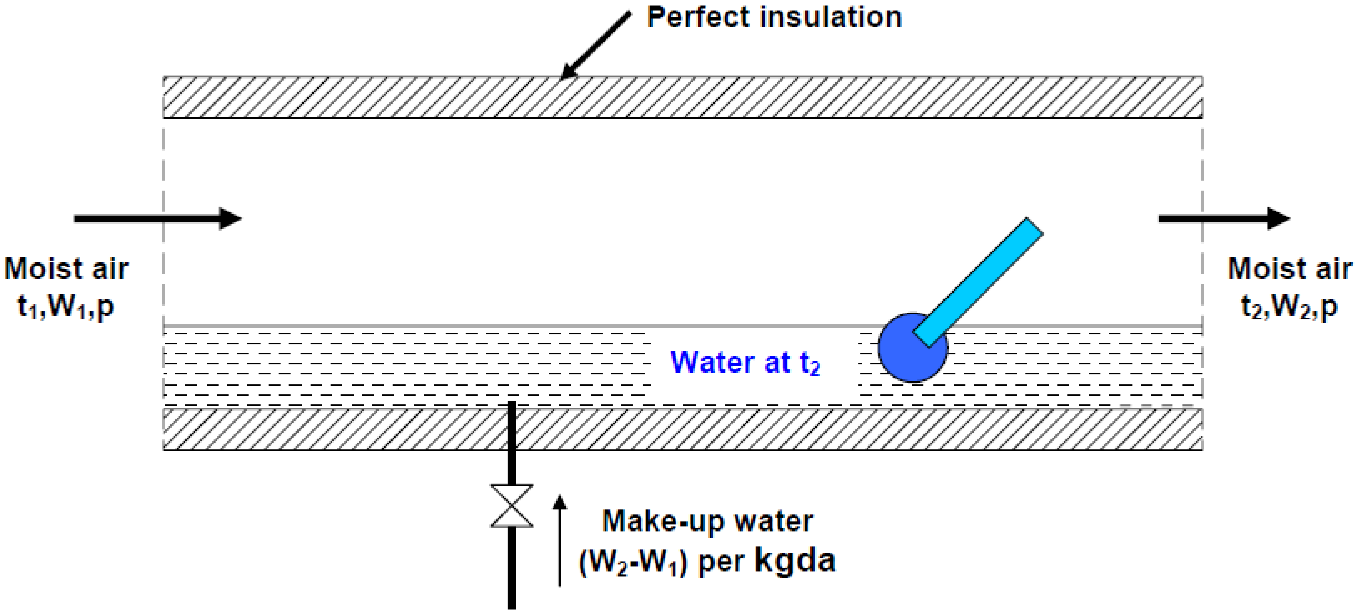

Fig.2.1 The process of adiabatic saturation of air

Example:

Moist air at 26°C dry bulb and 16°C wet bulb enters to adiabatic device. The air leaving the device completely saturated at standard atmospheric pressure (P_{atm}=101.325 kPa)

Water flow at 16°C, Calculate:

a) moisture content at the entry and exit W_1 & W_2

b) degree of saturation at the entry μ_1

c) specific volume at the entry and exit υ_1 & υ_2

d) enthalpy at the entry and exit h_1 & h_2

Solution:

a) From Table A-2 at t_w= 16°C, P_{wss}= 1.818 kPa

P_v= 1.818 – 101.325 x6.66 x10^{-4}(26 – 16) = 1.1432 kPa

W_1= 0.622(1.1432)/(101.325 – 1.1432) = 0.00709 kg/kg dry air

W_2= W_{sw} = 0.622(1.818)/(101.325 – 1.818) = 0.01136 kg/kg dry air

b) $\mu =[W/W_{ss1}]_{t, p}$

where (W_{ss}) is the moisture content for saturated air at entry state

From Table A-2 at t= 26°C, P_{ss}= 3.360 kPa

W_{ss1}= 0.622(3.360)/(101.325 – 3.360) = 0.0213 kg/kg dry air

Then; μ = (0.00709)/(0.0213) = 0.333 = 33.3%

c) $P_{a1} = P_B – P_1$ = 101.325 – 1.1432 = 100.182 kPa

$P_{a2} = P_B – P_2$ = 101.325 – 1.818 = 99.507 kPa

$\upsilon_{a1} = R_a T_{a1}/ P_{a1}$ = 0.287 (273+26)/(100.183) = 0.857 m^3/kg dry air

