CHAPTER 13

Humidification and Water Cooling

13.1. INTRODUCTION

In the processing of materials it is often necessary either to increase the amount of vapour present in a gas stream, an operation known as *humidification*; or to reduce the vapour present, a process referred to as *dehumidification*. In humidification, the vapour content may be increased by passing the gas over a liquid which then evaporates into the gas stream. This transfer into the main stream takes place by diffusion, and at the interface simultaneous heat and mass transfer take place according to the relations considered in previous chapters. In the reverse operation, that is dehumidification, partial condensation must be effected and the condensed vapour removed.

The most widespread application of humidification and dehumidification involves the air–water system, and a discussion of this system forms the greater part of the present chapter. Although the drying of wet solids is an example of a humidification operation, the reduction of the moisture content of the solids is the main objective, and the humidification of the air stream is a secondary effect. Much of the present chapter is, however, of vital significance in any drying operation. Air conditioning and gas drying also involve humidification and dehumidification operations. For example, moisture must be removed from wet chlorine so that the gas can be handled in steel equipment which otherwise would be severely corroded. Similarly, the gases used in the manufacture of sulphuric acid must be dried or dehumidified before entering the converters, and this is achieved by passing the gas through a dehydrating agent such as sulphuric acid, in essence an absorption operation, or by an alternative dehumidification process discussed later.

In order that hot condenser water may be re-used in a plant, it is normally cooled by contact with an air stream. The equipment usually takes the form of a tower in which the hot water is run in at the top and allowed to flow downwards over a packing against a countercurrent flow of air which enters at the bottom of the cooling tower. The design of such towers forms an important part of the present chapter, though at the outset it is necessary to consider basic definitions of the various quantities involved in humidification, in particular *wet-bulb* and *adiabatic saturation temperatures*, and the way in which humidity data are presented on charts and graphs. While the present discussion is devoted to the very important air-water system, which is in some ways unique, the same principles may be applied to other liquids and gases, and this topic is covered in a final section.

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13.2. HUMIDIFICATION TERMS

13.2.1. Definitions

The more important terms used in relation to humidification are defined as follows:

Humidity ($\mathcal{H}$)	mass of vapour associated with unit mass of dry gas
Humidity of saturated gas ($\mathcal{H}_0$)	humidity of the gas when it is saturated with vapour at a given temperature
Percentage humidity	$100(\mathcal{H}/\mathcal{H}_0)$
Humid heat (s)	heat required to raise unit mass of dry gas and its associated vapour through unit temperature difference at constant pressure, or:

$$s = C_a + \mathcal{H}C_w$$

where C_a and C_w are the specific heat capacities of the gas and the vapour, respectively. (For the air-water system, the humid heat is approximately:

$$s = 1.00 + 1.9\mathcal{H} \text{ kJ/kg K.})$$

Humid volume	volume occupied by unit mass of dry gas and its associated vapour
Saturated volume	humid volume of saturated gas
Dew point	temperature at which the gas is saturated with vapour. As a gas is cooled, the dew point is the temperature at which condensation will first occur.
Percentage relative humidity	$\left(\dfrac{\text{partial pressure of vapour in gas}}{\text{partial pressure of vapour in saturated gas}} \right) \times 100$

The above nomenclature conforms with the recommendations of BS1339[1], although there are some ambiguities in the standard.

The relationship between the partial pressure of the vapour and the humidity of a gas may be derived as follows. In unit volume of gas:

$$\text{mass of vapour} \quad = \frac{P_w M_w}{\mathbf{R}T}$$

$$\text{and mass of non-condensable gas} \quad = \frac{(P - P_w)M_A}{\mathbf{R}T}$$

The humidity is therefore given by:

$$\mathcal{H} = \frac{P_w}{P - P_w}\left(\frac{M_w}{M_A}\right) \tag{13.1}$$

and the humidity of the saturated gas is:

$$\mathcal{H}_0 = \frac{P_{w0}}{P - P_{w0}}\left(\frac{M_w}{M_A}\right) \tag{13.2}$$

where P_w is the partial pressure of vapour in the gas, P_{w0} the partial pressure of vapour in the saturated gas at the same temperature, M_A the mean molecular weight of the dry gas, M_w the molecular mass of the vapour, P the total pressure, **R** the gas constant (8314 J/kmol K in SI units), and T the absolute temperature.

For the air–water system, P_w is frequently small compared with P and hence, substituting for the molecular masses:

$$\mathscr{H} = \frac{18}{29}\left(\frac{P_w}{P}\right)$$

The relationship between the percentage humidity of a gas and the percentage relative humidity may be derived as follows:

The percentage humidity, by definition $= 100\mathscr{H}/\mathscr{H}_0$

Substituting from equations 13.1 and 13.2 and simplifying:

$$\text{Percentage humidity} = \left(\frac{P - P_{w0}}{P - P_w}\right) \cdot \left(\frac{P_w}{P_{w0}}\right) \times 100$$

$$= \frac{(P - P_{w0})}{(P - P_w)} \times (\text{percentage relative humidity}) \qquad (13.3)$$

When $(P - P_{w0})/(P - P_w) \approx 1$, the percentage relative humidity and the percentage humidity are equal. This condition is approached when the partial pressure of the vapour is only a small proportion of the total pressure or when the gas is almost saturated, that is as $P_w \rightarrow P_{w0}$.

Example 13.1

In a process in which it is used as a solvent, benzene is evaporated into dry nitrogen. At 297 K and 101.3 kN/m^2, the resulting mixture has a percentage relative humidity of 60. It is required to recover 80 per cent of the benzene present by cooling to 283 K and compressing to a suitable pressure. What should this pressure be? The vapour pressure of benzene is 12.2 kN/m^2 at 297 K and 6.0 kN/m^2 at 283 K.

Solution

From the definition of percentage relative humidity (RH):

$$P_w = P_{w0}\left(\frac{RH}{100}\right)$$

At 297 K: $P_w = (12.2 \times 1000) \times \left(\frac{60}{100}\right) = 7320$ N/m^2

In the benzene–nitrogen mixture:

$$\text{mass of benzene} = \frac{P_w M_w}{RT} = \frac{(7320 \times 78)}{(8314 \times 297)} = 0.231 \text{ kg}$$

$$\text{mass of nitrogen} = \frac{(P - P_w)M_A}{RT} = \frac{[(101.3 - 732) \times 1000 \times 28]}{(8314 \times 297)} = 1.066 \text{ kg}$$

Hence the humidity is: $\mathscr{H} = \left(\frac{0.231}{1.066}\right) = 0.217$ kg/kg

In order to recover 80 per cent of the benzene, the humidity must be reduced to 20 per cent of the initial value. As the vapour will be in contact with liquid benzene, the nitrogen will be saturated with benzene vapour

and hence at 283 K:

$$\mathscr{H}_0 = \frac{(0.217 \times 20)}{100} = 0.0433 \text{ kg/kg}$$

Thus in equation 13.2:

$$0.0433 = \left(\frac{6000}{P - 6000}\right)\left(\frac{78}{28}\right)$$

from which:

$$P = 3.92 \times 10^5 \text{ N/m}^2 = 392 \text{ kN/m}^2$$

Example 13.2

In a vessel at 101.3 kN/m^2 and 300 K, the percentage relative humidity of the water vapour in the air is 25. If the partial pressure of water vapour when air is saturated with vapour at 300 K is 3.6 kN/m^2, calculate:

(a) the partial pressure of the water vapour in the vessel;
(b) the specific volumes of the air and water vapour;
(c) the humidity of the air and humid volume; and
(d) the percentage humidity.

Solution

(a) From the definition of percentage relative humidity:

$$P_w = P_{w0}\frac{RH}{100} = 3600 \times \left(\frac{25}{100}\right) = 900 \text{ N/m}^2 = 0.9 \text{ kN/m}^2$$

(b) In 1 m^3 of air:

$$\text{mass of water vapour} = \frac{(900 \times 18)}{(8314 \times 300)} = 0.0065 \text{ kg}$$

$$\text{mass of air} = \frac{[(101.3 - 0.9) \times 1000 \times 29]}{(8314 \times 300)} = 1.167 \text{ kg}$$

Hence: specific volume of water vapour at 0.9 kN/m^2 $= \left(\dfrac{1}{0.0065}\right) = 154 \text{ m}^3\text{/kg}$

specific volume of air at 100.4 kN/m^2 $= \left(\dfrac{1}{1.167}\right) = 0.857 \text{ m}^3\text{/kg}$

(c) Humidity: $\mathscr{H} = \left(\dfrac{0.0065}{1.1673}\right) = 0.0056 \text{ kg/kg}$

(Using the approximate relationship:

$$\mathscr{H} = \frac{(18 \times 900)}{(29 \times 101.3 \times 1000)} = 0.0055 \text{ kg/kg.})$$

∴ Humid volume = volume of 1 kg air + associated vapour = specific volume of air at 100.4 kN/m^2

$$= 0.857 \text{ m}^3\text{/kg}$$

(d) From equation 13.3:

$$\text{percentage humidity} = \frac{[(101.3 - 3.6) \times 1000]}{[(101.3 - 0.9) \times 1000]} \times 25$$

$$= 24.3 \text{ per cent}$$

13.2.2. Wet-bulb temperature

When a stream of unsaturated gas is passed over the surface of a liquid, the humidity of the gas is increased due to evaporation of the liquid. The temperature of the liquid falls below that of the gas and heat is transferred from the gas to the liquid. At equilibrium the rate of heat transfer from the gas just balances that required to vaporise the liquid and the liquid is said to be at the *wet-bulb temperature*. The rate at which this temperature is reached depends on the initial temperatures and the rate of flow of gas past the liquid surface. With a small area of contact between the gas and the liquid and a high gas flowrate, the temperature and the humidity of the gas stream remain virtually unchanged.

The rate of transfer of heat from the gas to the liquid can be written as:

$$Q = hA(\theta - \theta_w) \tag{13.4}$$

where Q is the heat flow, h the coefficient of heat transfer, A the area for transfer, and θ and θ_w are the temperatures of the gas and liquid phases.

The liquid evaporating into the gas is transferred by diffusion from the interface to the gas stream as a result of a concentration difference $(c_0 - c)$, where c_0 is the concentration of the vapour at the surface (mass per unit volume) and c is the concentration in the gas stream. The rate of evaporation is then given by:

$$W = h_D A (c_0 - c) = h_D A \frac{M_w}{RT} (P_{w0} - P_w) \tag{13.5}$$

where h_D is the coefficient of mass transfer.

The partial pressures of the vapour, P_w and P_{w0}, may be expressed in terms of the corresponding humidities $\mathscr{H}$ and $\mathscr{H}_w$ by equations 13.1 and 13.2.

If P_w and P_{w0} are small compared with P, $(P - P_w)$ and $(P - P_{w0})$ may be replaced by a mean partial pressure of the gas P_A and:

$$W = h_{D_A} A \frac{(\mathscr{H}_w - \mathscr{H})M_w}{RT} \cdot \left(P_A \frac{M_A}{M_w} \right)$$

$$= h_D A \rho_A (\mathscr{H}_w - \mathscr{H}) \tag{13.6}$$

where ρ_A is the density of the gas at the partial pressure P_A.

The heat transfer required to maintain this rate of evaporation is:

$$Q = h_D A \rho_A (\mathscr{H}_w - \mathscr{H})\lambda \tag{13.7}$$

where λ is the latent heat of vaporisation of the liquid.

Thus, equating equations 13.4 and 13.7:

$$(\mathscr{H} - \mathscr{H}_w) = -\frac{h}{h_D \rho_A \lambda}(\theta - \theta_w) \tag{13.8}$$

Both h and h_D are dependent on the equivalent gas film thickness, and thus any decrease in the thickness, as a result of increasing the gas velocity for example, increases both h and h_D. At normal temperatures, (h/h_D) is virtually independent of the gas velocity provided this is greater than about 5 m/s. Under these conditions, heat transfer by convection from the gas stream is large compared with that from the surroundings by radiation and conduction.

The wet-bulb temperature θ_w depends only on the temperature and the humidity of the gas and values normally quoted are determined for comparatively high gas velocities, such that the condition of the gas does not change appreciably as a result of being brought into contact with the liquid and the ratio (h/h_D) has reached a constant value. For the air–water system, the ratio $(h/h_D\rho_A)$ is about 1.0 kJ/kg K and varies from 1.5 to 2.0 kJ/kg K for organic liquids.

Example 13.3

Moist air at 310 K has a wet-bulb temperature of 300 K. If the latent heat of vaporisation of water at 300 K is 2440 kJ/kg, estimate the humidity of the air and the percentage relative humidity. The total pressure is 105 kN/m^2 and the vapour pressure of water vapour at 300 K is 3.60 kN/m^2 and 6.33 kN/m^2 at 310 K.

Solution

The humidity of air saturated at the wet-bulb temperature is given by:

$$\mathscr{H}_w = \frac{P_{w0}}{P - P_{w0}} \frac{M_w}{M_A} \qquad \text{(equation 13.2)}$$

$$= \left(\frac{3.6}{105.0 - 3.6}\right)\left(\frac{18}{29}\right) = 0.0220 \text{ kg/kg}$$

Therefore, taking $(h/h_D\rho_A)$ as 1.0 kJ/kg K, in equation 13.8:

$$(0.0220 - \mathscr{H}) = \left(\frac{1.0}{2440}\right)(310 - 300)$$

or:

$$\mathscr{H} = \underline{\underline{0.018 \text{ kg/kg}}}$$

At 310 K, $P_{w0} = 6.33 \text{ kN/m}^2$

In equation 13.2: $0.0780 = \dfrac{18P_w}{(105.0 - P_w)29}$

$\therefore$ $P_w = 2.959 \text{ kN/m}^2$

and the percentage relative humidity $= \dfrac{(100 \times 2.959)}{6.33} = \underline{\underline{46.7 \text{ per cent}}}$

13.2.3. Adiabatic saturation temperature

In the system just considered, neither the humidity nor the temperature of the gas is appreciably changed. If the gas is passed over the liquid at such a rate that the time of contact is sufficient for equilibrium to be established, the gas will become saturated and both phases will be brought to the same temperature. In a thermally insulated system, the total sensible heat falls by an amount equal to the latent heat of the liquid evaporated. As a result of continued passage of the gas, the temperature of the liquid gradually approaches an equilibrium value which is known as the *adiabatic saturation temperature*.

These conditions are achieved in an infinitely tall thermally insulated humidification column through which gas of a given initial temperature and humidity flows

countercurrently to the liquid under conditions where the gas is completely saturated at
the top of the column. If the liquid is continuously circulated round the column, and if
any fresh liquid which is added is at the same temperature as the circulating liquid, the
temperature of the liquid at the top and bottom of the column, and of the gas at the top,
approach the adiabatic saturation temperature. Temperature and humidity differences are a
maximum at the bottom and zero at the top, and therefore the rates of transfer of heat and
mass decrease progressively from the bottom to the top of the tower. This is illustrated
in Figure 13.1.
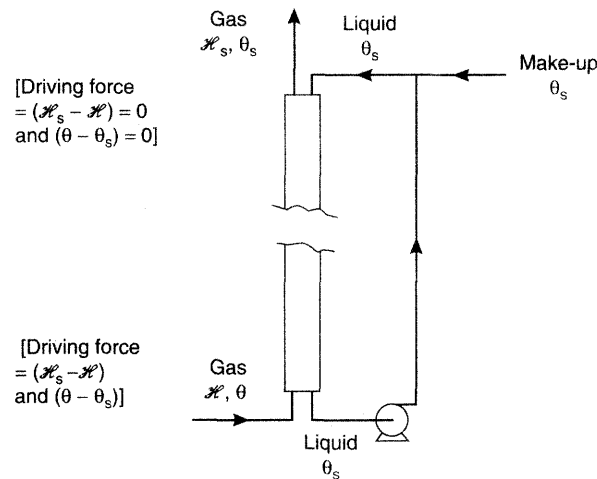
Figure 13.1.   Adiabatic saturation temperature θ_s

Making a heat balance over the column, it is seen that the heat of vaporisation of the
liquid must come from the sensible heat in the gas. The temperature of the gas falls from
θ to the adiabatic saturation temperature θ_s, and its humidity increases from $\mathscr{H}$ to $\mathscr{H}_s$
(the saturation value at θ_s). Then working on the basis of unit mass of dry gas:

$$(\theta - \theta_s)s = (\mathscr{H}_s - \mathscr{H})\lambda$$

or:
$$(\mathscr{H} - \mathscr{H}_s) = -\frac{s}{\lambda}(\theta - \theta_s) \qquad (13.9)$$

where s is the humid heat of the gas and λ the latent heat of vaporisation at θ_s. s is almost
constant for small changes in $\mathscr{H}$.

Equation 13.9 indicates an approximately linear relationship between humidity and
temperature for all mixtures of gas and vapour having the same adiabatic saturation
temperature θ_s. A curve of humidity versus temperature for gases with a given adiabatic
saturation temperature is known as an *adiabatic cooling line*. For a range of adiabatic
saturation temperatures, a family of curves, approximating to straight lines of slopes
equal to $-(s/\lambda)$, is obtained. These lines are not exactly straight and parallel because of
variations in λ and s.

Comparing equations 13.8 and 13.9, it is seen that the adiabatic saturation temperature is equal to the wet-bulb temperature when $s = h/h_D\rho_A$. This is the case for most water vapour systems and accurately so when $\mathscr{H} = 0.047$. The ratio $(h/h_D\rho_A s) = b$ is sometimes known as the *psychrometric ratio* and, as indicated, b is approximately unity for the air-water system. For most systems involving air and an organic liquid, $b = 1.3 - 2.5$ and the wet-bulb temperature is higher than the adiabatic saturation temperature. This was confirmed in 1932 by SHERWOOD and COMINGS[2] who worked with water, ethanol, n-propanol, n-butanol, benzene, toluene, carbon tetrachloride, and n-propyl acetate, and found that the wet-bulb temperature was always higher than the adiabatic saturation temperature except in the case of water.

In Chapter 12 it is shown that when the Schmidt and Prandtl numbers for a mixture of gas and vapour are approximately equal to unity, the *Lewis relation* applies, or:

$$h_D = \frac{h}{C_p\rho} \qquad \text{(equation 12.105)}$$

where C_p and ρ are the mean specific heat and density of the vapour phase.

Therefore:
$$\frac{h}{h_D\rho_A} = \frac{C_p\rho}{\rho_A} \qquad (13.10)$$

Where the humidity is relatively low, $C_p \approx s$ and $\rho \approx \rho_A$ and hence:

$$s \approx \frac{h}{h_D\rho_A} \qquad (13.11)$$

For systems containing vapour other than that of water, s is only approximately equal to $h/h_D\rho_A$ and the difference between the two quantities may be as high as 50 per cent.

If an unsaturated gas is brought into contact with a liquid which is at the adiabatic saturation temperature of the gas, a simultaneous transfer of heat and mass takes place. The temperature of the gas falls and its humidity increases (Figure 13.2). The temperature of the liquid at any instant tends to change and approach the wet-bulb temperature corresponding to the particular condition of the gas at that moment. For a liquid other than water, the adiabatic saturation temperature is less than the wet-bulb temperature and therefore in the initial stages, the temperature of the liquid rises. As the gas becomes humidified, however, its wet-bulb temperature falls and consequently the temperature to
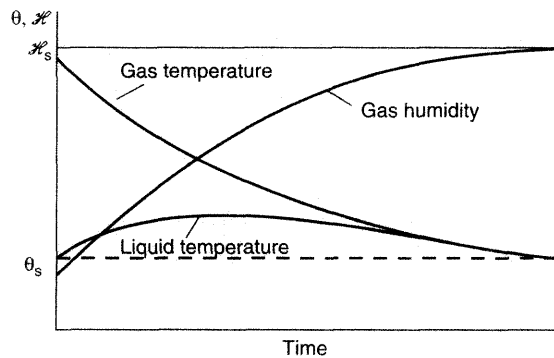

Figure 13.2. Saturation of gas with liquid other than water at the adiabatic saturation temperature

which the liquid is tending decreases as evaporation takes place. In due course, therefore, a point is reached where the liquid actually reaches the wet-bulb temperature of the gas in contact with it. It does not remain at this temperature, however, because the gas is not then completely saturated, and further humidification is accompanied by a continued lowering of the wet-bulb temperature. The temperature of the liquid therefore starts to fall and continues to fall until the gas is completely saturated. The liquid and gas are then both at the adiabatic saturation temperature.

The air–water system is unique, however, in that the Lewis relation holds quite accurately, so that the adiabatic saturation temperature is the same as the wet-bulb temperature. If, therefore, an unsaturated gas is brought into contact with water at the adiabatic saturation temperature of the gas, there is no tendency for the temperature of the water to change, and it remains in a condition of dynamic equilibrium through the whole of the humidification process (Figure 13.3). In this case, the adiabatic cooling line represents the conditions of gases of constant wet-bulb temperatures as well as constant adiabatic saturation temperatures. The change in the condition of a gas as it is humidified with water vapour is therefore represented by the adiabatic cooling line and the intermediate conditions of the gas during the process are readily obtained. This is particularly useful because only partial humidification is normally obtained in practice.
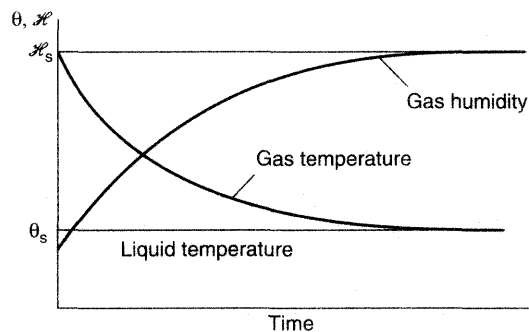
Figure 13.3.   Saturation of air with water at adiabatic saturation temperature

13.3. HUMIDITY DATA FOR THE AIR–WATER SYSTEM

To facilitate calculations, various properties of the air–water system are plotted on a *psychrometric* or *humidity chart*. Such a chart is based on either the temperature or the enthalpy of the gas. The temperature–humidity chart is the more commonly used though the enthalpy–humidity chart is particularly useful for determining the effect of mixing two gases or of mixing a gas and a liquid. Each chart refers to a particular total pressure of the system. A humidity–temperature chart for the air–water system at atmospheric pressure, based on the original chart by GROSVENOR[3], is given in Figure 13.4 and the corresponding humidity–enthalpy chart is given in Figure 13.5.