$\upsilon_{a2} = R_a T_{a2}/ P_{a2}$ = 0.287(273 +16)/(99.507) = 0.833 m^3/kg dry air

d) $h = (1.007\ t_d – 0.026) + W(2501 + 1.84\ t_d)$

h_1 = (1.007 x 26 – 0.026) + 0.00709(2501 + 1.84 x 26) = 44.23 kJ/kg dry air

h_2 = (1.007 x 16 – 0.026) + 0.01136(2501 + 1.84 x 16) = 44.83 kJ/kg dry air

Also, can be calculate (h_2) from Eqn.(2.21)

$h_2 = h_1 + (W_2 – W_1)\ h_f$

From Table A-2 at t = 16°C h_f = 67.19 kJ/kg

h_2 = 44.23 + (0.01136 – 0.00709) x 67.19 = 44.517 kJ/kg dry air

- ***Note here the enthalpy of the dry air decreases about 10 kJ/kg (from 26.208 to 16.138) while the enthalpy of water vapor is increases within the same amount 10 kJ/kg (from 18.071 to 28.745). This is an important fact in adiabatic saturation process.***

Exercises

1. The atmospheric condition of air are 25°C dry bulb temperature and moisture content of 0.01 kg/kg dry air. Find:

(a) partial pressure of vapor (b) relative humidity (c) dew point temperature.

[Ans. 0.016 bar, 50.6%, 14.1°C]

2. A sling psychrometer reads 40°C dry bulb temperature and 28°C wet bulb temperature. Calculate the following:

(a) moisture content (b) relative humidity (c) vapor density in air

(d) dew point temperature (e) enthalpy of mixture per kg of dry air.

[Ans. 0.019 kg/kg of dry air, 40.7%, 0.0208 kg/m^3, 24°C, 88.38 kJ/kg dry air]

3. A sample of moist air has a dry bulb temperature of 25°C and a relative humidity of 50%. The barometric pressure is 740 mm of Hg. Calculate:

(a) partial pressure of water vapor and dry air (b) dew point temperature

(c) specific humidity (moisture content) (d) enthalpy of air

[Ans. 0.01583 bar, 14°C, 0.0101 kg/kg dry air, 50.81 kJ/kg dry air]

4. The moist air exists at a total pressure of 1.01325 bar and 25°C dry bulb temperature. If the degree of saturation is 50%, determine the following using steam tables:

(a) moisture content (b) dew point temperature (c) specific volume of moist air.

[Ans. 10.03 g/kg dry air, 14°C, 0.857 m^3/kg]

5. The atmospheric conditions of air are 35°C dry bulb temperature, 60% relative humidity and 1.01325 bar pressure. If 0.005 kg of moisture per kg of dry air is removed, the temperature becomes 25°C. Determine the final relative humidity and dew point temperature.

[Ans. 88.6%, 23°C]

6. An atmospheric air enters the adiabatic saturator at 33°C dry bulb temperature and23°C wet bulb temperature. The barometric pressure is 740 mm Hg. Determine the moisture content and vapor pressure at 33°C.

[Ans. 0.012 kg/kg dry air, 13 mm Hg]

7. Air at 40°C DBT and 15% RH is passed through the adiabatic humidifier at the rate of 200 m^3/min. The outlet conditions of air are 25°C DBT and 20°C WBT. Find:

(a) dew point temperature (b) relative humidity of exit air

(c) amount of water vapor added to the air per minute.

[Ans. 17.8°C, 65%, 1.26 kg/min]

8. The atmospheric air has 35°C DBT and 50% RH and standard atmospheric pressure. Find:

(a) wet bulb temperature (b) moisture content (c) dew point temperature (d) enthalpy

[Ans. 26.20°C, 0.0178 $kg/kg_{d.a}$, 23°C, 81 kJ/kg]

9. An atmospheric air at 15°C DBT and 80% RH is supplied to the heating chamber at the rate of 100 m^3/min.. The leaving air has a temperature of 22°C without change in its moisture content. Determine the heat added to the air per min. and final relative humidity of the air.