Figure 13.4. Humidity-temperature chart (See also the Appendix)
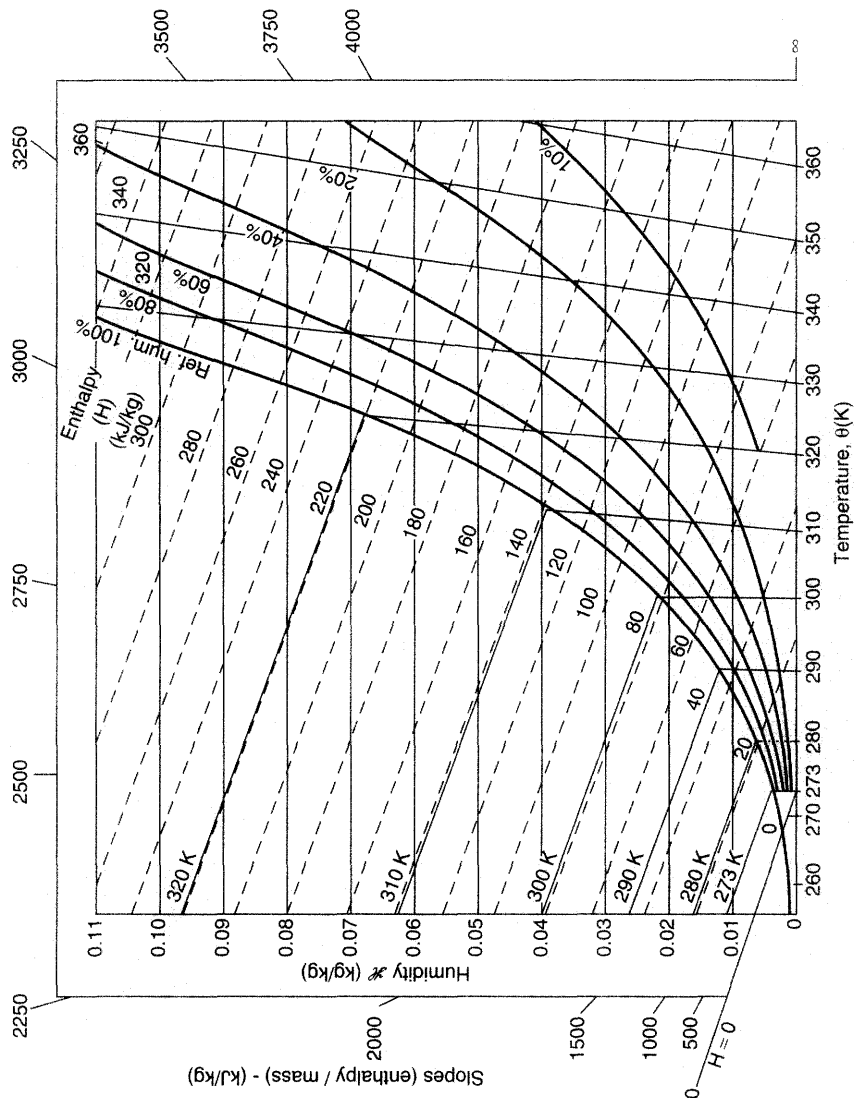
Figure 13.5.   Humidity–enthalpy diagram for air–water vapour system at atmospheric pressure

13.3.1. Temperature–humidity chart

In Figure 13.4 it will be seen that the following quantities are plotted against temperature:
(i) The *humidity* $\mathscr{H}$ for various values of the percentage humidity.

For saturated gas:
$$\mathscr{H}_0 = \frac{P_{w0}}{P - P_{w0}} \left(\frac{M_w}{M_A} \right) \qquad \text{(equation 13.2)}$$

From equation 13.1 for a gas with a humidity less than the saturation value:

$$\mathscr{H} = \frac{P_w}{P - P_w} \left(\frac{M_w}{M_A} \right) = \mathscr{H}_0 \frac{P_w}{P_{w0}} \frac{P - P_{w0}}{P - P_w} \qquad (13.12)$$

(ii) *The specific volume of dry gas.* This is a linear function of temperature.

(iii) *The saturated volume.* This increases more rapidly with temperature than the specific volume of dry gas because both the quantity and the specific volume of vapour increase with temperature. At a given temperature, the humid volume varies linearly with humidity and hence the humid volume of unsaturated gas can be found by interpolation.

(iv) *The latent heat of vaporisation*

In addition, the *humid heat* is plotted as the abscissa in Figure 13.4 with the humidity as the ordinate.

Adiabatic cooling lines are included in the diagram and, as already discussed, these have a slope of $-(s/\lambda)$ and they are slightly curved since s is a function of $\mathscr{H}$. On the chart they appear as straight lines, however, since the inclination of the axis has been correspondingly adjusted. Each adiabatic cooling line represents the composition of all gases whose adiabatic saturation temperature is given by its point of intersection with the 100 per cent humidity curve. For the air–water system, the adiabatic cooling lines represent conditions of constant wet-bulb temperature as well and, as previously mentioned, enable the change in composition of a gas to be followed as it is humidified by contact with water at the adiabatic saturation temperature of the gas.

Example 13.4

Air containing 0.005 kg water vapour per kg of dry air is heated to 325 K in a dryer and passed to the lower shelves. It leaves these shelves at 60 per cent humidity and is reheated to 325 K and passed over another set of shelves, again leaving at 60 per cent humidity. This is again repeated for the third and fourth sets of shelves, after which the air leaves the dryer. On the assumption that the material on each shelf has reached the wet-bulb temperature and that heat losses from the dryer may be neglected, determine:

(a) the temperature of the material on each tray;
(b) the amount of water removed in kg/s, if 5 m³/s moist air leaves the dryer;
(c) the temperature to which the inlet air would have to be raised to carry out the drying in a single stage.

Solution

For each of the four sets of shelves, the condition of the air is changed to 60 per cent humidity along an adiabatic cooling line.

Initial condition of air: $\qquad \theta = 325$ K, $\mathscr{H} = 0.005$ kg/kg

On humidifying to 60 per cent humidity:

$$\theta = 301 \text{ K}, \quad \mathscr{H} = 0.015 \text{ kg/kg and } \theta_w = 296 \text{ K}$$

At the end of the second pass: $\theta = 308$ K, $\mathscr{H} = 0.022$ kg/kg and $\theta_w = 301$ K

At the end of the third pass: $\theta = 312$ K, $\mathscr{H} = 0.027$ kg/kg and $\theta_w = 305$ K

At the end of the fourth pass: $\theta = 315$ K, $\mathscr{H} = 0.032$ kg/kg and $\theta_w = 307$ K

Thus the temperatures of the material on each of the trays are:

$$\underline{\underline{296 \text{ K}, 301 \text{ K}, 305 \text{ K, and } 307 \text{ K}}}$$

Total increase in humidity $= (0.032 - 0.005) = 0.027$ kg/kg

The air leaving the system is at 315 K and 60 per cent humidity.

From Figure 13.4, specific volume of dry air $= 0.893$ m^3/kg

Specific volume of saturated air (*saturated volume*) $= 0.968$ m^3/kg
    Therefore, by interpolation, the humid volume of air of 60 per cent humidity $= 0.937$ m^3/kg

Mass of air passing through the dryer $= \left(\dfrac{5}{0.937}\right) = 5.34$ kg/s

Mass of water evaporated $= (5.34 \times 0.027) = \underline{\underline{0.144 \text{ kg/s}}}$

If the material is to be dried by air in a single pass, the air must be heated before entering the dryer such that its wet-bulb temperature is 307 K.
    For air with a humidity of 0.005 kg/kg, this corresponds to a dry bulb temperature of $\underline{\underline{370 \text{ K}}}$.

The various steps in this calculation are shown in Figure 13.6.

Figure 13.6.   Humidification stages for Example 13.4 (schematic)

13.3.2. Enthalpy–humidity chart

In the calculation of enthalpies it is necessary to define some standard reference state at which the enthalpy is taken as zero. It is most convenient to take the melting point of the material constituting the vapour as the reference temperature, and the liquid state of the material as its standard state.

If H is the enthalpy of the humid gas per unit mass of dry gas, H_a the enthalpy of the dry gas per unit mass, H_w the enthalpy of the vapour per unit mass, C_a the specific heat of the gas at constant pressure, C_w the specific heat of the vapour at constant pressure, θ the temperature of the humid gas, θ_0 the reference temperature, λ the latent heat of vaporisation of the liquid at θ_0 and $\mathscr{H}$ the humidity of the gas,

then for an unsaturated gas: $H = H_a + H_w\mathscr{H}$ (13.13)

where: $H_a = C_a(\theta - \theta_0)$ (13.14)

and: $H_w = C_w(\theta - \theta_0) + \lambda$ (13.15)

Thus, in equation 13.13: $H = (C_a + \mathscr{H}C_w)(\theta - \theta_0) + \mathscr{H}\lambda$ (13.16)

$$= (\theta - \theta_0)(s + \mathscr{H}\lambda)$$

If the gas contains more liquid or vapour than is required to saturate it at the temperature in question, either the gas will be supersaturated or the excess material will be present in the form of liquid or solid according to whether the temperature θ is greater or less than the reference temperature θ_0. The supersaturated condition is unstable and will not be considered further.

If the temperature θ is greater than θ_0 and if the humidity $\mathscr{H}$ is greater than the humidity $\mathscr{H}_0$ of saturated gas, the enthalpy H per unit mass of dry gas is given by:

$$H = C_a(\theta - \theta_0) + \mathscr{H}_0[C_w(\theta - \theta_0) + \lambda] + C_L(\mathscr{H} - \mathscr{H}_0)(\theta - \theta_0) \qquad (13.17)$$

where C_L is the specific heat of the liquid.

If the temperature θ is less than θ_0, the corresponding enthalpy H is given by:

$$H = C_a(\theta - \theta_0) + \mathscr{H}_0[C_w(\theta - \theta_0) + \lambda] + (\mathscr{H} - \mathscr{H}_0)[C_s(\theta - \theta_0) + \lambda_f] \qquad (13.18)$$

where C_s is the specific heat of the solid and λ_f is the latent heat of freezing of the liquid, a negative quantity.

Equations 13.16 to 13.18 give the enthalpy in terms of the temperature and humidity of the humid gas for the three conditions: $\theta = \theta_0$, $\theta > \theta_0$, and $\theta < \theta_0$ respectively. Thus, given the percentage humidity and the temperature, the humidity may be obtained from Figure 13.4, the enthalpy calculated from equations 13.16, 13.17 or 13.18 and plotted against the humidity, usually with enthalpy as the abscissa. Such a plot is shown in Figure 13.7 for the air–water system, which includes the curves for 100 per cent humidity and for some lower value, say Z per cent.

Considering the nature of the isothermals for the three conditions dealt with previously, at constant temperature θ the relation between enthalpy and humidity for an unsaturated gas is:

$$H = \text{constant} + [C_w(\theta - \theta_0) + \lambda]\mathscr{H} \qquad (13.19)$$
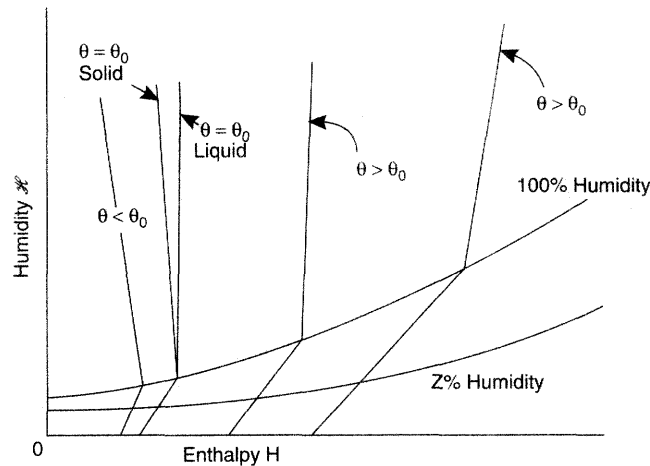
Figure 13.7.   Humidity–enthalpy diagram for air-water system — rectangular axes

Thus, the isothermal is a straight line of slope $[C_w(\theta - \theta_0) + \lambda]$ with respect to the humidity axis. At the reference temperature θ_0, the slope is λ; at higher temperatures, the slope is greater than λ, and at lower temperatures it is less than λ. Because the latent heat is normally large compared with the sensible heat, the slope of the isothermals remains positive down to very low temperatures. Since the humidity is plotted as the ordinate, the slope of the isothermal relative to the X-axis decreases with increase in temperature. When $\theta > \theta_0$ and $\mathscr{H} > \mathscr{H}_0$, the saturation humidity, the vapour phase consists of a saturated gas with liquid droplets in suspension. The relation between enthalpy and humidity at constant temperature θ is:

$$H = \text{constant} + C_L(\theta - \theta_0)\mathscr{H} \qquad (13.20)$$

The isothermal is therefore a straight line of slope $C_L(\theta - \theta_0)$. At the reference temperature θ_0, the slope is zero and the isothermal is parallel to the humidity axis. At higher temperatures, the slope has a small positive value. When $\theta < \theta_0$ and $\mathscr{H} > \mathscr{H}_0$, solid particles are formed and the equation of the isothermal is:

$$H = \text{constant} + [C_s(\theta - \theta_0) + \lambda_f]\mathscr{H} \qquad (13.21)$$

This represents a straight line of slope $[C_s(\theta - \theta_0) + \lambda_f]$. Both $C_s(\theta - \theta_0)$ and λ_f are negative and therefore the slopes of all these isothermals are negative. When $\theta = \theta_0$, the slope is λ_f. In the supersaturated region therefore, there are two distinct isothermals at temperature θ_0; one corresponds to the condition where the excess vapour is present in the form of liquid droplets and the other to the condition where it is present as solid particles. The region between these isothermals represents conditions where a mixture of liquid and solid is present in the saturated gas at the temperature θ_0.

The shape of the humidity-enthalpy line for saturated air is such that the proportion of the total area of the diagram representing saturated, as opposed to supersaturated, air is small when rectangular axes are used. In order to enable greater accuracy to be obtained in the use of the diagram, oblique axes are normally used, as in Figure 13.5, so

that the isothermal for unsaturated gas at the reference temperature θ_0 is parallel to the humidity axis.

It should be noted that the curves of humidity plotted against either temperature or enthalpy have a discontinuity at the point corresponding to the freezing point of the humidifying material. Above the temperature θ_0 the lines are determined by the vapour–liquid equilibrium and below it by the vapour–solid equilibrium.

Two cases may be considered to illustrate the use of enthalpy–humidity charts. These are the mixing of two streams of humid gas and the addition of liquid or vapour to a gas.

Mixing of two streams of humid gas

Consider the mixing of two gases of humidities $\mathscr{H}_1$ and $\mathscr{H}_2$, at temperatures θ_1 and θ_2, and with enthalpies H_1 and H_2 to give a mixed gas of temperature θ, enthalpy H, and humidity $\mathscr{H}$. If the masses of dry gas concerned are m_1, m_2, and m respectively, then taking a balance on the dry gas, vapour, and enthalpy:

$$m_1 + m_2 = m \tag{13.22}$$

$$m_1\mathscr{H}_1 + m_2\mathscr{H}_2 = m\mathscr{H} \tag{13.23}$$

and:

$$m_1 H_1 + m_2 H_2 = mH \tag{13.24}$$

Elimination of m gives:

$$m_1(\mathscr{H} - \mathscr{H}_1) = m_2(\mathscr{H}_2 - \mathscr{H}) \tag{13.25}$$

and:

$$m_1(H - H_1) = m_2(H_2 - H)$$

Dividing these two equations:

$$\frac{(\mathscr{H} - \mathscr{H}_1)}{(H - H_1)} = \frac{(\mathscr{H} - \mathscr{H}_2)}{(H - H_2)} \tag{13.26}$$

The condition of the resultant gas is therefore represented by a point on the straight line joining $(\mathscr{H}_1, H_1)$ and $(\mathscr{H}_2, H_2)$. The humidity $\mathscr{H}$ is given, from equation 13.25, by:

$$\frac{(\mathscr{H} - \mathscr{H}_1)}{(\mathscr{H}_2 - \mathscr{H})} = \frac{m_2}{m_1} \tag{13.27}$$

The gas formed by mixing two unsaturated gases may be either unsaturated, saturated, or supersaturated. The possibility of producing supersaturated gas arises because the 100 per cent humidity line on the humidity–enthalpy diagram is concave towards the humidity axis.

Example 13.5

In an air-conditioning system, 1 kg/s air at 350 K and 10 per cent humidity is mixed with 5 kg/s air at 300 K and 30 per cent humidity. What is the enthalpy, humidity, and temperature of the resultant stream?

Solution

From Figure 13.4:

at $\theta_1 = 350$ K and humidity = 10 per cent; $\mathscr{H}_1 = 0.043$ kg/kg

at $\theta_2 = 300$ K and humidity = 30 per cent; $\mathscr{H}_2 = 0.0065$ kg/kg

Thus, in equation 13.23:

$$(1 \times 0.043) + (5 \times 0.0065) = (1 + 5)\mathcal{H}$$

and:

$$\mathcal{H} = 0.0125 \text{ kg/kg}$$

From Figure 13.5:

$$\text{at } \theta_1 = 350 \text{ K and } \mathcal{H}_1 = 0.043 \text{ kg/kg}; \quad H_1 = 192 \text{ kJ/kg}$$

$$\text{at } \theta_2 = 300 \text{ K and } \mathcal{H}_2 = 0.0065 \text{ kg/kg}; \quad H_2 = 42 \text{ kJ/kg}$$

Thus, in equation 13.25:

$$1(H - 192) = 5(42 - H)$$

and:

$$H = 67 \text{ kJ/kg}$$

From Figure 13.5:

$$\text{at } H = 67 \text{ kJ/kg and } \mathcal{H} = 0.0125 \text{ kg/kg}$$

$$\theta = 309 \text{ K}$$

The data used in this example are shown in Figure 13.8.

Figure 13.8.   Data used in Example 13.5

Addition of liquid or vapour to a gas

If a mass m_3 of liquid or vapour of enthalpy H_3 is added to a gas of humidity $\mathcal{H}_1$ and enthalpy H_1 and containing a mass m_1 of dry gas, then:

$$m_1(\mathcal{H} - \mathcal{H}_1) = m_3 \tag{13.28}$$

$$m_1(H - H_1) = m_3 H_3 \tag{13.29}$$

Thus:
$$\frac{(H - H_1)}{(\mathscr{H} - \mathscr{H}_1)} = H_3 \tag{13.30}$$

where $\mathscr{H}$ and H are the humidity and enthalpy of the gas produced on mixing.

The composition and properties of the mixed stream are therefore represented by a point on the straight line of slope H_3, relative to the humidity axis, which passes through the point $(H_1, \mathscr{H}_1)$. In Figure 13.5 the edges of the plot are marked with points which, when joined to the origin, give a straight line of the slope indicated. Thus in using the chart, a line of slope H_3 is drawn through the origin and a parallel line drawn through the point $(H_1, \mathscr{H}_1)$. The point representing the final gas stream is then given from equation 13.28:

$$(\mathscr{H} - \mathscr{H}_1) = \frac{m_3}{m_1}$$

It can be seen from Figure 13.5 that for the air-water system a straight line, of slope equal to the enthalpy of dry saturated steam (2675 kJ/kg), is almost parallel to the isothermals, so that the addition of live steam has only a small effect on the temperature of the gas. The addition of water spray, even if the water is considerably above the temperature of the gas, results in a lowering of the temperature after the water has evaporated. This arises because the latent heat of vaporisation of the liquid constitutes the major part of the enthalpy of the vapour. Thus, when steam is added, it gives up a small amount of sensible heat to the gas, whereas when hot liquid is added a small amount of sensible heat is given up and a very much larger amount of latent heat is absorbed from the gas.

Example 13.6

0.15 kg/s steam at atmospheric pressure and superheated to 400 K is bled into an air stream at 320 K and 20 per cent relative humidity. What is the temperature, enthalpy, and relative humidity of the mixed stream if the air is flowing at 5 kg/s? How much steam would be required to provide an exit temperature of 330 K and what would be the humidity of this mixture?

Solution

Steam at atmospheric pressure is saturated at 373 K at which the latent heat

$$= 2258 \text{ kJ/kg}$$

Taking the specific heat of superheated steam as 2.0 kJ/kg K;

enthalpy of the steam: $H_3 = 4.18(373 - 273) + 2258 + 2.0(400 - 373)$
$$= 2730 \text{ kJ/kg}$$

From Figure 13.5:

at $\theta_1 = 320$ K and 20 per cent relative humidity; $\mathscr{H}_1 = 0.013$ kg/kg   and $H_1 = 83$ kJ/kg

The line joining the axis and slope $H_3 = 2730$ kJ/kg at the edge of the chart is now drawn in and a parallel line is drawn through $(H_1, \mathscr{H}_1)$.

Thus: $(\mathscr{H} - \mathscr{H}_1) = \frac{m_3}{m_1} = \left(\frac{0.15}{5}\right) = 0.03$ kg/kg

and: $\mathscr{H} = (0.03 + 0.013) = 0.043$ kg/kg

At the intersection of $\mathscr{H} = 0.043$ kg/kg and the line through $(\mathscr{H}_1, H_1)$

$$H = 165 \text{ kJ/kg and } \theta = 324 \text{ K}$$

When $\theta = 330$ K the intersection of this isotherm and the line through $(\mathscr{H}_1, H_1)$ gives an outlet stream in which $\mathscr{H} = 0.094$ kg/kg (83 per cent relative humidity) and $H = 300$ kJ/kg.
Thus, in equation 13.28:

$$m_3 = 5(0.094 - 0.013) = 0.41 \text{ kg/s}$$

The data used in this example are shown in Figure 13.9.
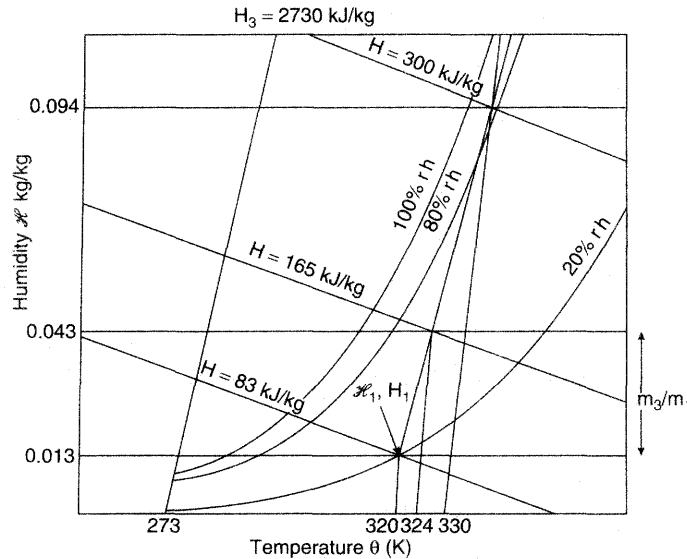
Figure 13.9.   Data used in Example 13.6 (schematic)

13.4. DETERMINATION OF HUMIDITY

The most important methods for determining humidity are as follows:

(1) *Chemical methods.* A known volume of the gas is passed over a suitable absorbent, the increase in mass of which is measured. The efficiency of the process can be checked by arranging a number of vessels containing absorbent in series and ascertaining that the increase in mass in the last of these is negligible. The method is very accurate but is laborious. Satisfactory absorbents for water vapour are phosphorus pentoxide dispersed in pumice, and concentrated sulphuric acid.

(2) *Determination of the wet-bulb temperature.* Equation 13.8 gives the humidity of a gas in terms of its temperature, its wet-bulb temperature, and various physical properties of the gas and vapour. The wet-bulb temperature is normally determined as the temperature attained by the bulb of a thermometer which is covered with a piece of material which is maintained saturated with the liquid. The gas should be passed over the surface of the wet bulb at a high enough velocity (>5 m/s) (a) for the condition of the gas stream not to be affected appreciably by the evaporation of liquid, (b) for the heat transfer by convection to be large compared with that by radiation and conduction from the surroundings, and

(c) for the ratio of the coefficients of heat and mass transfer to have reached a constant value. The gas should be passed long enough for equilibrium to be attained and, for accurate work, the liquid should be cooled nearly to the wet-bulb temperature before it is applied to the material.

The stream of gas over the liquid surface may be produced by a small fan or other similar means (Figure 13.10a). The crude forms of wet-bulb thermometer which make
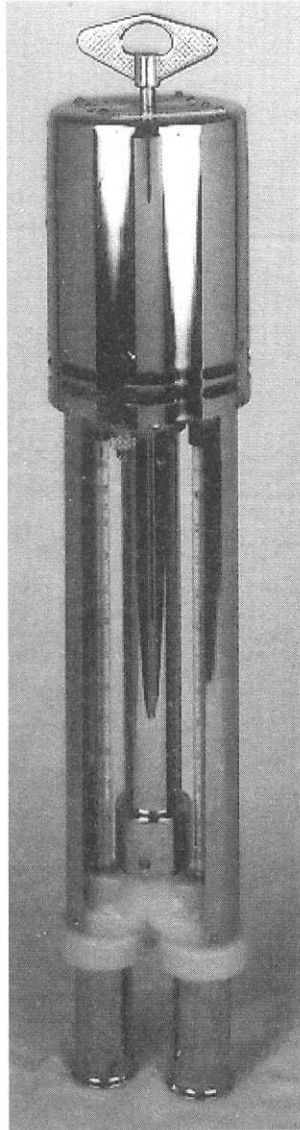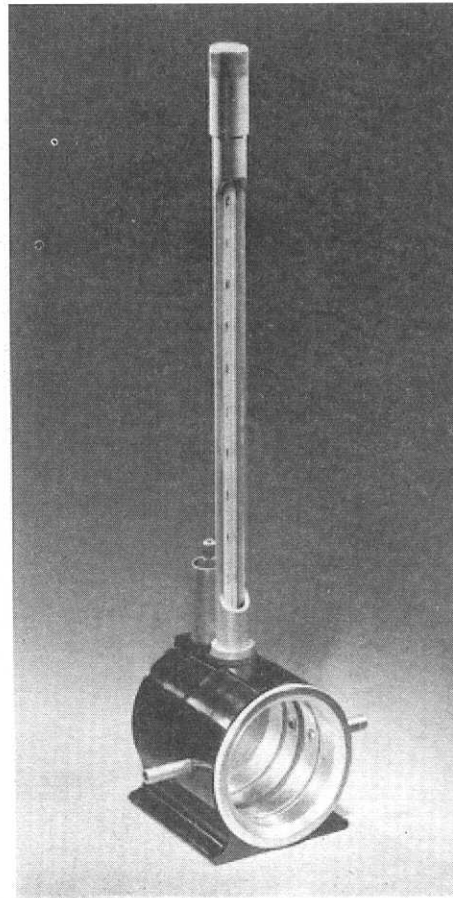
(a) Wet-bulb thermometer   (b) Dew-point meter

Figure 13.10.　Hygrometers

1. Solid gold mirror
2. Peltier cooling device
3. Optical fibres
4. Optical bridge
5. Dual stage filter
6. Carbon fibre
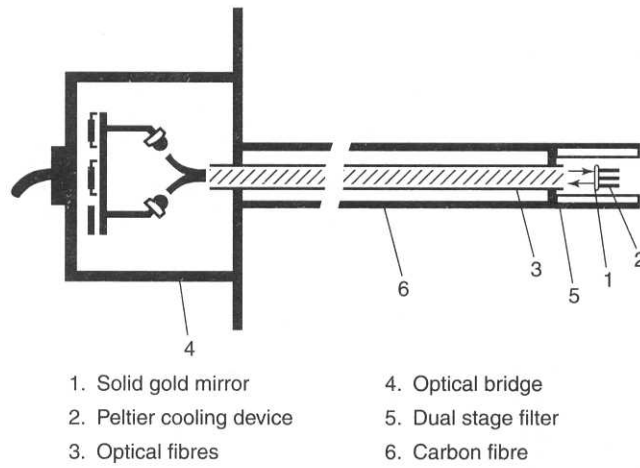
(c) Dew-point meter with cyclic chilled-mirror system

(d) Hair hygrometer

Figure 13.10.   (continued)

no provision for the rapid passage of gas cannot be used for accurate determinations of humidity.

(3) *Determination of the dew point.* The dew point is determined by cooling a highly polished surface in the gas and observing the highest temperature at which condensation takes place (Figure 13.10*b*). The humidity of the gas is equal to the humidity of saturated gas at the dew-point. The instrument illustrated in Figure 13.10*c* incorporates a polished gold mirror which is cooled using a thermo-electric module which utilises the *Peltier effect.*

(4) *Measurement of the change in length of a hair or fibre.* The length of a hair or fibre is influenced by the humidity of the surrounding atmosphere. Many forms of apparatus for automatic recording of humidity depend on this property. The method has the disadvantage that the apparatus needs frequent calibration because the zero tends to shift. This difficulty is most serious when the instrument is used over a wide range of humidities. A typical hair hygrometer is shown in Figure 13.10*d*.

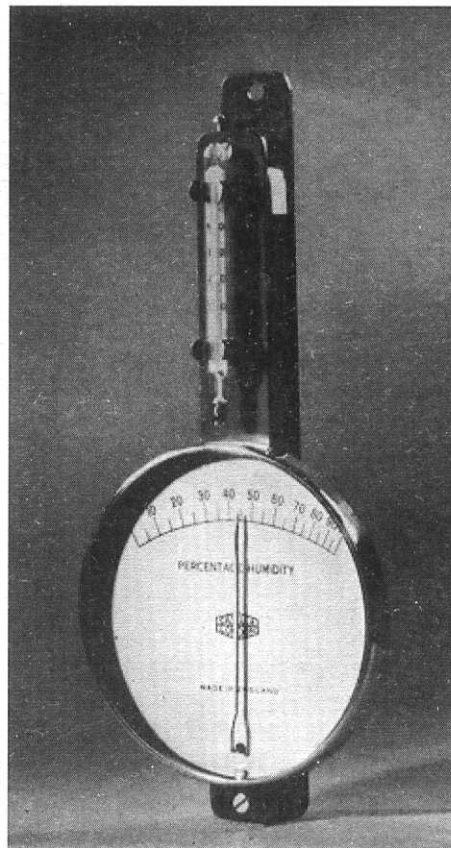(5) *Measurement of conductivity of a fibre.* If a fibre is impregnated with an electrolyte, such as lithium chloride, its electrical resistance will be governed by its moisture content, which in turn depends on the humidity of the atmosphere in which it is situated. In a lithium chloride cell, a skein of very fine fibres is wound on a plastic frame carrying the electrodes and the current flowing at a constant applied voltage gives a direct measure of the relative humidity.

(6) *Measurement of heat of absorption on to a surface.*

(7) *Electrolytic hygrometry* in which the quantity of electricity required to electrolyse water absorbed from the atmosphere on to a thin film of desiccant is measured.

(8) *Piezo-electric hygrometry* employing a quartz crystal with a hygroscopic coating in which moisture is alternately absorbed from a wet-gas and desorbed in a dry-gas stream; the dynamics is a function of the gas humidity.

(9) *Capacitance meters* in which the electrical capacitance is a function of the degree of deposition of moisture from the atmosphere.

(10) *Observation of colour changes* in active ingredients, such as cobaltous chloride.

Further details of instruments for the measurement of humidity are given in Volume 3. Reference should also be made to standard works on psychrometry[4,5,6].

13.5. HUMIDIFICATION AND DEHUMIDIFICATION

13.5.1. Methods of increasing humidity

The following methods may be used for increasing the humidity of a gas:

(1) Live steam may be added directly in the required quantity. It has been shown that this produces only a slight increase in the temperature, but the method is not generally favoured because any impurities that are present in the steam may be added at the same time.

(2) Water may be sprayed into the gas at such a rate that, on complete vaporisation, it gives the required humidity. In this case, the temperature of the gas will fall as the latent heat of vaporisation must be supplied from the sensible heat of the gas and liquid.

(3) The gas may be mixed with a stream of gas of higher humidity. This method is frequently used in laboratory work when the humidity of a gas supplied to an apparatus is controlled by varying the proportions in which two gas streams are mixed.

(4) The gas may be brought into contact with water in such a way that only part of the liquid is evaporated. This is perhaps the most common method and will now be considered in more detail.

In order to obtain a high rate of humidification, the area of contact between the air and the water is made as large as possible by supplying the water in the form of a fine spray; alternatively, the interfacial area is increased by using a packed column. Evaporation occurs if the humidity at the surface is greater than that in the bulk of the air; that is, if the temperature of the water is above the dew point of the air.

When humidification is carried out in a packed column, the water which is not evaporated can be recirculated so as to reduce the requirements of fresh water. As a result of continued recirculation, the temperature of the water will approach the adiabatic saturation temperature of the air, and the air leaving the column will be cooled — in some cases to within 1 deg K of the temperature of the water. If the temperature of the air is to be maintained constant, or raised, the water must be heated.

Two methods of changing the humidity and temperature of a gas from $A(\theta_1, \mathscr{H}_1)$ to $B(\theta_2, \mathscr{H}_2)$ may be traced on the humidity chart as shown in Figure 13.11. The first method consists of saturating the air by water artificially maintained at the dew point of air of humidity $\mathscr{H}_2$ (line AC) and then heating at constant humidity to θ_2 (line CB). In the second method, the air is heated (line AD) so that its adiabatic saturation temperature corresponds with the dew point of air of humidity $\mathscr{H}_2$. It is then saturated by water at the adiabatic saturation temperature (line DC) and heated at constant humidity to θ_2 (line CB). In this second method, an additional operation — the preliminary heating — is carried out on the air, but the water temperature automatically adjusts itself to the required value.
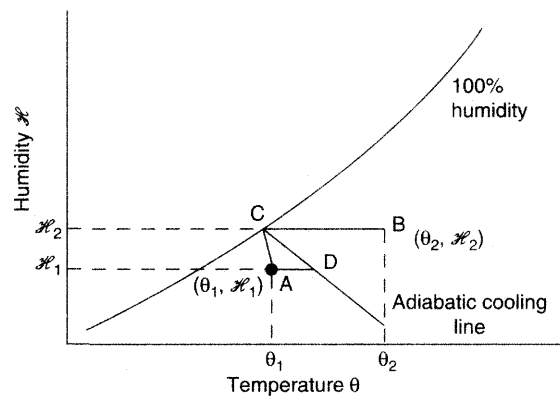
Figure 13.11.   Two methods of changing conditions of gas from $(\theta_1, \mathscr{H}_1)$ to $(\theta_2, \mathscr{H}_2)$

Since complete humidification is not always attained, an allowance must be made when designing air humidification cycles. For example, if only 95 per cent saturation is attained the adiabatic cooling line should be followed only to the point corresponding to that degree of saturation, and therefore the gas must be heated to a slightly higher temperature before adiabatic cooling is commenced.

Example 13.7

Air at 300 K and 20 per cent humidity is to be heated in two stages with intermediate saturation with water to 90 per cent humidity so that the final stream is at 320 K and 20 per cent humidity. What is the humidity of the exit stream and the conditions at the end of each stage?

Solution

At $\theta_1 = 300$ K and 20 per cent humidity: $\mathscr{H}_1 = 0.0045$ kg/kg, from Figure 13.4, and
at $\theta_2 = 320$ K and 20 per cent humidity: $\mathscr{H}_2 = 0.0140$ kg/kg

When $\mathscr{H}_2 = 0.0140$ kg/kg, air is saturated at 292 K and has a humidity of 90 per cent at 293 K.
The adiabatic cooling line corresponding to 293 K intersects with $\mathscr{H} = 0.0045$ kg/kg at a temperature, $\theta = 318$ K.

Thus the stages are:

(i) Heat the air at $\mathscr{H} = 0.0045$ from 300 to 318 K.
(ii) Saturate with water at an adiabatic saturation temperature of 293 K until 90 per cent humidity is attained. At the end of this stage:

$$\mathscr{H} = 0.0140 \text{ kg/kg} \quad \text{and} \quad \theta = 294.5 \text{ K}$$

(iii) Heat the saturated air at $\mathscr{H} = 0.0140$ kg/kg from 294.5 to 320 K

13.5.2. Dehumidification

Dehumidification of air can be effected by bringing it into contact with a cold surface, either liquid or solid. If the temperature of the surface is lower than the dew point of the gas, condensation takes place and the temperature of the gas falls. The temperature of the surface tends to rise because of the transfer of latent and sensible heat from the air. It would be expected that the air would cool at constant humidity until the dew point was reached, and that subsequent cooling would be accompanied by condensation. It is found, in practice, that this occurs only when the air is well mixed. Normally the temperature and humidity are reduced simultaneously throughout the whole of the process. The air in contact with the surface is cooled below its dew point, and condensation of vapour therefore occurs before the more distant air has time to cool. Where the gas stream is cooled by cold water, countercurrent flow should be employed because the temperature of the water and air are changing in opposite directions.

The humidity can be reduced by compressing air, allowing it to cool again to its original temperature, and draining off the water which has condensed. During compression, the partial pressure of the vapour is increased and condensation takes place as soon as it reaches the saturation value. Thus, if air is compressed to a high pressure, it becomes saturated with vapour, but the partial pressure is a small proportion of the total pressure. Compressed air from a cylinder therefore has a low humidity. Gas is frequently compressed before it is circulated so as to prevent condensation in the mains.

Many large air-conditioning plants incorporate automatic control of the humidity and temperature of the issuing air. Temperature control is effected with the aid of a thermocouple or resistance thermometer, and humidity control by means of a thermocouple recording the difference between the wet- and dry-bulb temperatures.

13.6. WATER COOLING

13.6.1. Cooling towers

Cooling of water can be carried out on a small scale either by allowing it to stand in an open pond or by the spray pond technique in which it is dispersed in spray form and then collected in a large, open pond. Cooling takes place both by the transference of sensible heat and by evaporative cooling as a result of which sensible heat in the water provides the latent heat of vaporisation.

On the large scale, air and water are brought into countercurrent contact in a cooling tower which may employ either natural draught or mechanical draught. The water flows down over a series of wooden slats which give a large interfacial area and promote turbulence in the liquid. The air is humidified and heated as it rises, while the water is cooled mainly by evaporation.

The natural draught cooling tower depends on the chimney effect produced by the presence in the tower of air and vapour of higher temperature and therefore of lower density than the surrounding atmosphere. Thus atmospheric conditions and the temperature and quantity of the water will exert a very important effect on the operation of the tower. Not only will these factors influence the quantity of air drawn through the tower, but they will also affect the velocities and flow patterns and hence the transfer coefficients between gas and liquid. One of the prime considerations in design therefore is to construct a tower in such a way that the resistance to air flow is low. Hence the packings and distributors must be arranged in open formation. The draught of a cooling tower at full load is usually only about 50 N/m^2,[7] and the air velocity in the region of 1.2–1.5 m/s, so that under the atmospheric conditions prevailing in the UK the air usually leaves the tower in a saturated condition. The density of the air stream at outlet is therefore determined by its temperature. Calculation of conditions within the tower is carried out in the manner described in the following pages. It is, however, necessary to work with a number of assumed air flowrates and to select the one which fits both the transfer conditions and the relationship between air rate and pressure difference in the tower.

The *natural draught cooling tower* consists of an empty shell, constructed either of timber or ferroconcrete, where the upper portion is empty and merely serves to increase the draught. The lower portion, amounting to about 10–12 per cent of the total height, is usually fitted with grids on to which the water is fed by means of distributors or sprays as shown in Figure 13.12. The shells of cooling towers are now generally constructed in ferroconcrete in a shape corresponding approximately to a hyperboloid of revolution. The shape is chosen mainly for constructional reasons, but it does take account of the fact that the entering air will have a radial velocity component; the increase in cross-section towards the top causes a reduction in the outlet velocity and there is a small recovery of kinetic energy into pressure energy.

The *mechanical draught cooling tower* may employ forced draught with the fan at the bottom, or induced draught with the fan driving the moist air out at the top. The air velocity can be increased appreciably above that in the natural draught tower, and a greater depth of packing can be used. The tower will extend only to the top of the packing unless atmospheric conditions are such that a chimney must be provided in order to prevent recirculation of the moist air. The danger of recirculation is considerably
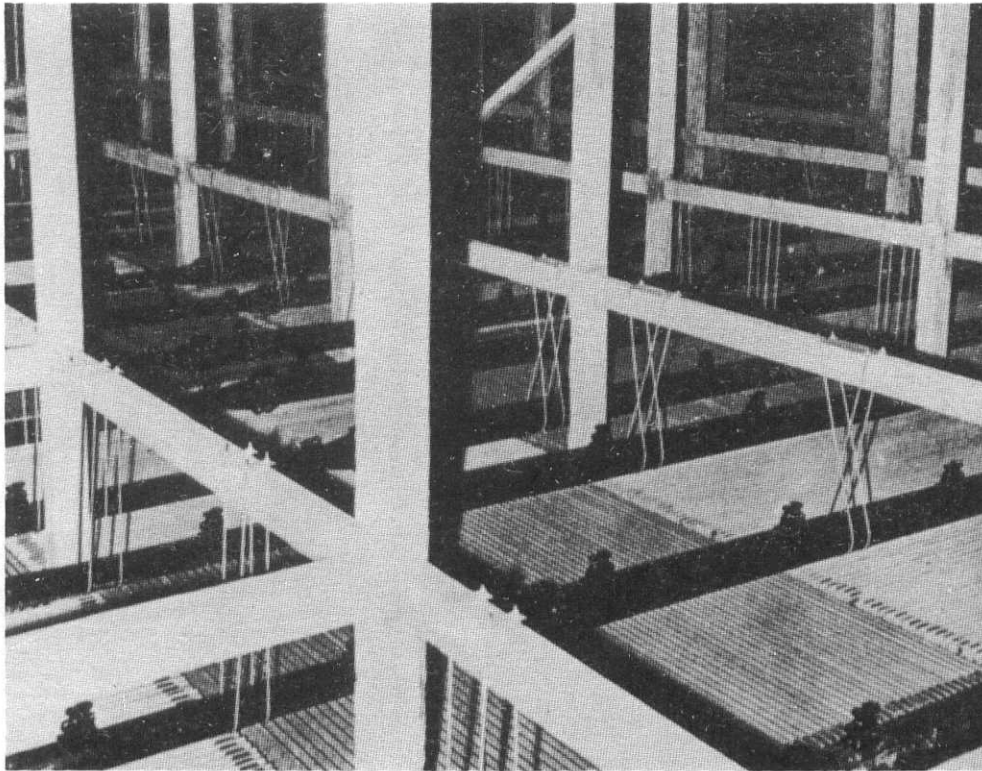
Figure 13.12.   Water-cooling tower. View of spray distribution system

less with the induced-draught type because the air is expelled with a higher velocity. Mechanical draught towers are generally confined to small installations and to conditions where the water must be cooled to as low a temperature as possible. In some cases it is possible to cool the water to within 1 deg K of the wet-bulb temperature of the air. Although the initial cost of the tower is less, maintenance and operating costs are of course higher than in natural draught towers which are now used for all large installations. A typical steel-framed mechanical draught cooling tower is shown in Figure 13.13.