[Ans. 865.3 kJ/min, 53%]

10. Moist air at 20°C DBT and the barometric pressure is 82.5 kPa. Calculate the enthalpy and the degree of saturation, if the air was:

(a) saturated (b) at a relative humidity of 50%

[Ans. 66.124 kJ/kg, 1.0 and 42.792 kJ/kg, 0.493]

Chapter Three

The Psychrometry of Air Conditioning Processes

3.1 The Psychrometric Chart

This provides a picture of the way in which the state of moist air alters as an air conditioning process takes place or a physical change occurs. Familiarity with the psychrometric chart is essential for a proper understanding of air conditioning.

Any point on the chart is termed a *state point*, the location of which, at a given barometric pressure, is fixed by any two of the psychrometric properties discussed in chapter 2. It is customary and convenient to design charts at a constant barometric pressure because barometric pressure does not alter greatly over much of the inhabited surface of the earth. When the barometric pressure is significantly different from the standard adopted for the chart or psychrometric tables to hand, then the required properties can be calculated using the equations derived earlier.

The British standard is that adopted by the Chartered Institution of Building Services Engineers for their Tables of Psychrometric Data and for their psychrometric chart. It is 101.325 kPa. The American standard is also 101.325 kPa and this value is used by the American Society of Heating, Refrigeration and Air Conditioning Engineers.

The psychrometric chart published by the CIBSE uses two fundamental properties, mass and energy, in the form of moisture content and enthalpy, as co-ordinates. As a result, mixture states lie on the straight line which joins the state points of the two constituents. Lines of constant dry-bulb temperature are virtually straight but divergent, only the isotherm for 30°C being vertical. The reason for this is that to preserve the usual appearance of a psychrometric chart, in spite of choosing the two fundamental properties as co-ordinates, the co-ordinate axes are oblique, not rectangular. Hence, lines of constant enthalpy are both straight and parallel, as are lines of constant moisture content. Since both these properties are taken as linear, the lines of constant enthalpy are equally spaced as are, also, the lines of constant moisture content. This is not true of the lines of constant humid volume and constant wet-bulb temperature, which are slightly curved and divergent. Since their curvature is only slight in the region of practical use on the chart, they can be regarded as straight without significant error resulting. In the sketches of psychrometric charts used throughout this text to illustrate changes of state, only lines of percentage saturation are shown curved. All others are shown straight, and dry-bulb isotherms are shown as vertical, for convenience.

The chart also has a protractor which allows the value of the ratio of the sensible heat gain to the total heat gain to be plotted on the chart. This ratio is an indication of the slope of the room ratio line and is of value in determining the correct supply state of the air that must be delivered to a conditioned space. The zero value for the ratio is parallel to the isotherm for 30°C because the enthalpy of the added vapour depends on the temperature at which evaporation takes place, it being assumed that most of the latent heat gain to the air in a conditioned room is by evaporation from the skin of the occupants and that their skin surface temperature is about 30°C.

Figure 3.1 shows a state point on a psychrometric chart.