The operation of the conventional water cooling tower is often characterised by the discharge of a plume consisting of a suspension of minute droplets of water in air. This is formed when the hot humid air issuing from the top of the tower mixes with the ambient atmosphere, and precipitation takes place as described earlier (Section 13.3.2). In the *hybrid* (or wet/dry) cooling tower[8], mist formation is avoided by cooling *part* of the water in a finned-tube exchanger bundle which thus generates a supply of warm dry air which is then blended with the air issuing from the evaporative section. By adjusting the proportion of the water fed to the heat exchanger, the plume can be completely eliminated.

In the cooling tower the temperature of the liquid falls and the temperature and humidity of the air rise, and its action is thus similar to that of an air humidifier. The limiting temperature to which the water can be cooled is the wet-bulb temperature corresponding to the condition of the air at inlet. The enthalpy of the air stream does not remain
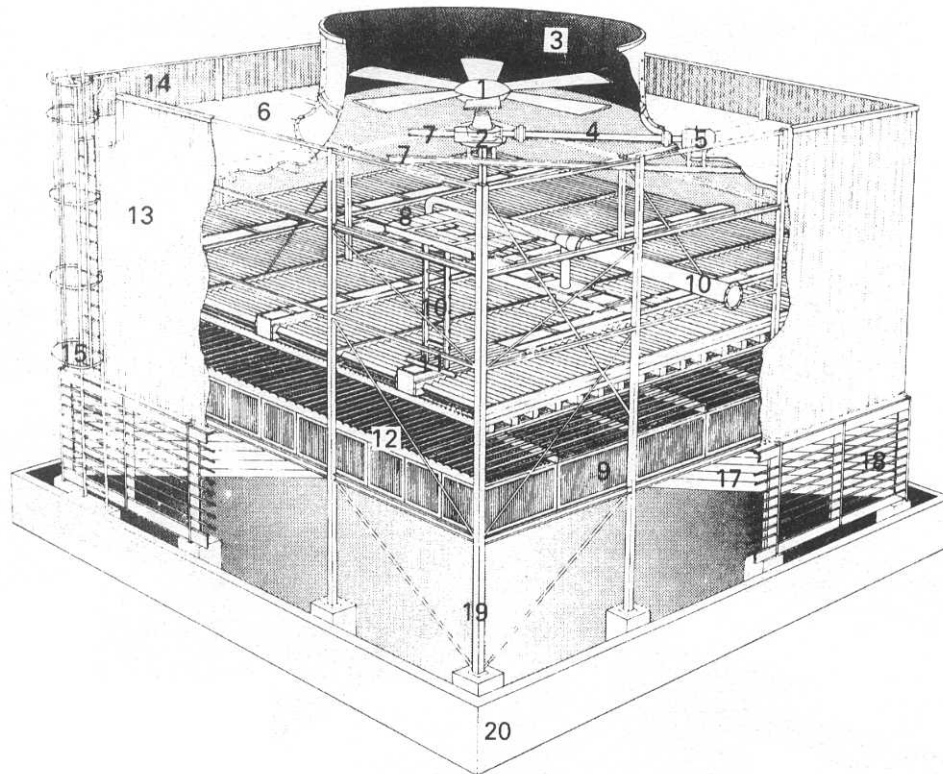
1 Fan assembly
2 Gearbox
3 Fan stack
4 Drive shaft assembly
5 Motor
6 Fan deck
7 Mechanical equipment supports
8 Drift eliminators (PVC or Timber - Timber shown)
9 Cooling tower packing (plastic plate or wooden lath)
10 Inlet water distribution pipe
11 Open type distribution system
12 Timber laths for even water distribution
13 Cladding
14 Cladding extended to form handrail
15 Access ladder
16 Internal access ladder to distribution system and drift
   eliminators
17 Diagonal wind baffles
18 Air inlet louvres
19 Steel structures with horizontal and diagonal ties
20 Cold water sump

   Some structural members have been omitted for clarity

Figure 13.13.   Visco 2000 series steel framed, mechanical draught, water cooling tower

constant since the temperature of the liquid changes rapidly in the upper portion of the tower. Towards the bottom, however, the temperature of the liquid changes less rapidly because the temperature differences are smaller. At the top of the tower, the temperature falls from the bulk of the liquid to the interface and then again from the interface to the bulk of the gas. Thus the liquid is cooled by transfer of sensible heat and by evaporation at the surface. At the bottom of a tall tower, however, the temperature gradient in the liquid is in the same direction, though smaller, but the temperature gradient in the gas is in the opposite direction. Transfer of sensible heat to the interface therefore takes place from the bulk of the liquid and from the bulk of the gas, and all the cooling is caused by the evaporation at the interface. In most cases, about 80 per cent of the heat loss from the water is accounted for by evaporative cooling.

13.6.2. Design of natural-draught towers

The air flow through a natural-draught or hyperbolic-type tower (Figure 13.14) is due largely to the difference in density between the warm air in the tower and the external ambient air; thus a draught is created in the stack by a chimney effect which eliminates the need for mechanical fans. It has been noted by McKELVEY and BROOKE[9] that natural-draught towers commonly operate at a pressure difference of some 50 N/m^2 under full load, and above the packing the mean air velocity is typically 1–2 m/s. The performance of a natural-draught tower differs from that of a mechanical-draught installation in that the cooling achieved depends upon the relative humidity as well as the wet-bulb temperature. It is important therefore, at the design stage, to determine correctly, and to specify, the density of the inlet and exit air streams in addition to the usual tower design conditions of water temperature range, how closely the water temperature should approach the wet bulb temperature of the air, and the quantity of water to be handled. Because the performance

Figure 13.14.   Natural draught water-cooling towers

depends to a large extent on atmospheric humidity, the outlet water temperature is difficult to control with natural-draught towers.

In the design of natural-draught towers, a ratio of height to base diameter of 3:2 is normally used and a design method has been proposed by CHILTON[10]. Chilton has shown that the duty coefficient D_t of a tower is approximately constant over the normal range of operation and is related to tower size by an efficiency factor or performance coefficient C_t given by:

$$D_t = \frac{19.50 A_b z_t^{0.5}}{C_t^{1.5}} \tag{13.31}$$

where for water loadings in excess of 1 kg/m²s, C_t is usually about 5.2 though lower values are obtained with new packings which are being developed.

The duty coefficient is given by the following equation (in which SI units must be used as it is not dimensionally consistent):

$$\frac{W_L}{D_t} = 0.00369 \frac{\Delta H'}{\Delta T} (\Delta T' + 0.0752 \Delta H')^{0.5} \tag{13.32}$$

where W_L (kg/s) is the water load in the tower, $\Delta H'$ (kJ/kg) the change in enthalpy of the air passing through the tower, ΔT(deg K) the change in water temperature in passing through the tower and $\Delta T'$(deg K), the difference between the temperature of the air leaving the packing and the dry-bulb temperature of the inlet air. The air leaving the packing inside the tower is assumed to be saturated at the mean of the inlet and outlet water temperatures. Any divergence between theory and practice of a few degrees in this respect does not significantly affect the results as the draught component depends on the ratio of the change of density to change in enthalpy and not on change in temperature alone.[11] The use of equations 13.31 and 13.32 is illustrated in the following example.

Example 13.8

What are the diameter and height of a hyperbolic natural-draught cooling tower handling 4810 kg/s of water with the following temperature conditions:

$$\text{water entering the tower} = 301 \text{ K}$$

$$\text{water leaving the tower} = 294 \text{ K}.$$

$$\text{air: dry bulb} = 287 \text{ K}$$

$$\text{wet bulb} = 284 \text{ K}$$

Solution

Temperature range for the water, $\Delta T = (301 - 294) = 7$ deg K.
At a mean water temperature of $0.5(301 + 294) = 297.5$ K, the enthalpy $= 92.6$ kJ/kg
At a dry bulb temperature of 287 K, the enthalpy $= 49.5$ kJ/kg

$$\therefore \qquad \Delta T' = (297.5 - 287) = 10.5 \text{ deg K}$$

and: $\Delta H' = (92.6 - 49.5) = 43.1$ kJ/kg

In equation 13.32:

$$\frac{4810}{D_t} = 0.00369 \left(\frac{43.1}{7}\right) [10.5 + (0.0752 \times 43.1)]^{0.5}$$

and: $D_t = 57,110$

Taking C_t as 5.0 and assuming as a first estimate a tower height of 100 m, then in equation 13.31:

$$57.110 = 19.50 A_b \frac{100^{0.5}}{5.0^{1.5}}$$

and: $A_b = 3274 \text{ m}^2$

Thus the internal diameter of the column at sill level $= \left(\frac{3274 \times 4}{\pi} \right)^{0.5}$

$$= \underline{64.6 \text{ m}}$$

Since this gives a height: diameter ratio of (100 : 64.6) $\approx$ 3 : 2, the design is acceptable.

13.6.3. Height of packing for both natural and mechanical draught towers

The height of a water-cooling tower can be determined[12] by setting up a material balance on the water, an enthalpy balance, and rate equations for the transfer of heat in the liquid and gas and for mass transfer in the gas phase. There is no concentration gradient in the liquid and therefore there is no resistance to mass transfer in the liquid phase.

Considering the countercurrent flow of water and air in a tower of height z (Figure 13.15), the mass rate of flow of air per unit cross-section G' is constant throughout the whole height of the tower and, because only a small proportion of the total supply of water is normally evaporated (1–5 per cent), the liquid rate per unit area L' can be taken as constant. The temperature, enthalpy, and humidity will be denoted by the symbols θ, H, and $\mathscr{H}$ respectively, suffixes G, L, 1, 2, and f being used to denote conditions in the gas and liquid, at the bottom and top of the column, and of the air in contact with the water.
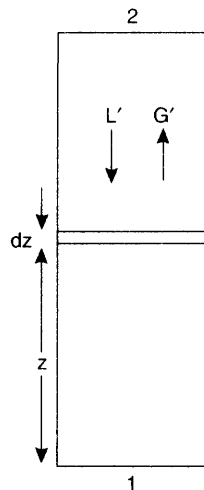
Figure 13.15. Flow in water-cooling tower

The five basic equations for an incremental height of column, dz, are:

(1) Water balance:

$$dL' = G' \, d\mathcal{H} \tag{13.33}$$

(2) Enthalpy balance:

$$G' \, dH_G = L' \, dH_L \tag{13.34}$$

since only a small proportion of the liquid is evaporated.

Now:

$$H_G = s(\theta_G - \theta_0) + \lambda \mathcal{H} \tag{13.35}$$

and:

$$H_L = C_L(\theta_L - \theta_0) \tag{13.36}$$

Thus:

$$G' \, dH_G = L' C_L \, d\theta_L \tag{13.37}$$

and:

$$dH_G = s \, d\theta_G + \lambda \, d\mathcal{H} \tag{13.38}$$

Integration of this expression over the whole height of the column, on the assumption that the physical properties of the materials do not change appreciably, gives:

$$G'(H_{G2} - H_{G1}) = L' C_L(\theta_{L2} - \theta_{L1}) \tag{13.39}$$

(3) Heat transfer from the body of the liquid to the interface:

$$h_L a \, dz(\theta_L - \theta_f) = L' C_L \, d\theta_L \tag{13.40}$$

where h_L is the heat transfer coefficient in the liquid phase and a is the interfacial area per unit volume of column. It will be assumed that the area for heat transfer is equal to that available for mass transfer, though it may be somewhat greater if the packing is not completely wetted.

Rearranging equation 13.40:

$$\frac{d\theta_L}{(\theta_L - \theta_f)} = \frac{h_L a}{L' C_L} \, dz \tag{13.41}$$

(4) Heat transfer from the interface to the bulk of the gas:

$$h_G a \, dz(\theta_f - \theta_G) = G' s \, d\theta_G \tag{13.42}$$

where h_G is the heat transfer coefficient in the gas phase.

Rearranging:

$$\frac{d\theta_G}{(\theta_f - \theta_G)} = \frac{h_G a}{G' s} \, dz \tag{13.43}$$

(5) Mass transfer from the interface to the gas:

$$h_D \rho a \, dz(\mathcal{H}_f - \mathcal{H}) = G' \, d\mathcal{H} \tag{13.44}$$

where h_D is the mass transfer coefficient for the gas and ρ is the mean density of the air (see equation 13.6).

Rearranging:

$$\frac{d\mathcal{H}}{(\mathcal{H}_f - \mathcal{H})} = \frac{h_D a \rho}{G'} \, dz \tag{13.45}$$

These equations cannot be integrated directly since the conditions at the interface are not necessarily constant; nor can they be expressed directly in terms of the corresponding property in the bulk of the gas or liquid.

If the Lewis relation (equation 13.11) is applied, it is possible to obtain workable equations in terms of enthalpy instead of temperature and humidity. Thus, writing h_G as $h_D \rho s$, from equation 13.42:

$$G's \, d\theta_G = h_D \rho a \, dz(s\theta_f - s\theta_G) \tag{13.46}$$

and from equation 13.44:

$$G'\lambda \, d\mathcal{H} = h_D \rho a \, dz(\lambda \mathcal{H}_f - \lambda \mathcal{H}) \tag{13.47}$$

Adding these two equations gives:

$$G'(s \, d\theta_G + \lambda \, d\mathcal{H}) = h_D \rho a \, dz[(s\theta_f + \lambda \mathcal{H}_f) - (s\theta_G + \lambda \mathcal{H})]$$

$$G' \, dH_G = h_D \rho a \, dz(H_f - H_G) \quad \text{(from equation 13.35)} \tag{13.48}$$

or:
$$\frac{dH_G}{(H_f - H_G)} = \frac{h_D a \rho}{G'} \, dz \tag{13.49}$$

The use of an enthalpy driving force, as in equation 13.48, was first suggested by MERKEL[13], and the following development of the treatment was proposed by MICKLEY[12].

Combining of equations 13.37, 13.40, and 13.48 gives:

$$\frac{(H_G - H_f)}{(\theta_L - \theta_f)} = -\frac{h_L}{h_D \rho} \tag{13.50}$$

From equations 13.46 and 13.48:

$$\frac{(H_G - H_f)}{(\theta_G - \theta_f)} = \frac{dH_G}{d\theta_G} \tag{13.51}$$

and from equations 13.46 and 13.44:

$$\frac{(\mathcal{H} - \mathcal{H}_f)}{(\theta_G - \theta_f)} = \frac{d\mathcal{H}}{d\theta_G} \tag{13.52}$$

These equations are now employed in the determination of the required height of a cooling tower for a given duty. The method consists of the graphical evaluation of the relation between the enthalpy of the body of gas and the enthalpy of the gas at the interface with the liquid. The required height of the tower is then obtained by integration of equation 13.49.

It is supposed that water is to be cooled at a mass rate L' per unit area from a temperature θ_{L2} to θ_{L1}. The air will be assumed to have a temperature θ_{G1}, a humidity $\mathcal{H}_1$, and an enthalpy H_{G1} (which can be calculated from the temperature and humidity), at the inlet point at the bottom of the tower, and its mass flow per unit area will be taken as G'. The change in the condition of the liquid and gas phases will now be followed on an enthalpy–temperature diagram (Figure 13.16). The enthalpy–temperature curve PQ for saturated air is plotted either using calculated data or from the humidity chart (Figure 13.4). The region below this line relates to unsaturated air and the region above it to supersaturated air. If it is assumed that the air in contact with the liquid surface
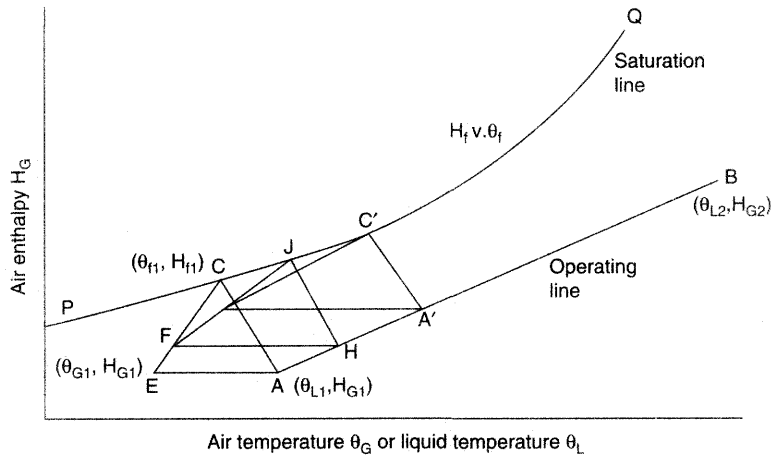
Figure 13.16.   Construction for determining the height of water-cooling tower

is saturated with water vapour, this curve represents the relation between air enthalpy H_f and temperature θ_f at the interface.

The curve connecting air enthalpy and water temperature is now drawn using equation 13.39. This is known as the operating line and is a straight line of slope $(L'C_L/G')$, passing through the points $A(\theta_{L1}, H_{G1})$ and $B(\theta_{L2}, H_{G2})$. Since θ_{L1}, H_{G1} are specified, the procedure is to draw a line through (θ_{L1}, H_{G1}) of slope $L'C_L/G'$ and to produce it to a point whose abscissa is equal to θ_{L2}. This point B then corresponds to conditions at the top of the tower and the ordinate gives the enthalpy of the air leaving the column.

Equation 13.50 gives the relation between liquid temperature, air enthalpy, and conditions at the interface, for any position in the tower, and is represented by a family of straight lines of slope $-(h_L/h_D\rho)$. The line for the bottom of the column passes through the point $A(\theta_{L1}, H_{G1})$ and cuts the enthalpy-temperature curve for saturated air at the point C, representing conditions at the interface. The difference in ordinates of points A and C is the difference in the enthalpy of the air at the interface and that of the bulk air at the bottom of the column.

Similarly, line $A'C'$, parallel to AC, enables the difference in the enthalpies of the bulk air and the air at the interface to be determined at some other point in the column. The procedure can be repeated for a number of points and the value of $(H_f - H_G)$ obtained as a function of H_G for the whole tower.

Now:
$$\frac{dH_G}{(H_f - H_G)} = \frac{h_D a\rho}{G'} dz$$
(equation 13.49)

On integration:
$$z = \int_1^2 dz = \frac{G'}{h_D a\rho} \int_1^2 \frac{dH_G}{(H_f - H_G)}$$
(13.53)

assuming h_D to remain approximately constant.

Since $(H_f - H_G)$ is now known as a function of H_G, $1/(H_f - H_G)$ can be plotted against H_G and the integral evaluated between the required limits. The height of the tower is thus determined.

The integral in equation 13.53 cannot be evaluated by taking a logarithmic mean driving force because the saturation line PQ is far from linear. CAREY and WILLIAMSON[14] have given a useful approximate method of evaluating the integral. They assume that the enthalpy difference $(H_f - H_G) = \Delta H$ varies in a parabolic manner. The three fixed points taken to define the parabola are at the bottom and top of the column (ΔH_1 and ΔH_2 respectively) and ΔH_m, the value at the mean water temperature in the column. The effective mean driving force is $f \Delta H_m$, where f is a factor for converting the driving force at the mean water temperature to the effective value. In Figure 13.17, $(\Delta H_m/\Delta H_1)$ is plotted against $(\Delta H_m/\Delta H_2)$ and contours representing constant values of f are included.
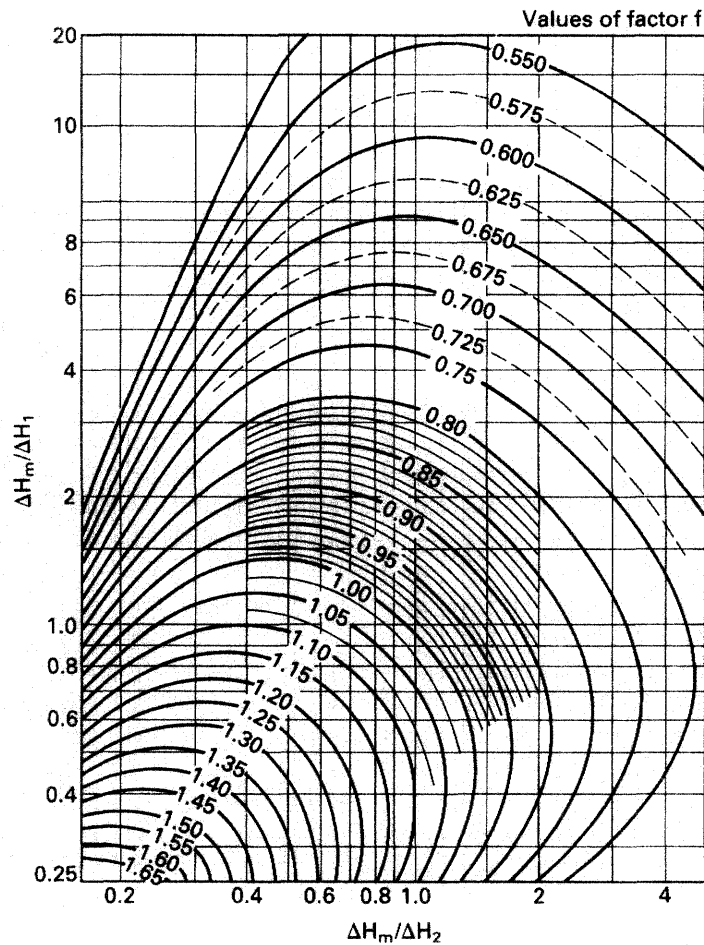
Figure 13.17. Correction factor f for obtaining the mean effective driving force in column

Using the mean driving force, integration of equation 13.53 gives:

$$\frac{(H_{G2} - H_{G1})}{f \Delta H_m} = \frac{h_D a \rho}{G'} z$$ (13.54)

or:

$$z = \frac{G'}{h_D a \rho} \frac{(H_{G2} - H_{G1})}{f \Delta H_m}$$

13.6.4. Change in air condition

The change in the humidity and temperature of the air is now obtained. The enthalpy and temperature of the air are known only at the bottom of the tower, where fresh air is admitted. Here the condition of the air may be represented by a point E with coordinates (H_{G1}, θ_{G1}). Thus the line AE (Figure 13.16) is parallel to the temperature axis.

Since:

$$\frac{H_G - H_f}{\theta_G - \theta_f} = \frac{dH_G}{d\theta_G}$$ (13.51)

the slope of the line EC is $(dH_G/d\theta_G)$ and represents the rate of change of air enthalpy with air temperature at the bottom of the column. If the gradient $(dH_G/d\theta_G)$ is taken as constant over a small section, the point F, on EC, will represent the condition of the gas at a small distance from the bottom. The corresponding liquid temperature is found by drawing through F a line parallel to the temperature axis. This cuts the operating line at some point H, which indicates the liquid temperature. The corresponding value of the temperature and enthalpy of the gas at the interface is then obtained by drawing a line through H, parallel to AC. This line then cuts the curve for saturated air at a point J, which represents the conditions of the gas at the interface. The rate of change of enthalpy with temperature for the gas is then given by the slope of the line FJ. Again, this slope can be considered to remain constant over a small height of the column, and the condition of the gas is thus determined for the next point in the tower. The procedure is then repeated until the curve representing the condition of the gas has been extended to a point whose ordinate is equal to the enthalpy of the gas at the top of the column. This point is obtained by drawing a straight line through B, parallel to the temperature axis. The final point on the line then represents the condition of the air which leaves the top of the water-cooling tower.

The size of the individual increments of height which are considered must be decided for the particular problem under consideration and will depend, primarily, on the rate of change of the gradient $(dH_G/d\theta_G)$. It should be noted that, for the gas to remain unsaturated throughout the whole of the tower, the line representing the condition of the gas must be below the curve for saturated gas. If at any point in the column, the air has become saturated, it is liable to become supersaturated as it passes further up the column and comes into contact with hotter liquid. It is difficult to define precisely what happens beyond this point as partial condensation may occur, giving rise to a mist. Under these conditions the preceding equations will no longer be applicable. However, an approximate solution is obtained by assuming that once the air stream becomes saturated it remains so during its subsequent contact with the water through the column.

13.6.5. Temperature and humidity gradients in a water cooling tower

In a water cooling tower, the temperature profiles depend on whether the air is cooler or hotter than the surface of the water. Near the top, hot water makes contact with the exit air which is at a lower temperature, and sensible heat is therefore transferred both from the water to the interface and from the interface to the air. The air in contact with the water is saturated at the interface temperature and humidity therefore falls from the interface to the air. Evaporation followed by mass transfer of water vapour therefore takes place and latent heat is carried away from the interface in the vapour. The sensible heat removed from the water is then equal to the sum of the latent and sensible heats transferred to the air. Temperature and humidity gradients are then as shown in Figure 13.18a.
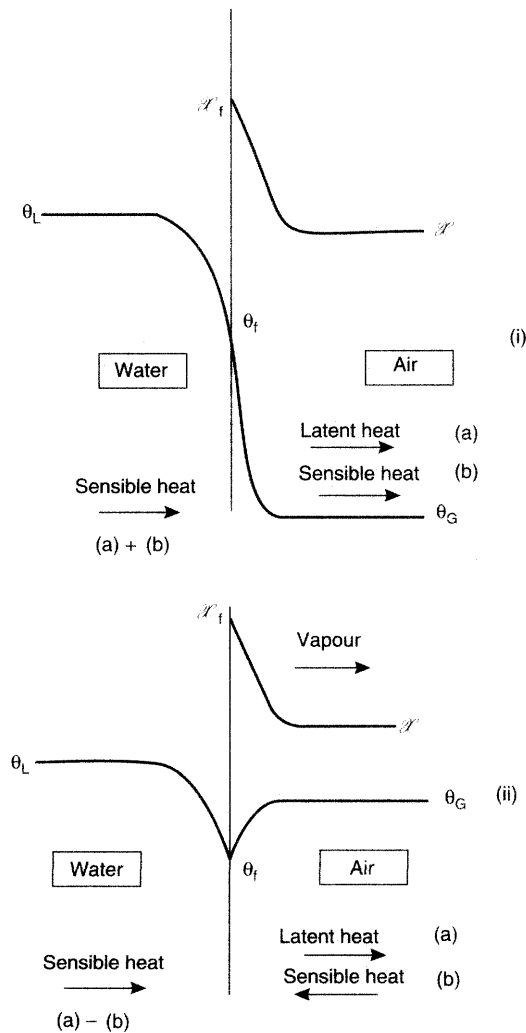
Figure 13.18.   Temperature and humidity gradients in a water cooling tower (i) upper sections of tower (ii) bottom of tower

If the tower is sufficiently tall, the interface temperature can fall below the dry bulb temperature of the air (but not below its wet bulb temperature), and sensible heat will then be transferred from both the air and the water to the interface. The corresponding temperature and humidity profiles are given in Figure 13.18b. In this part of the tower, therefore, the sensible heat removed from the water will be that transferred as latent heat *less* the sensible heat transferred from the air.

13.6.6. Evaluation of heat and mass transfer coefficients

In general, coefficients of heat and mass transfer in the gas phase and the heat transfer coefficient for the liquid phase are not known. They may be determined, however, by carrying out tests in the laboratory or pilot scale using the same packing. If, for the air-water system, a small column is operated at steady water and air rates and the temperature of the water at the top and bottom and the initial and final temperatures and humidities of the air stream are noted, the operating line for the system is obtained. Assuming a value of the ratio $-(h_L/h_D\rho)$, for the slope of the tie-lines AC, etc., the graphical construction is carried out, starting with the conditions at the bottom of the tower. The condition of the gas at the top of the tower is thus calculated and compared with the measured value. If the difference is significant, another value of $-(h_L/h_D\rho)$ is assumed and the procedure repeated. Now that the slope of the tie line is known, the value of the integral of $dH_G/(H_f - H_G)$ over the whole column can be calculated. Since the height of the column is known, the product $h_D a$ is found by solution of equation 13.49. $h_G a$ may then be calculated using the Lewis relation. The values of the three transfer coefficients are therefore obtained at any given flow rates from a single experimental run. The effect of liquid and gas rate may be found by means of a series of similar experiments.

Several workers have measured heat and mass transfer coefficients in water-cooling towers and in humidifying towers. THOMAS and HOUSTON[15], using a tower 2 m high and 0.3 m square in cross-section, fitted with wooden slats, give the following equations for heat and mass transfer coefficients for packed heights greater than 75 mm:

$$h_G a = 3.0 L'^{0.26} G'^{0.72} \tag{13.55}$$

$$h_L a = 1.04 \times 10^4 L'^{0.51} G'^{1.00} \tag{13.56}$$

$$h_D a = 2.95 L'^{0.26} G'^{0.72} \tag{13.57}$$

In these equations, L' and G' are expressed in $kg/m^2 s$, s in $J/kg\ K$, $h_G a$ and $h_L a$ in $W/m^3\ K$, and $h_D a$ in s^{-1}. A comparison of the gas and liquid film coefficients may then be made for a number of gas and liquid rates. Taking the humid heat s as $1.17 \times 10^3\ J/kg\ K$:

	$L' = G' = 0.5$ kg/m²s	$L' = G' = 1.0$ kg/m²s	$L' = G' = 2.0$ kg/m²s
$h_G a$	1780	3510	6915
$h_L a$	3650	10,400	29,600
$h_L a/h_G a$	2.05	2.96	4.28

CRIBB[16] quotes values of the ratio h_L/h_G ranging from 2.4 to 8.5.

It is seen that the liquid film coefficient is generally considerably higher than the gas film coefficient, but that it is not always safe to ignore the resistance to transfer in the liquid phase.

LOWE and CHRISTIE[17] used a 1.3 m square experimental column fitted with a number of different types of packing and measured heat and mass transfer coefficients and pressure drops. They showed that in most cases:

$$h_D a \propto L'^{1-n} G'^m \tag{13.58}$$

The index n was found to vary from about 0.4 to 0.8 according to the type of packing. It will be noted that when $n \approx 0.75$, there is close agreement with the results given by equation 13.57.

The heat-transfer coefficient for the liquid is often large compared with that for the gas phase. As a first approximation, therefore, it can be assumed that the whole of the resistance to heat transfer lies within the gas phase and that the temperature at the water–air interface is equal to the temperature of the bulk of the liquid. Thus, everywhere in the tower, $\theta_f = \theta_L$. This simplifies the calculations, since the lines AC, HJ, and so on, have a slope of $-\infty$, that is, they become parallel to the enthalpy axis.

Some workers have attempted to base the design of humidifiers on the overall heat transfer coefficient between the liquid and gas phases. This treatment is not satisfactory since the quantities of heat transferred through the liquid and through the gas are not the same, as some of the heat is utilised in effecting evaporation at the interface. In fact, at the bottom of a tall tower, the transfer of heat in both the liquid and the gas phases may be towards the interface, as already indicated. A further objection to the use of overall coefficients is that the Lewis relation may be applied only to the heat and mass transfer coefficients in the gas phase.

In the design of commercial units, nomographs[18,19] are available which give a performance characteristic (KaV/L'), where K is a mass transfer coefficient (kg water/m²s) and V is the active cooling volume (m³/m² plan area), as a function of θ, θ_w and (L'/G'). For a given duty (KaV/L') is calculated from:

$$\frac{KaV}{C_L L'} = \int_{\theta_1}^{\theta_2} \frac{d\theta}{(H_f - H_G)} \tag{13.59}$$

and then a suitable tower with this value of (KaV/L') is sought from performance curves[20,21]. In normal applications the performance characteristic varies between 0.5–2.5.

Example 13.9

Water is to be cooled from 328 to 293 K by means of a countercurrent air stream entering at 293 K with a relative humidity of 20 per cent. The flow of air is 0.68 m³/m²s and the water throughput is 0.26 kg/m²s. The whole of the resistance to heat and mass transfer may be assumed to be in the gas phase and the product, $(h_D a)$, may be taken as 0.2 (m/s)(m²/m³), that is 0.2 s⁻¹.

What is the required height of packing and the condition of the exit air stream?

Solution

Assuming the latent heat of water at 273 K = 2495 kJ/kg
specific heat of air = 1.003 kJ/kg K
and specific heat of water vapour = 2.006 kJ/kg K

the enthalpy of the inlet air stream,

$$H_{G1} = 1.003(293 - 273) + \mathscr{H}[2495 + 2.006(293 - 273)]$$

From Figure 13.4:

at $\theta = 293$ K and 20 per cent RH, $\mathscr{H} = 0.003$ kg/kg, and hence

$$H_{G1} = (1.003 \times 20) + 0.003[2495 + (2.006 \times 20)]$$

$$= 27.67 \text{ kJ/kg}$$

In the inlet air, water vapour $= 0.003$ kg/kg dry air

or:

$$\frac{(0.003/18)}{(1/29)} = 0.005 \text{ kmol/kmol dry air}$$

Thus flow of dry air $\qquad = (1 - 0.005)0.68 = 0.677 \text{ m}^3/\text{m}^2\text{s}$

Density of air at 293 K $\qquad = \left(\frac{29}{22.4}\right)\left(\frac{273}{293}\right) = 1.206 \text{ kg/m}^3$

and mass flow of dry air $\qquad = (1.206 \times 0.677) = 0.817 \text{ kg/m}^2\text{s}$

Slope of operating line: $\quad (L'C_L/G') = \dfrac{(0.26 \times 4.18)}{0.817} = 1.33$

The coordinates of the bottom of the operating line are:

$$\theta_{L1} = 293 \text{ K}, \quad H_{G1} = 27.67 \text{ kJ/kg}$$

Hence on an enthalpy–temperature diagram, the operating line of slope 1.33 is drawn through the point $(293, 27.67) = (\theta_{L1}, H_{G1})$.

The top point of the operating line is given by $\theta_{L2} = 328$ K, and H_{G2} is found to be 76.5 kJ/kg (Figure 13.19).

From Figures 13.4 and 13.5 the curve representing the enthalpy of saturated air as a function of temperature is obtained and drawn in. Alternatively, this plot may be calculated from:

$$H_F = C_a(\theta_f - 273) + \mathscr{H}_0[C_w(\theta_f - 273) + \lambda] \text{ kJ/kg}$$

The curve represents the relation between enthalpy and temperature at the interface, that is H_f as a function of θ_f.

It now remains to evaluate the integral $\int dH_G/(H_f - H_G)$ between the limits, $H_{G1} = 27.7$ kJ/kg and $H_{G2} = 76.5$ kJ/kg. Various values of H_G between these limits are selected and the value of θ obtained from the operating line. At this value of θ_1, now θ_f, the corresponding value of H_f is obtained from the curve for saturated air. The working is as follows:

H_G	$\theta = \theta_f$	H_f	$(H_f - H_G)$	$1/(H_f - H_G)$
27.7	293	57.7	30	0.0330
30	294.5	65	35	0.0285
40	302	98	58	0.0172
50	309	137	87	0.0114
60	316	190	130	0.0076
70	323	265	195	0.0051
76.5	328	355	279	0.0035

A plot of $1/(H_f - H_G)$ and H_G is now made as shown in Figure 13.20 from which the area under the curve $= 0.65$. This value may be checked using the approximate solution of CAREY and WILLIAMSON[14]. At the bottom of the column:

$$H_{G1} = 27.7 \text{ kJ/kg}, \quad H_{f1} = 57.7 \text{ kJ/kg} \quad \therefore \; \Delta H_1 = 30 \text{ kJ/kg}$$
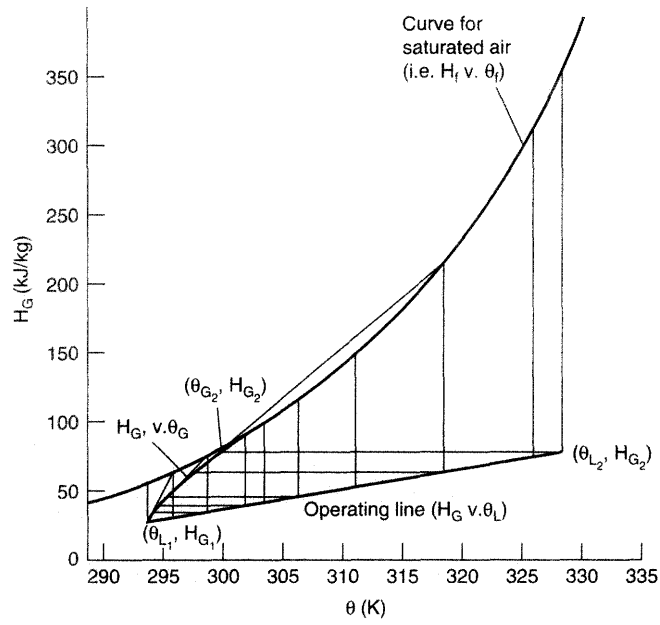
Figure 13.19. Calculation of the height of a water-cooling tower
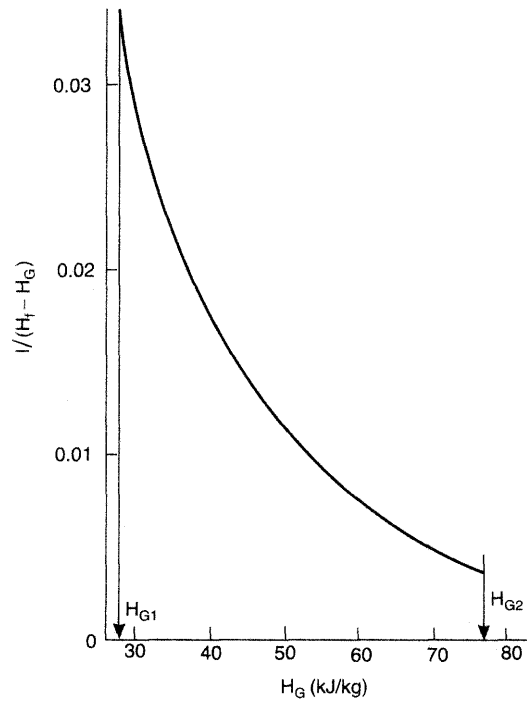
Figure 13.20. Evaluation of the integral of $dH_G/(H_f - H_G)$

At the top of the column:

$$H_{G2} = 76.5 \text{ kJ/kg}, \quad H_{f2} = 355 \text{ kJ/kg} \quad \therefore \Delta H_2 = 279 \text{ kJ/kg}$$

At the mean water temperature of $0.5(328 + 293) = 310.5$ K:

$$H_{Gm} = 52 \text{ kJ/kg}, \quad H_f = 145 \text{ kJ/kg} \quad \therefore \Delta H_m = 93 \text{ kJ/kg}$$

$$\frac{\Delta H_m}{\Delta H_1} = 3.10, \quad \frac{\Delta H_m}{\Delta H_2} = 0.333,$$

and from Figure 13.16: $f = 0.79$

Thus:
$$\frac{(H_{G2} - H_{G1})}{f \Delta H_m} = \frac{(76.5 - 27.7)}{(0.79 \times 93)} = 0.66$$

which agrees well with the value (0.65) obtained by graphical integration.

Thus, in equation 13.53:

$$\text{height of packing}, z = \int_{H_{G1}}^{H_{G2}} \frac{dH_G}{(H_f - H_G)} \frac{G'}{h_D a \rho}$$

$$= \frac{(0.65 \times 0.817)}{(0.2 \times 1.206)}$$

$$= \underline{\underline{2.20 \text{ m}}}$$

Assuming that the resistance to mass transfer lies entirely within the gas phase, the lines connecting θ_L and θ_f are parallel with the enthalpy axis.

In Figure 13.18 a plot of H_G and θ_G is obtained using the construction given in Section 13.6.4 and shown in Figure 13.15. From this curve, the value of θ_{G2} corresponding to $H_{G2} = 76.5$ kJ/kg is 300 K. From Figure 13.5, under these conditions, the exit air has a humidity of 0.019 kg/kg which from Figure 13.4 corresponds to a relative humidity of 83 per cent.

13.6.7. Humidifying towers

If the main function of the tower is to produce a stream of humidified air, the final temperature of the liquid will not be specified, and the humidity of the gas leaving the top of the tower will be given instead. It is therefore not possible to fix any point on the operating line, though its slope can be calculated from the liquid and gas rates. In designing a humidifier, therefore, it is necessary to calculate the temperature and enthalpy, and hence the humidity, of the gas leaving the tower for a number of assumed water outlet temperatures and thereby determine the outlet water temperature resulting in the air leaving the tower with the required humidity. The operating line for this water-outlet temperature is then used in the calculation of the height of the tower required to effect this degree of humidification. The calculation of the dimensions of a humidifier is therefore rather more tedious than that for the water-cooling tower.

In a humidifier in which the make-up liquid is only a small proportion of the total liquid circulating, its temperature approaches the adiabatic saturation temperature θ_s, and remains constant, so that there is no temperature gradient in the liquid. The gas in contact with the liquid surface is approximately saturated and has a humidity $\mathcal{H}_s$.

Thus: $d\theta_L = 0$

and: $\theta_{L1} = \theta_{L2} = \theta_L = \theta_f = \theta_s$

Hence: $-G's \, d\theta_G = h_G a \, dz(\theta_G - \theta_s)$ (from equation 13.42)

and: $-G' \, d\mathcal{H} = h_D \rho a \, dz(\mathcal{H} - \mathcal{H}_s)$ (from equation 13.44)

Integration of these equations gives:

$$\ln \frac{(\theta_{G1} - \theta_s)}{(\theta_{G2} - \theta_s)} = \frac{h_G a}{G's} z \tag{13.60}$$

and:

$$\ln \frac{(\mathcal{H}_s - \mathcal{H}_1)}{(\mathcal{H}_s - \mathcal{H}_2)} = \frac{h_D a \rho}{G'} z \tag{13.61}$$

assuming h_G, h_D, and s remain approximately constant.

From these equations the temperature θ_{G2} and the humidity $\mathcal{H}_2$ of the gas leaving the humidifier may be calculated in terms of the height of the tower. Rearrangement of equation 13.61 gives:

$$\ln \left(1 + \frac{\mathcal{H}_1 - \mathcal{H}_2}{\mathcal{H}_s - \mathcal{H}_1} \right) = -\frac{h_D a \rho}{G'} z$$

or:

$$\frac{(\mathcal{H}_2 - \mathcal{H}_1)}{(\mathcal{H}_s - \mathcal{H}_1)} = 1 - e^{-h_D a \rho z / G'} \tag{13.62}$$

Thus the ratio of the actual increase in humidity produced in the saturator to the maximum possible increase in humidity (that is, the production of saturated gas) is equal to $(1 - e^{-h_D a \rho z / G'})$, and complete saturation of the gas is reached exponentially. A similar relation exists for the change in the temperature of the gas stream:

$$\frac{(\theta_{G1} - \theta_{G2})}{(\theta_{G2} - \theta_s)} = 1 - e^{-h_G a z / G's} \tag{13.63}$$

Further, the relation between the temperature and the humidity of the gas at any stage in the adiabatic humidifier is given by:

$$\frac{d\mathcal{H}}{d\theta_G} = \frac{(\mathcal{H} - \mathcal{H}_s)}{(\theta_G - \theta_s)} \quad \text{(from equation 13.52)}$$

On integration:

$$\ln \frac{(\mathcal{H}_s - \mathcal{H}_2)}{(\mathcal{H}_s - \mathcal{H}_1)} = \ln \frac{(\theta_{G2} - \theta_s)}{(\theta_{G1} - \theta_s)} \tag{13.64}$$

or:

$$\frac{(\mathcal{H}_s - \mathcal{H}_2)}{(\mathcal{H}_s - \mathcal{H}_1)} = \frac{(\theta_{G2} - \theta_s)}{(\theta_{G1} - \theta_s)} \tag{13.65}$$

13.7. SYSTEMS OTHER THAN AIR–WATER

Calculations involving to systems where the Lewis relation is not applicable are very much more complicated because the adiabatic saturation temperature and the wet-bulb temperature do not coincide. Thus the significance of the adiabatic cooling lines on the psychrometric chart is very much restricted. They no longer represent the changes which take place in a gas as it is humidified by contact with liquid initially at the adiabatic saturation temperature of the gas, but simply give the compositions of all gases with the same adiabatic saturation temperature.