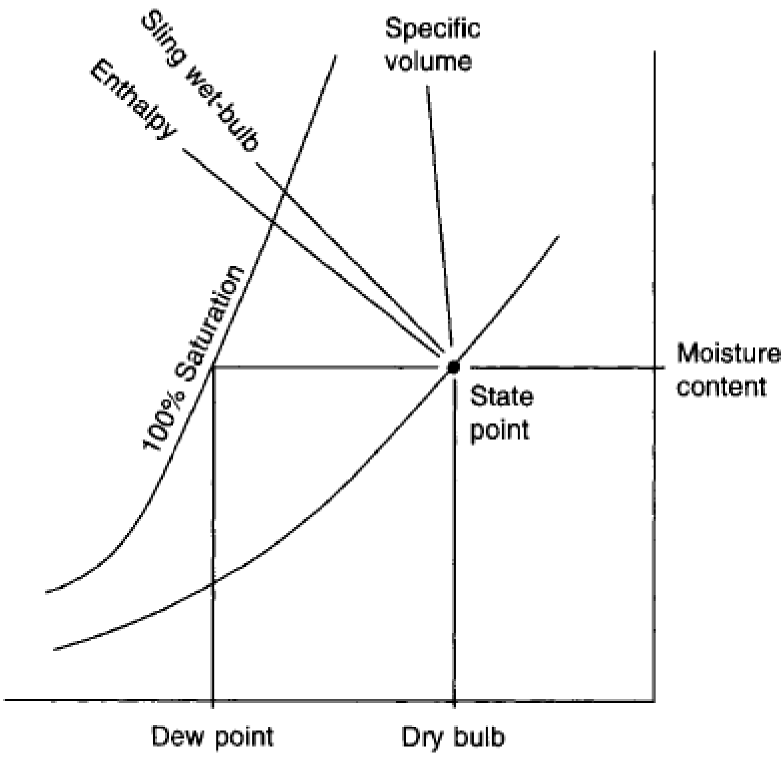

Fig. 3.1 The variables shown on the psychrometric chart.

3.2 Mixtures

Figure 3.2 shows what happens when two airstreams meet and mix adiabatically. Moist air at state 1 mixes with moist air at state 2, forming a mixture at state 3. The principle of the conservation of mass allows two mass balance equations to be written:

$m_{a1} + m_{a2} = m_{a3}$ for the dry air and

$g_1 m_{a1} + g_2 m_{a2} = g_3 m_{a3}$ for the associated water vapour

Hence

$$(g_1 - g_3)m_{a1} = (g_3 - g_2)m_{a2}$$

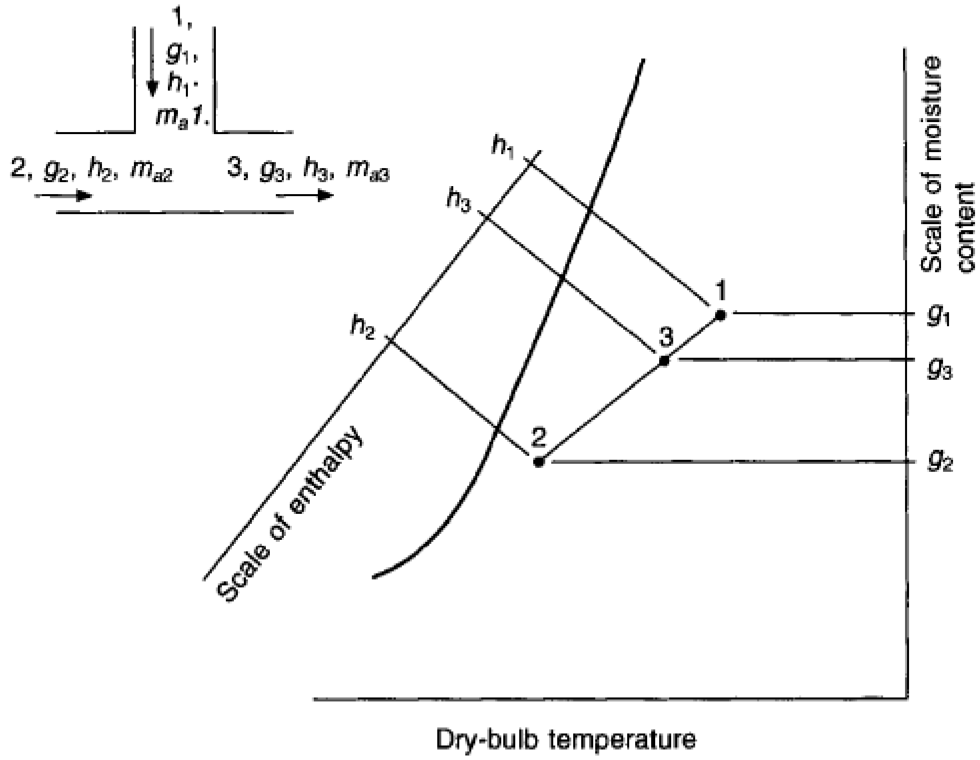

Fig. 3.2 The adiabatic mixing of two airstreams.

Therefore

$$\frac{g_1 - g_3}{g_3 - g_2} = \frac{m_{a2}}{m_{a1}}$$

Similarly, making use of the principle of the conservation of energy,

$$\frac{h_1 - h_3}{h_3 - h_2} = \frac{m_{a2}}{m_{a1}}$$

From this it follows that the three state points must lie on a straight line in a mass–energy co-ordinate system. When two airstreams mix adiabatically, the mixture state lies on the straight line which joins the state points of the constituents, and the position of the mixture state point is such that the line is divided inversely as the ratio of the masses of dry air in the constituent airstreams.