Calculation of the change in the condition of the liquid and the gas in a humidification tower is rendered more difficult since equation 13.49, which was derived for the air–water system, is no longer applicable. LEWIS and WHITE[22] have developed a method of

calculation based on the use of a *modified enthalpy* in place of the true enthalpy of the system.

For the air–water system, from equation 13.11:

$$h_G = h_D \rho s \tag{13.66}$$

This relationship applies quite closely for the conditions normally encountered in practice. For other systems, the relation between the heat and mass transfer coefficients in the gas phase is given by:

$$h_G = b h_D \rho s \tag{13.67}$$

where b is approximately constant and generally has a value greater than unity.

For these systems, equation 13.46 becomes:

$$G' s \, d\theta_G = b h_D \rho a \, dz(s\theta_f - s\theta_G) \tag{13.68}$$

Adding equations 13.68 and 13.47 to obtain the relationship corresponding to equation 13.48 gives:

$$G'(s \, d\theta_G + \lambda \, d\mathscr{H}) = h_D \rho a \, dz[(bs\theta_f + \lambda \mathscr{H}_f) - (bs\theta_G + \lambda \mathscr{H})] \tag{13.69}$$

Lewis and White use a *modified latent heat of vaporisation* λ' defined by:

$$b = \frac{\lambda}{\lambda'} \tag{13.70}$$

and a *modified enthalpy* per unit mass of dry gas defined by:

$$H'_G = s(\theta_G - \theta_0) + \lambda' \mathscr{H} \tag{13.71}$$

Substituting in equation 13.67; from equations 13.38, 13.70, and 13.71:

$$G' \, dH_G = b h_D \rho a \, dz(H'_f - H'_G) \tag{13.72}$$

and:

$$\frac{dH_G}{(H'_f - H'_G)} = \frac{b h_D \rho a}{G'} \, dz \tag{13.73}$$

Combining equations 13.37, 13.40, and 13.72:

$$\frac{(H'_G - H'_f)}{(\theta_L - \theta_f)} = -\frac{h_L}{h_D \rho b} \quad \text{(cf. equation 13.50)} \tag{13.74}$$

From equations 13.66 and 13.72:

$$\frac{(H'_G - H'_f)}{(\theta_G - \theta_f)} = \frac{dH_G}{d\theta_G} \quad \text{(cf. equation 13.51)} \tag{13.75}$$

From equations 13.44 and 13.67:

$$\frac{(\mathscr{H} - \mathscr{H}_f)}{(\theta_G - \theta_f)} = b\frac{d\mathscr{H}}{d\theta_G} \quad \text{(cf. equation 13.52)} \tag{13.76}$$

The calculation of conditions within a countercurrent column operating with a system other than air–water is carried out in a similar manner to that already described by

applying equations 13.73, 13.74, and 13.75 in conjunction with equation 3.39:

$$G'(H_{G2} - H_{G1}) = L'C_L(\theta_{L2} - \theta_{L1}) \qquad \text{(equation 13.39)}$$

On an enthalpy-temperature diagram (Figure 13.20) the enthalpy of saturated gas is plotted against its temperature. If equilibrium between the liquid and gas exists at the interface, this curve PQ represents the relation between gas enthalpy and temperature at the interface (H_f v. θ_f). The modified enthalpy of saturated gas is then plotted against temperature (curve RS) to give the relation between H'_f and θ_f. Since b is greater than unity, RS will lie below PQ. By combining equations 13.35, 13.70, and 13.72, H'_G is obtained in terms of H_G.

$$H'_G = \frac{1}{b}[H_G + (b-1)s(\theta_G - \theta_0)] \qquad (13.77)$$

H'_G may be conveniently plotted against H_G for a number of constant temperatures. If b and s are constant, a series of straight lines is obtained. The operating line AB given by equation 13.39 is drawn in Figure 13.21. Point A has coordinates (θ_{L1}, H_{G1}) corresponding to the bottom of the column. Point a has coordinates (θ_{L1}, H'_{G1}), H'_{G1} being obtained from equation 13.77.

Figure 13.21. Construction for height of a column for vapour other than water

From equation 13.72, a line through a, of slope $-(h_L/h_D\rho b)$, will intersect curve RS at c, (θ_{f1}, H'_{f1}) to give the interface conditions at the bottom of the column. The corresponding air enthalpy is given by C, (θ_{f1}, H_{f1}). The difference between the ordinates of c and a then gives the driving force in terms of modified enthalpy at the bottom of the column $(H'_{f1} - H'_{G1})$. A similar construction at other points, such as A', enables the

driving force to be calculated at any other point. Hence $(H'_f - H'_G)$ is obtained as a function of H_G throughout the column. The height of column corresponding to a given change in air enthalpy can be obtained from equation 13.71 since the left-hand side can now be evaluated.
Thus:

$$\int_{H_{G1}}^{H_{G2}} \frac{dH_G}{(H'_f - H'_G)} = \frac{bh_D a \rho}{G'} z \qquad (13.78)$$

The change in the condition of the gas stream is obtained as follows: E, with coordinates (θ_{G1}, H_{G1}), represents the condition of the inlet gas. The modified enthalpy of this gas is given by $e(\theta_{G1}, H'_{G1})$. From equation 13.75 it is seen that ec gives the rate of change of gas enthalpy with temperature $(dH_G/d\theta_G)$ at the bottom of the column. Thus ED, parallel to ec, describes the way in which gas enthalpy changes at the bottom of the column. At some arbitrary small distance from the bottom, F represents the condition of the gas and H gives the corresponding liquid temperature. In exactly the same way the next small change is obtained by drawing a line hj through h parallel to ac. The slope of fj gives the new value of $(dH_G/d\theta_G)$ and therefore the gas condition at a higher point in the column is obtained by drawing FT parallel to fj. In this way the change in the condition of the gas through the column can be followed by continuing the procedure until the gas enthalpy reaches the value H_{G2} corresponding to the top of the column.

A detailed description of the method of construction of psychrometric charts is given by SHALLCROSS and LOW[23], who illustrate their method by producing charts for three systems; air–water, air–benzene and air–toluene at pressures of 1 and 2 bar.

Example 13.10

In a countercurrent packed column, n-butanol flows down at a rate of 0.25 kg/m^2 s and is cooled from 330 to 295 K. Air at 290 K, initially free of n-butanol vapour, is passed up the column at the rate of 0.7 m^3/m^2 s. Calculate the required height of tower and the condition of the exit air.
Data:

Mass transfer coefficient per unit volume, $h_D a = 0.1$ s^{-1}
Psychrometric ratio, $h_G/(h_D \rho_A s) = b = 2.34$
Heat transfer coefficients, $h_L = 3h_G$
Latent heat of vaporisation of n-butanol, $\lambda = 590$ kJ/kg
Specific heat of liquid n-butanol, $C_L = 2.5$ kJ/kg K
Humid heat of gas, $s = 1.05$ kJ/kg K

Temperature (K)	Vapour pressure of butanol (kN/m^2)
295	0.59
300	0.86
305	1.27
310	1.75
315	2.48
320	3.32
325	4.49
330	5.99
335	7.89
340	10.36
345	14.97
350	17.50

Solution

The first stage is to calculate the enthalpy of the saturated gas by way of the saturated humidity, $\mathcal{H}_0$ given by:

$$\mathcal{H}_0 = \frac{P_{w0}}{P - P_{w0}} \frac{M_w}{M_A} = \frac{P_{w0}}{(101.3 - P_{w0})} \left(\frac{74}{29}\right)$$

The enthalpy is then:

$$H_f = \frac{1}{(1 + \mathcal{H}_0)} \times 1.001(\theta_f - 273) + \mathcal{H}_0[2.5(\theta_f - 273) + 590] \text{ kJ/kg}$$

where 1.001 kJ/kg K is the specific heat of dry air.

Thus:
$$H_f = \frac{1.001\theta_f - 273.27}{(1 + \mathcal{H}_0)} + \mathcal{H}_0(2.5\theta_f - 92.5) \text{ kJ/kg moist air}$$

The results of this calculation are presented in the following table and H_f is plotted against θ_f in Figure 13.21.

The modified enthalpy at saturation H'_f is given by:

$$H'_f = \frac{(1.001\theta_f - 273.27)}{(1 + \mathcal{H}_0)} + \mathcal{H}_0[2.5(\theta_f - 273) + \lambda']$$

where from equation 13.70: $\lambda' = \lambda/b = (590/2.34)$ or 252 kJ/kg

$$\therefore \quad H'_f = \frac{(1.001\theta_f - 273.27)}{(1 + \mathcal{H}_0)} + \mathcal{H}_0(2.5\theta_f - 430.5) \text{ kJ/kg moist air}$$

These results are also given in the following Table and plotted as H'_f against θ_f in Figure 13.21.

θ_f (K)	P_{w0} (kN/m²)	$\mathcal{H}_0$ (kg/kg)	$(1.001\theta_f - 273.27)/(1 + \mathcal{H}_0)$ (kJ/kg)	$\mathcal{H}_0(2.5\theta_f - 92.5)$ (kJ/kg)	H_f (kJ/kg)	$\mathcal{H}_0(2.5\theta_f - 430.5)$ (kJ/kg)	H'_f (kJ/kg)
295	0.59	0.0149	21.70	9.61	31.31	4.57	26.28
300	0.86	0.0218	24.45	14.33	40.78	6.97	33.42
305	1.27	0.0324	31.03	21.71	52.74	10.76	41.79
310	1.75	0.0448	35.45	30.58	66.03	15.43	50.88
315	2.48	0.0640	39.52	44.48	84.00	22.85	62.37
320	3.32	0.0864	43.31	61.13	104.44	31.92	75.23
325	4.49	0.1183	46.55	85.18	131.73	45.19	91.74
330	5.99	0.1603	49.18	117.42	166.60	63.23	112.41
335	7.89	0.2154	51.07	160.47	211.54	87.67	138.73
340	10.36	0.2905	51.97	220.05	272.02	121.87	173.83
345	14.97	0.4422	49.98	340.49	390.47	191.03	241.01
350	17.50	0.5325	50.30	416.68	466.98	236.70	287.00

The bottom of the operating line (point a) has coordinates, $\theta_{L1} = 295$ K and H_{G1}, where:

$$H_{G1} = 1.05(290 - 273) = 17.9 \text{ kJ/kg}.$$

At a mean temperature of, say, 310 K, the density of air is:

$$\left(\frac{29}{22.4}\right)\left(\frac{273}{310}\right) = 1.140 \text{ kg/m}^3$$

and: $$G' = (0.70 \times 1.140) = 0.798 \text{ kg/m}^2 \text{ s}$$

Thus, the slope of the operating line becomes:

$$\frac{L'C_L}{G'} = \frac{(0.25 \times 2.5)}{0.798} = 0.783 \text{ kJ/kg K}$$

and this is drawn in as AB in Figure 13.22 and at $\theta_{L2} = 330$ K, $H_{G2} = 46$ kJ/kg.
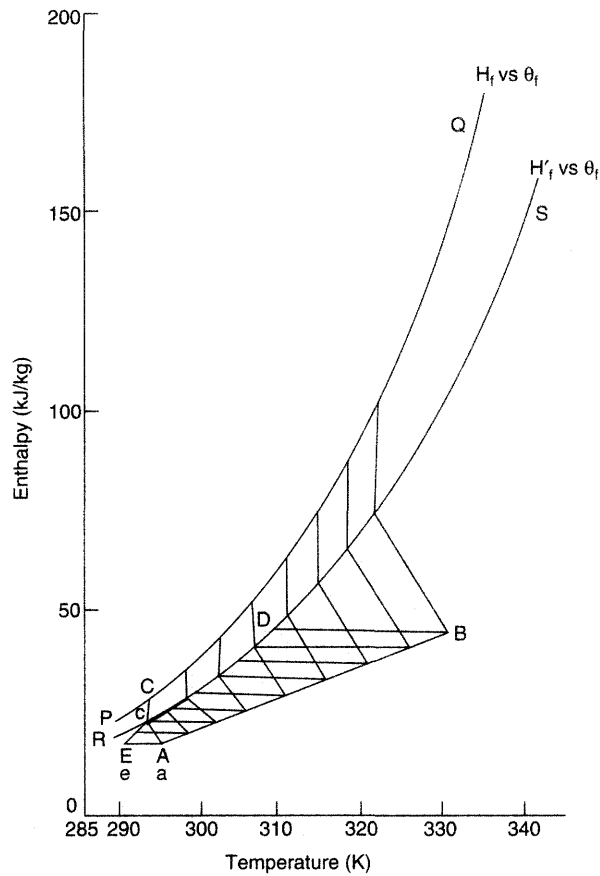
Figure 13.22.   Graphical construction for Example 13.10

From equation 13.77: $H'_G = [H_G + (b - 1)s(\theta_G - \theta_0)]/b$

$$H'_{G1} = \frac{17.9 + (2.34 - 1)1.05(290 - 273)}{2.34} = 17.87 \text{ kJ/kg}$$

Point a coincides with the bottom of the column.

A line is drawn through a of slope $-\dfrac{h_L}{h_D\rho b} = -\left(\dfrac{3h_G}{h_D\rho b}\right) \cdot \left(\dfrac{h_D\rho s}{h_G}\right)$

$$= -3s\ \ = -3.15 \text{ kJ/kg K}$$

This line meets curve RS at c (θ_{f1}, H'_{f1}) to give the interface conditions at the bottom of the column. The corresponding air enthalpy is given by point C whose co-ordinates are:

$$\theta_{f1} = 293 \text{ K} \qquad H_{f1} = 29.0 \text{ kJ/kg}$$

The difference between the ordinates of c and a gives the driving force in terms of the modified enthalpy at the bottom of the column, or:

$$(H'_{f1} - H'_{G1}) = (23.9 - 17.9) = 6.0 \text{ kJ/kg}$$

A similar construction is made at other points along the operating line with the results shown in the following table.

θ_f (K)	H_G (kJ/kg)	H'_G (kJ/kg)	H'_f (kJ/kg)	$(H'_f - H'_G)$ (kJ/kg)	$1/(H'_f - H'_G)$ (kg/kJ)	Mean value in interval	Interval	Value of integral over interval
295	17.9	17.9	23.9	6.0	0.167			
300	22.0	22.0	29.0	7.0	0.143	0.155	4.1	0.636
305	26.0	26.0	35.3	9.3	0.108	0.126	4.0	0.504
310	30.0	30.0	42.1	12.1	0.083	0.096	4.0	0.384
315	34.0	34.0	50.0	16.0	0.063	0.073	4.0	0.292
320	38.1	38.1	57.9	19.8	0.051	0.057	4.1	0.234
325	42.0	42.0	66.7	24.7	0.041	0.046	3.9	0.179
330	46.0	46.0	75.8	29.8	0.034	0.0375	4.0	0.150
						Value of integral $= 2.379$		

from which:

$$\int_{H_{G1}}^{H_{G2}} \frac{dH_G}{H'_f - H'_G} = 2.379$$

Substituting in equation 13.78:

$$\frac{bh_D\rho az}{G'} = 2.379$$

and:

$$z = \frac{(2.379 \times 0.798)}{(2.34 \times 0.1)} = \underline{\underline{8.1 \text{ m}}}$$

It remains to evaluate the change in gas conditions.

Point e, $(\theta_{G1} = 290$ K, $H_{G1} = 17.9$ kJ/kg) represents the condition of the inlet gas. ec is now drawn in, and from equation 13.75, this represents $dH_G/d\theta_G$. As for the air-water system, this construction is continued until the gas enthalpy reaches H_{G2}. The final point is given by D at which $\theta_{G2} = 308$ K.

It is fortuitous that, in this problem, $H'_G = H_G$. This is not always the case and reference should be made to Section 13.7 for elaboration of this point.

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13.10. NOMENCLATURE

		Units in SI system	Dimensions in M, N, L, T, θ
A	Interfacial area	m^2	L^2
A_b	Base area of hyperbolic tower	m^2	L^2
a	Interfacial area per unit volume of column	m^2/m^3	L^{-1}
b	Psychrometric ratio $(h/h_D \rho_A s)$	—	—
C_a	Specific heat of gas at constant pressure	J/kg K	L^2 T$^{-2}\theta^{-1}$
C_L	Specific heat of liquid	J/kg K	L^2 T$^{-2}\theta^{-1}$
C_p	Specific heat of gas and vapour mixture at constant pressure	J/kg K	L^2 T$^{-2}\theta^{-1}$
C_s	Specific heat of solid	J/kg K	L^2 T$^{-2}\theta^{-1}$
C_t	Performance coefficient or efficiency factor	—	—
C_w	Specific heat of vapour at constant pressure	J/kg K	L^2 T$^{-2}\theta^{-1}$
c	Mass concentration of vapour	kg/m^3	ML^{-3}
c_0	Mass concentration of vapour in saturated gas	kg/m^3	ML^{-3}
D_t	Duty coefficient of tower (equation 13.31)	—	—
f	Correction factor for mean driving force	—	—
G'	Mass rate of flow of gas per unit area	kg/m^2 s	ML^{-2} T^{-1}
H	Enthalpy of humid gas per unit mass of dry gas	J/kg	L^2 T^{-2}
H_a	Enthalpy per unit mass, of dry gas	J/kg	L^2 T^{-2}
H_w	Enthalpy per unit mass, of vapour	J/kg	L^2 T^{-2}
H_1	Enthalpy of stream of gas, per unit mass of dry gas	J/kg	L^2 T^{-2}
H_2	Enthalpy of another stream of gas, per unit mass of dry gas	J/kg	L^2 T^{-2}
H_3	Enthalpy per unit mass of liquid or vapour	J/kg	L^2 T^{-2}
H'	Modified enthalpy of humid gas defined by (13.69)	J/kg	L^2 T^{-2}
ΔH	Enthalpy driving force $(H_f - H_G)$	J/kg	L^2 T^{-2}
$\Delta H'$	Change in air enthalpy on passing through tower	J/kg	L^2 T^{-2}
h	Heat transfer coefficient	W/m^2 K	MT$^{-3}\theta^{-1}$
h_D	Mass transfer coefficient	kmol/(kmol/m^3)m^2 s	LT^{-1}
h_G	Heat transfer coefficient for gas phase	W/m^2 K	MT$^{-3}\theta^{-1}$
h_L	Heat transfer coefficient for liquid phase	W/m^2 K	MT$^{-3}\theta^{-1}$
$\mathscr{H}$	Humidity	kg/kg	—
$\mathscr{H}_s$	Humidity of gas saturated at the adiabatic saturation temperature	kg/kg	—
$\mathscr{H}_w$	Humidity of gas saturated at the wet-bulb temperature	kg/kg	—
$\mathscr{H}_0$	Humidity of saturated gas	kg/kg	—
$\mathscr{H}_1$	Humidity of a gas stream	kg/kg	—
$\mathscr{H}_2$	Humidity of second gas stream	kg/kg	—
L'	Mass rate of flow of liquid per unit area	kg/m^2 s	ML^{-2} T^{-1}
M_A	Molecular weight of gas	kg/kmol	MN^{-1}
M_w	Molecular weight of vapour	kg/kmol	MN^{-1}
m, m_1, m_2	Masses of dry gas	kg	M
m_3	Mass of liquid or vapour	kg	M
P	Total pressure	N/m^2	ML^{-1} T^{-2}
P_A	Mean partial pressure of gas	N/m^2	ML^{-1} T^{-2}
P_w	Partial pressure of vapour	N/m^2	ML^{-1} T^{-2}
P_{w0}	Partial pressure of vapour in saturated gas	N/m^2	ML^{-1} T^{-2}
Q	Rate of transfer of heat to liquid surface	W	ML^2 T^{-3}
$\mathbf{R}$	Universal gas constant	8314 J/kmol K	MN^{-1} L^2 T$^{-2}\theta^{-1}$
s	Humid heat of gas	J/kg K	L^2 T$^{-2}\theta^{-1}$
T	Absolute temperature	K	θ

		Units in SI system	Dimensions in M, N, L, T, θ
ΔT	Change in water temperature in passing through the tower	K	θ
$\Delta T'$	(Temperature of air leaving packing — ambient dry-bulb temperature)	K	θ
V	Active volume per plan area of column	m^3/m^2	L
W_L	Water loading on tower	kg/s	MT^{-1}
w	Rate of evaporation	kg/s	MT^{-1}
Z	Percentage humidity	—	—
z	Height from bottom of tower	m	L
z_t	Height of cooling tower	m	L
θ	Temperature of gas stream	K	θ
θ_0	Reference temperature, taken as the melting point of the material	K	θ
θ_s	Adiabatic saturation temperature	K	θ
θ_w	Wet bulb temperature	K	θ
λ	Latent heat of vaporisation per unit mass, at datum temperature	J/kg	$L^2\,T^{-2}$
λ_f	Latent heat of freezing per unit mass, at datum temperature	J/kg	$L^2\,T^{-2}$
λ'	Modified latent heat of vaporisation per unit mass defined by (13.68)	J/kg	$L^2\,T^{-2}$
ρ	Mean density of gas and vapour	kg/m^3	ML^{-3}
ρ_A	Mean density of gas at partial pressure P_A	kg/m^3	ML^{-3}
Pr	Prandtl number	—	—
Sc	Schmidt number	—	—

Suffixes 1, 2, f, L, G denote conditions at the bottom of the tower, the top of the tower, the interface, the liquid, and the gas, respectively.

Suffix m refers to the mean water temperature.

Appendix

A1. TABLES OF PHYSICAL PROPERTIES

Table 1. Thermal conductivities of liquids*

A linear variation with temperature may be assumed. The extreme values given constitute also the temperature limits over which the data are recommended.

Liquid	k (W/m K)	(K)	k (Btu/h ft °F)
Acetic acid 100 per cent	0.171	293	0.099
50 per cent	0.35	293	0.20
Acetone	0.177	303	0.102
	0.164	348	0.095
Allyl alcohol	0.180	298 to 303	0.104
Ammonia	0.50	258 to 303	0.29
Ammonia, aqueous	0.45	293	0.261
	0.50	333	0.29
Amyl acetate	0.144	283	0.083
Amyl alcohol (n-)	0.163	303	0.094
	0.154	373	0.089
Amyl alcohol (iso-)	0.152	303	0.088
	0.151	348	0.087
Aniline	0.173	273 to 293	0.100
Benzene	0.159	303	0.092
	0.151	333	0.087
Bromobenzene	0.128	303	0.074
	0.121	373	0.070
Butyl acetate (n-)	0.147	298 to 303	0.085
Butyl alcohol (n-)	0.168	303	0.097
	0.164	348	0.095
Butyl alcohol (iso-)	0.157	283	0.091
Calcium chloride brine			
30 per cent	0.55	303	0.32
15 per cent	0.59	303	0.34
Carbon disulphide	0.161	303	0.093
	0.152	348	0.088
Carbon tetrachloride	0.185	273	0.107
	0.163	341	0.094
Chlorobenzene	0.144	283	0.083
Chloroform	0.138	303	0.080

Liquid	k (W/m K)	(K)	k (Btu/h ft °F)
Hexane (n-)	0.138	303	0.080
	0.135	333	0.078
Heptyl alcohol (n-)	0.163	303	0.094
	0.157	348	0.091
Hexyl alcohol (n-)	0.161	303	0.093
	0.156	348	0.090
Kerosene	0.149	293	0.086
	0.140	348	0.081
Mercury	8.36	301	4.83
Methyl alcohol 100 per cent	0.215	293	0.124
80 per cent	0.267	293	0.154
60 per cent	0.329	293	0.190
40 per cent	0.405	293	0.234
20 per cent	0.492	293	0.284
100 per cent	0.197	323	0.114
Methyl chloride	0.192	258	0.111
	0.154	303	0.089
Nitrobenzene	0.164	303	0.095
	0.152	373	0.088
Nitromethane	0.216	303	0.125
	0.208	333	0.120
Nonane (n-)	0.145	303	0.084
	0.142	333	0.082
Octane (n-)	0.144	303	0.083
	0.140	333	0.081
Oils, Petroleum	0.138-0.156	273	0.08-0.09
Oil, Castor	0.180	293	0.104
	0.173	373	0.100
	0.168	293	0.097

Table 1. (continued)

Liquid	k (W/m K)	(K)	k (Btu/h ft °F)
Cymene (para)	0.135	303	0.078
	0.137	333	0.079
Decane (n-)	0.147	303	0.085
	0.144	333	0.083
Dichlorodifluoromethane	0.099	266	0.057
	0.092	289	0.053
	0.083	311	0.048
	0.074	333	0.043
	0.066	355	0.038
Dichloroethane	0.142	323	0.082
Dichloromethane	0.192	258	0.111
	0.166	303	0.096
Ethyl acetate	0.175	293	0.101
Ethyl alcohol 100 per cent	0.182	293	0.105
80 per cent	0.237	293	0.137
60 per cent	0.305	293	0.176
40 per cent	0.388	293	0.224
20 per cent	0.486	293	0.281
100 per cent	0.151	323	0.087
Ethyl benzene	0.149	303	0.086
	0.142	333	0.082
Ethyl bromide	0.121	293	0.070
Ethyl ether	0.138	303	0.080
	0.135	348	0.078
Ethyl iodide	0.111	313	0.064
	0.109	348	0.063
Ethylene glycol	0.265	273	0.153
Gasoline	0.135	303	0.078
Glycerol 100 per cent	0.284	293	0.164
80 per cent	0.327	293	0.189
60 per cent	0.381	293	0.220
40 per cent	0.448	293	0.259
20 per cent	0.481	293	0.278
100 per cent	0.284	373	0.164
Heptane (n-)	0.140	303	0.081
	0.137	333	0.079

Liquid	k (W/m K)	(K)	k (Btu/h ft °F)
Oil, Olive	0.164	373	0.095
Paraldehyde	0.145	303	0.084
	0.135	373	0.078
Pentane (n-)	0.135	303	0.078
	0.128	348	0.074
Perchloroethylene	0.159	323	0.092
Petroleum ether	0.130	303	0.075
	0.126	348	0.073
Propyl alcohol (n-)	0.171	303	0.099
	0.164	348	0.095
Propyl alcohol (iso-)	0.157	303	0.091
	0.155	333	0.090
Sodium	0.85	373	49
	0.80	483	46
Sodium chloride brine 25.0 per cent	0.57	303	0.33
12.5 per cent	0.59	303	0.34
Sulphuric acid 90 per cent	0.36	303	0.21
60 per cent	0.43	303	0.25
30 per cent	0.52	303	0.30
Sulphur dioxide	0.22	258	0.128
	0.192	303	0.111
Toluene	0.149	303	0.086
	0.145	348	0.084
-trichloroethane	0.133	323	0.077
Trichloroethylene	0.138	323	0.080
Turpentine	0.128	288	0.074
Vaseline	0.184	288	0.106
Water	0.57	273	0.330
	0.615	303	0.356
	0.658	333	0.381
	0.688	353	0.398
Xylene (ortho-)	0.155	293	0.090
(meta-)	0.155	293	0.090

Table 2.   Latent heats of vaporisation*

Example: For water at 373 K, $\theta_c - \theta = (647 - 373) = 274$ K, and the latent heat of vaporisation is 2257 kJ/kg

No.	Compound	Range $\theta_c - \theta$ (°F)	θ_c (°F)	Range $\theta_c - \theta$ (K)	θ_c (K)	No.	Compound	Range $\theta_c - \theta$ (°F)	θ_c (°F)	Range $\theta_c - \theta$ (K)	θ_c (K)
18	Acetic acid	180–405	610	100–225	594	2	Freon-12 (CCl_2F_2)	72–360	232	40–200	384
22	Acetone	216–378	455	120–210	508	5	Freon-21 ($CHCl_2F$)	126–450	354	70–250	451
29	Ammonia	90–360	271	50–200	406	6	Freon-22 ($CHClF_2$)	90–306	205	50–170	369
13	Benzene	18–720	552	10–00	562	1	Freon-113 (CCl_2F-$CClF_2$)	162–450	417	90–250	487
16	Butane	162–360	307	90–200	426	10	Heptane	36–540	512	20–300	540
21	Carbon dioxide	18–180	88	10–100	304	11	Hexane	90–450	455	50–225	508
4	Carbon disulphide	252–495	523	140–275	546	15	Isobutane	144–360	273	80–200	407
2	Carbon tetrachloride	54–450	541	30–250	556	27	Methanol	72–450	464	40–250	513
7	Chloroform	252–495	505	140–275	536	20	Methyl chloride	126–450	289	70–250	416
8	Dichloromethane	270–450	421	150–250	489	19	Nitrous oxide	45–270	97	25–150	309
3	Diphenyl	315–720	981	175–400	800	9	Octane	54–540	565	30–300	569
25	Ethane	45–270	90	25–150	305	12	Pentane	36–360	387	20–200	470
26	Ethyl alcohol	36–252	469	20–140	516	23	Propane	72–360	205	40–200	369
28	Ethyl alcohol	252–540	469	140–300	516	24	Propyl alcohol	36–360	507	20–200	537
17	Ethyl chloride	180–450	369	100–250	460	14	Sulphur dioxide	162–288	314	90–160	430
13	Ethyl ether	18–720	381	10–00	467	30	Water	180–900	705	100–500	647
2	Freon-11 (CCl_3F)	126–450	389	70–250	471						

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Latent heats of vaporisation
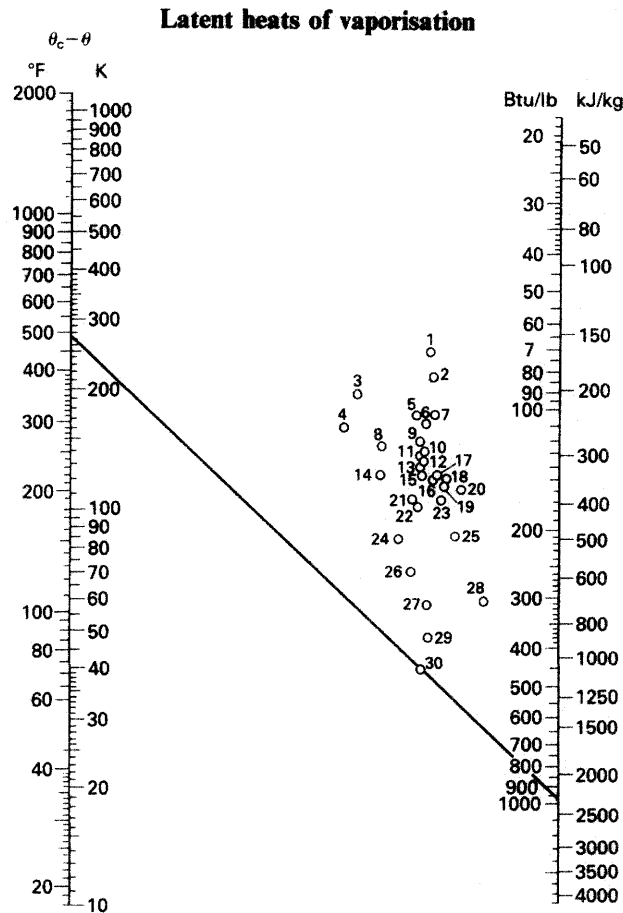
Table 3.   Specific heats of liquids*

No.	Liquid	Range (K)
29	Acetic acid, 100 per cent	273–353
32	Acetone	293–323
52	Ammonia	203–323
37	Amyl alcohol	223–298
26	Amyl acetate	273–373
30	Aniline	273–403
23	Benzene	283–353
27	Benzyl alcohol	253–303
10	Benzyl chloride	243–303
49	Brine, 25 per cent CaCl$_2$	233–293
51	Brine, 25 per cent NaCl	233–293
44	Butyl alcohol	273–373
2	Carbon disulphide	173–298
3	Carbon tetrachloride	283–333
8	Chlorobenzene	273–373
4	Chloroform	273–323
21	Decane	193–298
6A	Dichloroethane	243–333
5	Dichloromethane	233–323
15	Diphenyl	353–393
22	Diphenylmethane	303–373
16	Diphenyl oxide	273–473
16	Dowtherm A	273–473
24	Ethyl acetate	223–298
42	Ethyl alcohol, 100 per cent	303–353
46	Ethyl alcohol, 95 per cent	293–353
50	Ethyl alcohol, 50 per cent	293–353
25	Ethyl benzene	273–373
1	Ethyl bromide	278–298
13	Ethyl chloride	243–313
36	Ethyl ether	173–298
7	Ethyl iodide	273–373
39	Ethylene glycol	233–473
2A	Freon-11 (CCl$_3$F)	253–343
6	Freon-12 (CCl$_2$F$_2$)	233–288
4A	Freon-21 (CHCl$_2$F)	253–343
7A	Freon-22 (CHClF$_2$)	253–333
3A	Freon-113 (CCl$_2$F-CClF$_2$)	253–343
38	Glycerol	233–293
28	Heptane	273–333
35	Hexane	193–293
48	Hydrochloric acid, 30 per cent	293–373
41	Isoamyl alcohol	283–373
43	Isobutyl alcohol	273–373
47	Isopropyl alcohol	253–323
31	Isopropyl ether	193–293
40	Methyl alcohol	233–293
13A	Methyl chloride	193–293
14	Naphthalene	363–473
12	Nitrobenzene	273–373
34	Nonane	223–298
33	Octane	223–298
3	Perchloroethylene	243–413
45	Propyl alcohol	253–373
20	Pyridine	223–298
9	Sulphuric acid, 98 per cent	283–318
11	Sulphur dioxide	253–373
23	Toluene	273–333
53	Water	283–473
19	Xylene (ortho)	273–373
18	Xylene (meta)	273–373
17	Xylene (para)	273–373
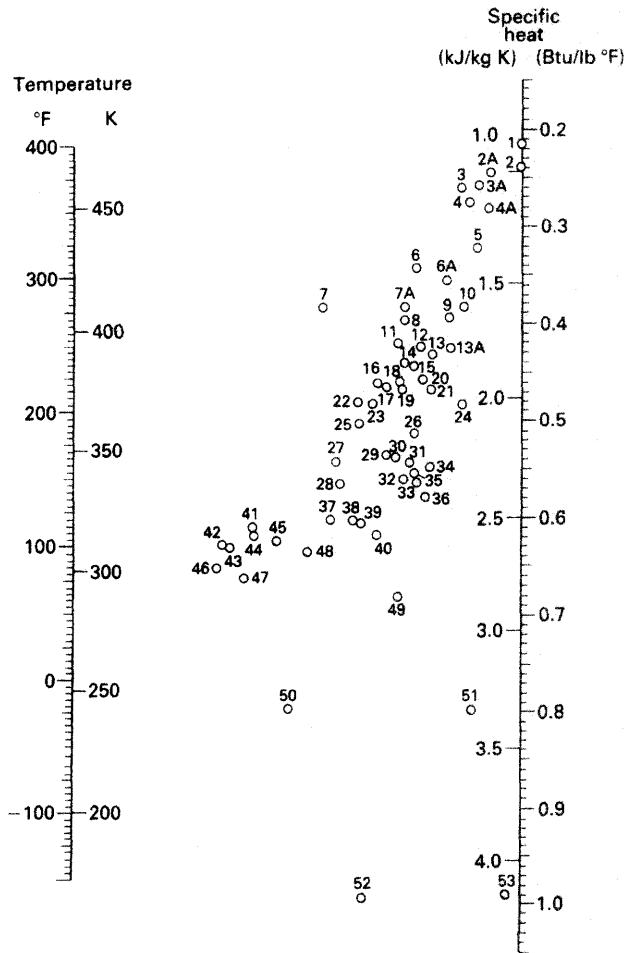
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Specific heats of liquids

Table 4.   Specific heats at constant pressure of gases and vapours at 101.3 kN/m²*

No.	Gas	Range (K)	No.	Gas	Range (K)
10	Acetylene	273–473	1	Hydrogen	273–873
15	Acetylene	473–673	2	Hydrogen	873–1673
16	Acetylene	673–1673	35	Hydrogen bromide	273–1673
27	Air	273–1673	30	Hydrogen chloride	273–1673
12	Ammonia	273–873	20	Hydrogen fluoride	273–1673
14	Ammonia	873–1673	36	Hydrogen iodide	273–1673
18	Carbon dioxide	273–673	19	Hydrogen sulphide	273–973
24	Carbon dioxide	673–1673	21	Hydrogen sulphide	973–1673
26	Carbon monoxide	273–1673	5	Methane	273–573
32	Chlorine	273–473	6	Methane	573–973
34	Chlorine	473–1673	7	Methane	973–1673
3	Ethane	273–473	25	Nitric oxide	273–973
9	Ethane	473–873	28	Nitric oxide	973–1673
8	Ethane	873–1673	26	Nitrogen	273–1673
4	Ethylene	273–473	23	Oxygen	273–773
11	Ethylene	473–873	29	Oxygen	773–1673
13	Ethylene	873–1673	33	Sulphur	573–1673
17B	Freon-11 (CCl_3F)	273–423	22	Sulphur dioxide	273–673
17C	Freon-21 ($CHCl_2F$)	273–423	31	Sulphur dioxide	673–1673
17A	Freon-22 ($CHClF_2$)	273–423	17	Water	273–1673
17D	Freon-113 (CCl_2F-$CClF_2$)	273–423			

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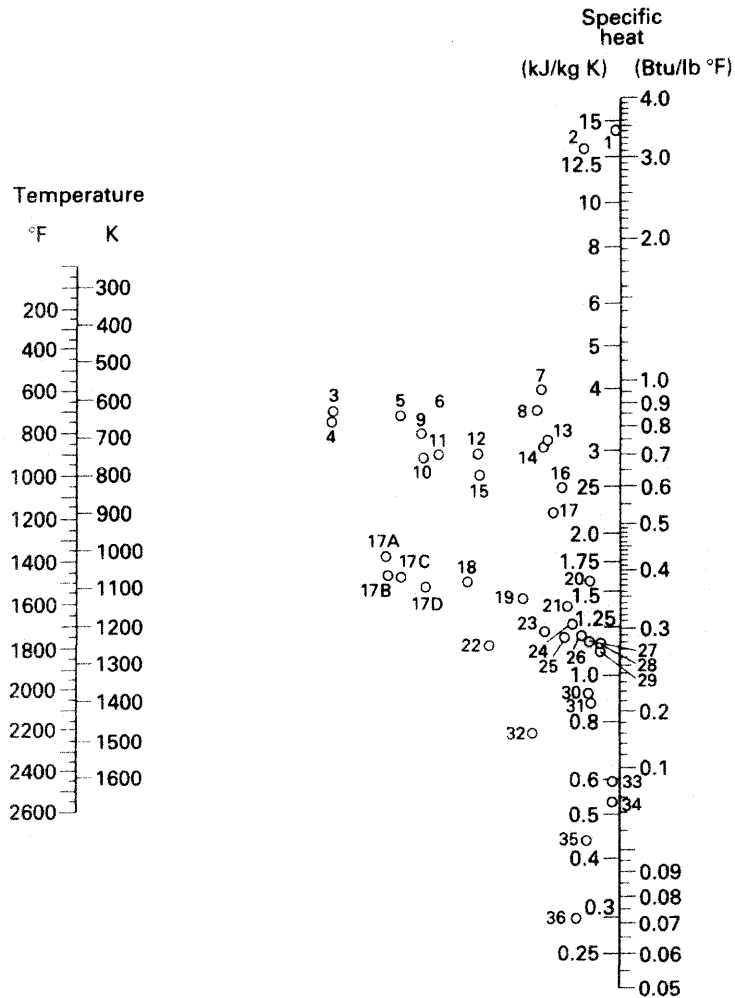
Table 5. Viscosity of water*

Temperature (θ) (K)	Viscosity (μ) (mN s/m^2)	Temperature (θ) (K)	Viscosity (μ) (mN s/m^2)	Temperature (θ) (K)	Viscosity (μ) (mN s/m^2)
273	1.7921	306	0.7523	340	0.4233
274	1.7313	307	0.7371	341	0.4174
275	1.6728	308	0.7225	342	0.4117
276	1.6191	309	0.7085	343	0.4061
277	1.5674	310	0.6947	344	0.4006
278	1.5188	311	0.6814	345	0.3952
279	1.4728	312	0.6685	346	0.3900
280	1.4284	313	0.6560	347	0.3849
281	1.3860	314	0.6439	348	0.3799
282	1.3462	315	0.6321	349	0.3750
283	1.3077	316	0.6207	350	0.3702
284	1.2713	317	0.6097	351	0.3655
285	1.2363	318	0.5988	352	0.3610
286	1.2028	319	0.5883	353	0.3565
287	1.1709	320	0.5782	354	0.3521
288	1.1404	321	0.5683	355	0.3478
289	1.1111	322	0.5588	356	0.3436
290	1.0828	323	0.5494	357	0.3395
291	1.0559	324	0.5404	358	0.3355
292	1.0299	325	0.5315	359	0.3315
293	1.0050	326	0.5229	360	0.3276
293.2	1.0000	327	0.5146	361	0.3239
294	0.9810	328	0.5064	362	0.3202
295	0.9579	329	0.4985	363	0.3165
296	0.9358	330	0.4907	364	0.3130
297	0.9142	331	0.4832	365	0.3095
298	0.8937	332	0.4759	366	0.3060
299	0.8737	333	0.4688	367	0.3027
300	0.8545	334	0.4618	368	0.2994
301	0.8360	335	0.4550	369	0.2962
302	0.8180	336	0.4483	370	0.2930
303	0.8007	337	0.4418	371	0.2899
304	0.7840	338	0.4355	372	0.2868
305	0.7679	339	0.4293	373	0.2838

*Calculated by the formula:

$$1/\mu = 21.482 \left[(\theta - 281.435) + \sqrt{(8078.4 + (\theta - 281.435)^2}\, \right] - 1200 \ (\mu \text{ in Ns/m}^2)$$

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Table 6.   Thermal conductivities of gases and vapours

The extreme temperature values given constitute the experimental range. For extrapolation to other temperatures, it is suggested that the data given be plotted as $\log k$ vs. $\log T$, or that use be made of the assumption that the ratio $C_p \mu / k$ is practically independent of temperature (and of pressure, within moderate limits).