EXAMPLE 3.1

Moist air at a state of 60°C dry-bulb, 32.1°C wet-bulb (sling) and 101.325 kPa barometric pressure mixes adiabatically with moist air at 5°C dry-bulb, 0.5°C wet-bulb (sling) and 101.325 kPa barometric pressure. If the masses of dry air are 3 kg and 2 kg, respectively, calculate the moisture content, enthalpy and dry-bulb temperature of the mixture.

Answer

g_1 = 18.400 g per kg dry air

g_2 = 2.061 g per kg dry air
h_1 = 108.40 kJ per kg dry air
h_2 = 10.20 kJ per kg dry air

The principle of the conservation of mass demands that

$$g_1 m_{a1} + g_2 m_{a2} = g_3 m_{a3}$$
$$= g_3(m_{a1} + m_{a2})$$

hence

$$g_3 = \frac{g_1 m_{a1} + g_2 m_{a2}}{m_{a1} + m_{a2}}$$
$$= \frac{18.4 \times 3 + 2.061 \times 2}{3 + 2}$$
$$= \frac{59.322}{5}$$
$$= 11.864 \text{ g per kg dry air}$$

Similarly, by the principle of the conservation of energy,

$$h_3 = \frac{h_1 m_{a1} + h_2 m_{a2}}{m_{a1} + m_{a2}}$$
$$= \frac{108.40 \times 3 + 10.20 \times 2}{3 + 2}$$
$$= 69.12 \text{ kJ per kg dry air}$$

To determine the dry-bulb temperature, the following practical equation must be used

$$h = (1.007t - 0.026) + g(2501 + 1.84t)$$

Substituting the values calculated for moisture content and enthalpy, this equation can be solved for temperature:

$$h = 69.12 = (1.007t - 0.026) + 0.011\,86(2501 + 1.84t)$$

$$t = \frac{39.48}{1.029} = 38.4\text{°C}$$

On the other hand, if the temperature were calculated by proportion, according to the masses of the dry air in the two mixing airstreams, a slightly different answer results:

$$t = \frac{3 \times 60 + 2 \times 5}{5}$$
$$= 38\text{°C}$$

EXAMPLE 3.2

A stream of moist air at a state of 21°C dry-bulb and 14.5°C wet-bulb (sling) mixes with another stream of moist air at a state of 28°C dry-bulb and 20.2°C wet-bulb (sling), the respective masses of the associated dry air being 3 kg and 1 kg. With the aid of CIBSE tables of psychrometric data calculate the dry-bulb temperature of the mixture (*a*) using the principles of conservation of energy and of mass and, (*b*), using a direct proportionality between temperature and mass.

3.3 Sensible heating and cooling

Sensible heat transfer occurs when moist air flows across a heater battery or over the coils of a sensible cooler. In the heater, the temperature of the medium used to provide the heat is not critical. The sole requirement for heat transfer is that the temperature shall exceed the final air temperature. In sensible cooling there is a further restriction: the lowest water temperature must not be so low that moisture starts to condense on the cooler coils. If such condensation does occur, through a poor choice of chilled water temperature, then the process will no longer be one of sensible cooling since dehumidification will also be taking place.

Figure 3.3 shows the changes of state which occur, sketched upon a psychrometric chart. The essence of both processes is that the change of state must occur along a line of constant moisture content. The variations in the physical properties of the moist air, for the two cases, are summarised below:

	Sensible heating	*Sensible cooling*
Dry-bulb	increases	decreases
Enthalpy	increases	decreases
Humid volume	increases	decreases
Wet-bulb	increases	decreases
Percentage saturation	decreases	increases
Moisture content	constant	constant
Dew point	constant	constant
Vapour pressure	constant	constant

EXAMPLE 3.3

Calculate the load on a battery which heats 1.5 $m^3 s^{-1}$ of moist air, initially at a state of 21°C dry-bulb, 15°C wet-bulb (sling) and 101.325 kPa barometric pressure, by 20 degrees. If low temperature hot water at 85°C flow and 75°C return is used to achieve this, calculate the flow rate necessary, in kilograms of water per second.