Substance	k (W/m K)	(K)	k (Btu/h ft °F)	Substance	k (W/m K)	(K)	k (Btu/h ft °F)
Acetone	0.0098	273	0.0057	Chlorine	0.0074	273	0.0043
	0.0128	319	0.0074	Chloroform	0.0066	273	0.0038
	0.0171	373	0.0099		0.0080	319	0.0046
	0.0254	457	0.0147		0.0100	373	0.0058
Acetylene	0.0118	198	0.0068		0.0133	457	0.0077
	0.0187	273	0.0108	Cyclohexane	0.0164	375	0.0095
	0.0242	323	0.0140				
	0.0298	373	0.0172	Dichlorodifluoromethane	0.0083	273	0.0048
Air	0.0164	173	0.0095		0.0111	323	0.0064
	0.0242	273	0.0140		0.0139	373	0.0080
	0.0317	373	0.0183		0.0168	423	0.0097
	0.0391	473	0.0226				
	0.0459	573	0.0265	Ethane	0.0114	203	0.0066
Ammonia	0.0164	213	0.0095		0.0149	239	0.0086
	0.0222	273	0.0128		0.0183	273	0.0106
	0.0272	323	0.0157		0.0303	373	0.0175
	0.0320	373	0.0185	Ethyl acetate	0.0125	319	0.0072
					0.0166	373	0.0096
Benzene	0.0090	273	0.0052		0.0244	457	0.0141
	0.0126	319	0.0073	alcohol	0.0154	293	0.0089
	0.0178	373	0.0103		0.0215	373	0.0124
	0.0263	457	0.0152	chloride	0.0095	273	0.0055
	0.0305	485	0.0176		0.0164	373	0.0095
Butane (n-)	0.0135	273	0.0078		0.0234	457	0.0135
	0.0234	373	0.0135		0.0263	485	0.0152
(iso-)	0.0138	273	0.0080	ether	0.0133	273	0.0077
	0.0241	373	0.0139		0.0171	319	0.0099
					0.0227	373	0.0131
Carbon dioxide	0.0118	223	0.0068		0.0327	457	0.0189
	0.0147	273	0.0085		0.0362	485	0.0209
	0.0230	373	0.0133	Ethylene	0.0111	202	0.0064
	0.0313	473	0.0181		0.0175	273	0.0101
	0.0396	573	0.0228		0.0267	323	0.0131
disulphide	0.0069	273	0.0040		0.0279	373	0.0161
	0.0073	280	0.0042				
monoxide	0.0071	84	0.0041	Heptane (n-)	0.0194	473	0.0112
	0.0080	94	0.0046		0.0178	373	0.0103
	0.0234	213	0.0135	Hexane (n-)	0.0125	273	0.0072
tetrachloride	0.0071	319	0.0041		0.0138	293	0.0080
	0.0090	373	0.0052	Hexene	0.0106	273	0.0061
	0.0112	457	0.0065		0.0109	373	0.0189
Hydrogen	0.0113	173	0.065		0.0225	457	0.0130
	0.0144	223	0.083		0.0256	485	0.0148
	0.0173	273	0.100	Methylene chloride	0.0067	273	0.0039
	0.0199	323	0.115		0.0085	319	0.0049
	0.0223	373	0.129		0.0109	373	0.0063
	0.0308	573	0.178		0.0164	485	0.0095

Table 6. (*continued*)

Substance	k (W/m K)	(K)	k (Btu/h ft °F)	Substance	k (W/m K)	(K)	k (Btu/h ft °F)
Hydrogen and carbon dioxide		273		Nitric oxide	0.0178	203	0.0103
0 per cent H_2	0.0144		0.0083		0.0239	273	0.0138
20 per cent	0.0286		0.0165	Nitrogen	0.0164	173	0.0095
40 per cent	0.0467		0.0270		0.0242	273	0.0140
60 per cent	0.0709		0.0410		0.0277	323	0.0160
80 per cent	0.1070		0.0620		0.0312	373	0.0180
100 per cent	0.173		0.10	Nitrous oxide	0.0116	201	0.0067
Hydrogen and nitrogen		273			0.0157	273	0.0087
0 per cent H_2	0.0230		0.0133		0.0222	373	0.0128
20 per cent	0.0367		0.0212				
40 per cent	0.0542		0.0313	Oxygen	0.0164	173	0.0095
60 per cent	0.0758		0.0438		0.0206	223	0.0119
80 per cent	0.1098		0.0635		0.0246	273	0.0142
Hydrogen and nitrous oxide		273			0.0284	323	0.0164
0 per cent H_2	0.0159		0.0092		0.0321	373	0.0185
20 per cent	0.0294		0.0170				
40 per cent	0.0467		0.0270				
60 per cent	0.0709		0.0410	Pentane (n-)	0.0128	273	0.0074
80 per cent	0.112		0.0650		0.0144	293	0.0083
Hydrogen sulphide	0.0132	273	0.0076	(iso-)	0.0125	273	0.0072
					0.0220	373	0.0127
Mercury	0.0341	473	0.0197	Propane	0.0151	273	0.0087
Methane	0.0173	173	0.0100		0.0261	373	0.0151
	0.0251	223	0.0145				
	0.0302	273	0.0175	Sulphur dioxide	0.0087	273	0.0050
	0.0372	323	0.0215		0.0119	373	0.0069
Methyl alcohol	0.0144	273	0.0083				
	0.0222	373	0.0128	Water vapour	0.0208	319	0.0120
acetate	0.0102	273	0.0059		0.0237	373	0.0137
	0.0118	293	0.0068		0.0324	473	0.0187
chloride	0.0092	273	0.0053		0.0429	573	0.0248
	0.0125	319	0.0072		0.0545	673	0.0315
	0.0163	373	0.0094		0.0763	773	0.0441

Table 7.   Viscosities of gases*
Co-ordinates for use with graph on facing page

No.	Gas	X	Y
1	Acetic acid	7.7	14.3
2	Acetone	8.9	13.0
3	Acetylene	9.8	14.9
4	Air	11.0	20.0
5	Ammonia	8.4	16.0
6	Argon	10.5	22.4
7	Benzene	8.5	13.2
8	Bromine	8.9	19.2
9	Butene	9.2	13.7
10	Butylene	8.9	13.0
11	Carbon dioxide	9.5	18.7
12	Carbon disulphide	8.0	16.0
13	Carbon monoxide	11.0	20.0
14	Chlorine	9.0	18.4
15	Chloroform	8.9	15.7
16	Cyanogen	9.2	15.2
17	Cyclohexane	9.2	12.0
18	Ethane	9.1	14.5
19	Ethyl acetate	8.5	13.2
20	Ethyl alcohol	9.2	14.2
21	Ethyl chloride	8.5	15.6
22	Ethyl ether	8.9	13.0
23	Ethylene	9.5	15.1
24	Fluorine	7.3	23.8
25	Freon-11 (CCl_3F)	10.6	15.1
26	Freon-12 (CCl_2F_2)	11.1	16.0
27	Freon-21 ($CHCl_2F$)	10.8	15.3
28	Freon-22 ($CHClF_2$)	10.1	17.0
29	Freon-113 (CCl_2F-$CClF_3$)	11.3	14.0
30	Helium	10.9	20.5
31	Hexane	8.6	11.8
32	Hydrogen	11.2	12.4
33	$3H_2 + 1N_2$	11.2	17.2
34	Hydrogen bromide	8.8	20.9
35	Hydrogen chloride	8.8	18.7
36	Hydrogen cyanide	9.8	14.9
37	Hydrogen iodide	9.0	21.3
38	Hydrogen sulphide	8.6	18.0
39	Iodine	9.0	18.4
40	Mercury	5.3	22.9
41	Methane	9.9	15.5
42	Methyl alcohol	8.5	15.6
43	Nitric oxide	10.9	20.5
44	Nitrogen	10.6	20.0
45	Nitrosyl chloride	8.0	17.6
46	Nitrous oxide	8.8	19.0
47	Oxygen	11.0	21.3
48	Pentane	7.0	12.8
49	Propane	9.7	12.9
50	Propyl alcohol	8.4	13.4
51	Propylene	9.0	13.8
52	Sulphur dioxide	9.6	17.0
53	Toluene	8.6	12.4
54	2, 3, 3-trimethylbutane	9.5	10.5
55	Water	8.0	16.0
56	Xenon	9.3	23.0

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by Perry, R. H. and Green, D. W. (eds) 6th edn. Copyright
1984, McGraw-Hill Book Company Inc.)
[To convert to lb/ft h multiply by 2.42.]

Viscosities of gases

Temperature

(K)   (°F)

Viscosity
(mN s/m²) or (cP)
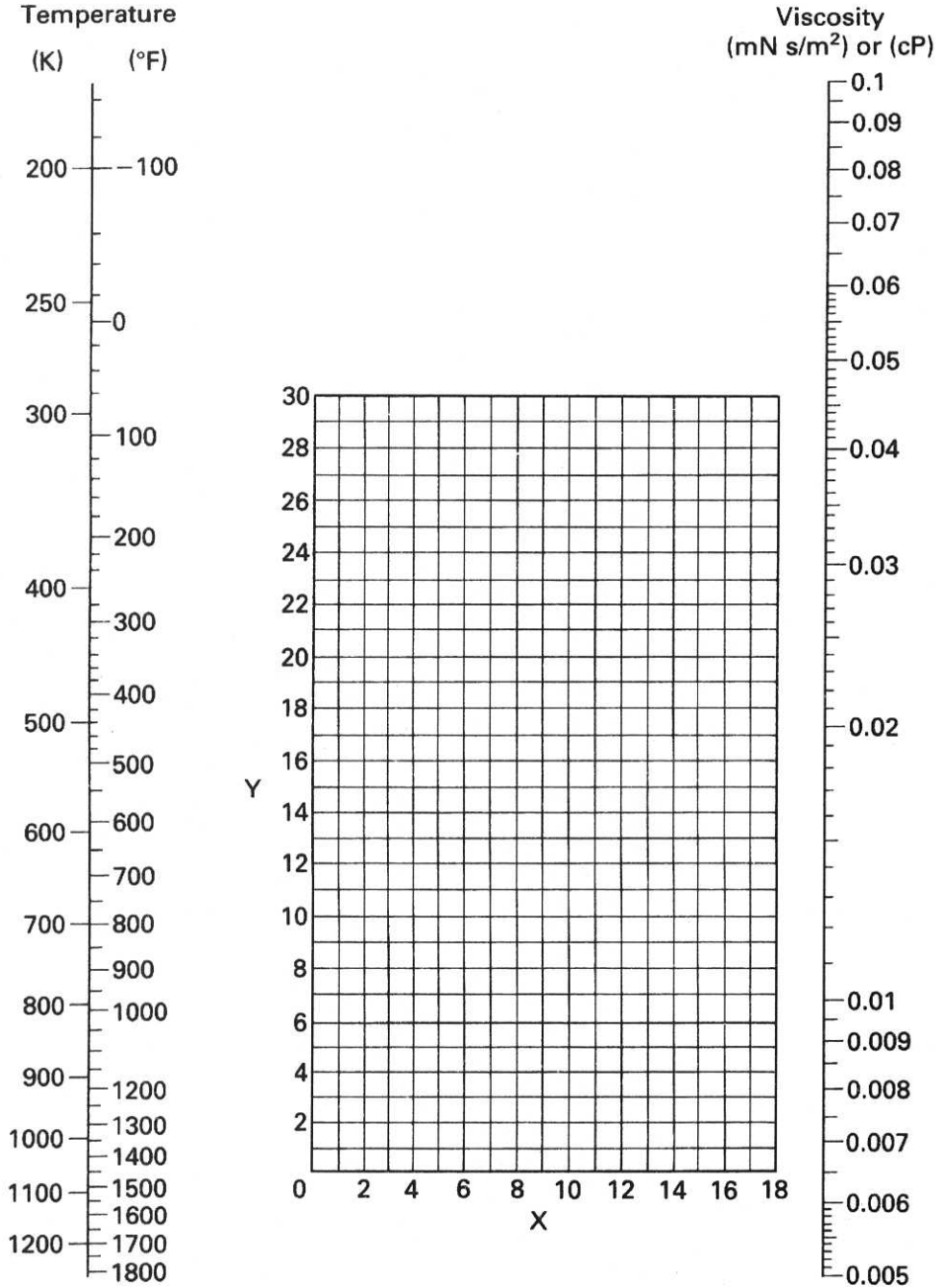
Table 8.   Viscosities and densities of liquids*

Co-ordinates for graph on following page

No.	Liquid	X	Y	Density at 293 K (kg/m³)		No.	Liquid	X	Y	Density at 293 K (kg/m³)	
1	Acetaldehyde	15.2	4.8	783	(291 K)	57	Freon-113 (CCl₂F-CClF₂)	12.5	11.4	1576	
2	Acetic acid, 100 per cent	12.1	14.2	1049		58	Glycerol, 100 per cent	2.0	30.0	1261	
3	Acetic acid, 70 per cent	9.5	17.0	1069		59	Glycerol, 50 per cent	6.9	19.6	1126	
4	Acetic anhydride	12.7	12.8	1083		60	Heptane	14.1	8.4	684	
5	Acetone, 100 per cent	14.5	7.2	792		61	Hexane	14.7	7.0	659	
6	Acetone, 35 per cent	7.9	15.0	948		62	Hydrochloric acid,				
7	Allyl alcohol	10.2	14.3	854			31.5 per cent	13.0	16.6	1157	
8	Ammonia, 100 per cent	12.6	2.0	817	(194 K)	63	Isobutyl alcohol	7.1	18.0	779	(299 K)
9	Ammonia, 26 per cent	10.1	13.9	904		64	Isobutyric acid	12.2	14.4	949	
10	Amyl acetate	11.8	12.5	879		65	Isopropyl alcohol	8.2	16.0	789	
11	Amyl alcohol	7.5	18.4	817		66	Kerosene	10.2	16.9	780–820	
12	Aniline	8.1	18.7	1022		67	Linseed oil, raw	7.5	27.2	934 ± 4 (288 K)	
13	Anisole	12.3	13.5	990		68	Mercury	18.4	16.4	13546	
14	Arsenic trichloride	13.9	14.5	2163		69	Methanol, 100 per cent	12.4	10.5	792	
15	Benzene	12.5	10.9	880		70	Methanol, 90 per cent	12.3	11.8	820	
16	Brine, CaCl₂, 25 per cent	6.6	15.9	1228		71	Methanol, 40 per cent	7.8	15.5	935	
17	Brine, NaCl, 25 per cent	10.2	16.6	1186	(298 K)	72	Methyl acetate	14.2	8.2	924	
18	Bromine	14.2	13.2	3119		73	Methyl chloride	15.0	3.8	952	(273 K)
19	Bromotoluene	20.0	15.9	1410		74	Methyl ethyl ketone	13.9	8.6	805	
20	Butyl acetate	12.3	11.0	882		75	Naphthalene	7.9	18.1	1145	
21	Butyl alcohol	8.6	17.2	810		76	Nitric acid, 95 per cent	12.8	13.8	1493	
22	Butyric acid	12.1	15.3	964		77	Nitric acid, 60 per cent	10.8	17.0	1367	
23	Carbon dioxide	11.6	0.3	1101	(236 K)	78	Nitrobenzene	10.6	16.2	1205	(291 K)
24	Carbon disulphide	16.1	7.5	1263		79	Nitrotoluene	11.0	17.0	1160	
25	Carbon tetrachloride	12.7	13.1	1595		80	Octane	13.7	10.0	703	
26	Chlorobenzene	12.3	12.4	1107		81	Octyl alcohol	6.6	21.1	827	
27	Chloroform	14.4	10.2	1489		82	Pentachloroethane	10.9	17.3	1671	(298 K)
28	Chlorosulphonic acid	11.2	18.1	1787	(298 K)	83	Pentane	14.9	5.2	630	(291 K)
29	Chlorotoluene, ortho	13.0	13.3	1082		84	Phenol	6.9	20.8	1071	(298 K)
30	Chlorotoluene, meta	13.3	12.5	1072		85	Phosphorus tribromide	13.8	16.7	2852	(288 K)
31	Chlorotoluene, para	13.3	12.5	1070		86	Phosphorus trichloride	16.2	10.9	1574	
32	Cresol, meta	2.5	20.8	1034		87	Propionic acid	12.8	13.8	992	
33	Cyclohexanol	2.9	24.3	962		88	Propyl alcohol	9.1	16.5	804	
34	Dibromoethane	12.7	15.8	2495		89	Propyl bromide	14.5	9.6	1353	
35	Dichloroethane	13.2	12.2	1256		90	Propyl chloride	14.4	7.5	890	
36	Dichloromethane	14.6	8.9	1336		91	Propyl iodide	14.1	11.6	1749	
37	Diethyl oxalate	11.0	16.4	1079		92	Sodium	16.4	13.9	970	
38	Dimethyl oxalate	12.3	15.8	1148	(327 K)	93	Sodium hydroxide, 50%	3.2	25.8	1525	
39	Diphenyl	12.0	18.3	992	(346 K)	94	Stannic chloride	13.5	12.8	2226	
40	Dipropyl oxalate	10.3	17.7	1038	(273 K)	95	Sulphur dioxide	15.2	7.1	1434	(273 K)
41	Ethyl acetate	13.7	9.1	901		96	Sulphuric acid, 110 per cent	7.2	27.4	1980	
42	Ethyl alcohol, 100 per cent	10.5	13.8	789		97	Sulphuric acid, 98 per cent	7.0	24.8	1836	
43	Ethyl alcohol, 95 per cent	9.8	14.3	804		98	Sulphuric acid, 60 per cent	10.2	21.3	1498	
44	Ethyl alcohol, 40 per cent	6.5	16.6	935		99	Sulphuryl chloride	15.2	12.4	1667	
45	Ethyl benzene	13.2	11.5	867		100	Tetrachloroethane	11.9	15.7	1600	
46	Ethyl bromide	14.5	8.1	1431		101	Tetrachloroethylene	14.2	12.7	1624	(288 K)
47	Ethyl chloride	14.8	6.0	917	(279 K)	102	Titanum tetrachloride	14.4	12.3	1726	
48	Ethyl ether	14.5	5.3	708	(298 K)	103	Toluene	13.7	10.4	866	
49	Ethyl formate	14.2	8.4	923		104	Trichloroethylene	14.8	10.5	1466	
50	Ethyl iodide	14.7	10.3	1933		105	Turpentine	11.5	14.9	861–867	
51	Ethylene glycol	6.0	23.6	1113		106	Vinyl acetate	14.0	8.8	932	
52	Formic acid	10.7	15.8	1220		107	Water	10.2	13.0	998	
53	Freon-11 (CCl₃F)	14.4	9.0	1494	(290 K)	108	Xylene, ortho	13.5	12.1	881	
54	Freon-12 (CCl₂F₂)	16.8	5.6	1486	(293 K)	109	Xylene, meta	13.9	10.6	867	
55	Freon-21 (CHCl₂F)	15.7	7.5	1426	(273 K)	110	Xylene, para	13.9	10.9	861	
56	Freon-22 (CHClF₂)	17.2	4.7	3870	(273 K)						

Viscosities of liquids

Temperature

(K) (°F)

Viscosity
(mN s/m²) or (cP)

Table 9. Critical constants of gases*

	Critical temperature T_c(K)	Critical pressure P_c (MN/m^2)	Compressibility constant in critical state Z_c
Paraffins			
Methane	191	4.64	0.290
Ethane	306	4.88	0.284
Propane	370	4.25	0.276
n-Butane	425	3.80	0.274
Isobutane	408	3.65	0.282
n-Pentane	470	3.37	0.268
Isopentane	461	3.33	0.268
Neopentane	434	3.20	0.268
n-Hexane	508	3.03	0.264
n-Heptane	540	2.74	0.260
n-Octane	569	2.49	0.258
Mono-olefins			
Ethylene	282	5.07	0.268
Propylene	365	4.62	0.276
1-Butene	420	4.02	0.276
1-Pentene	474	4.05	
Miscellaneous organic compounds			
Acetic acid	595	5.78	0.200
Acetone	509	4.72	0.237
Acetylene	309	6.24	0.274
Benzene	562	4.92	0.274
1,3-Butadiene	425	4.33	0.270
Cyclohexane	553	4.05	0.271
Dichlorodifluoromethane (Freon-12)	385	4.01	0.273
Diethyl ether	467	3.61	0.261
Ethyl alcohol	516	6.38	0.249
Ethylene oxide	468	7.19	0.25
Methyl alcohol	513	7.95	0.220
Methyl chloride	416	6.68	0.276
Methyl ethyl ketone	533	4.00	0.26
Toluene	594	4.21	0.27
Trichlorofluoromethane (Freon-11)	471	4.38	0.277
Trichlorotrifluoroethane (Freon-113)	487	3.41	0.274
Elementary gases			
Bromine	584	10.33	0.307
Chlorine	417	7.71	0.276
Helium	5.3	0.23	0.300
Hydrogen	33.3	1.30	0.304
Neon	44.5	2.72	0.307
Nitrogen	126	3.39	0.291
Oxygen	155	5.08	0.29
Miscellaneous inorganic compounds			
Ammonia	406	11.24	0.242
Carbon dioxide	304	7.39	0.276
Carbon monoxide	133	3.50	0.294
Hydrogen chloride	325	8.26	0.266
Hydrogen sulphide	374	9.01	0.284
Nitric oxide (NO)	180	6.48	0.25
Nitrous oxide (N$_2$O)	310	7.26	0.271
Sulphur	1313	11.75	
Sulphur dioxide	431	7.88	0.268
Sulphur trioxide	491	8.49	0.262
Water	647	22.1	0.23

*Selected values from K. A. Kobe and R. E. Lynn, Jr, *Chem. Rev.*, **52**, 117 (1953). By permission.

Table 10. Emissivities of surfaces*

Surface	$T(K)$	Emissivity
A. Metals and metallic oxides		
Aluminium		
highly polished plate	500–850	0.039–0.057
polished plate	296	0.040
rough plate	299	0.055
plate oxidised at 872 K	472–872	0.11–0.19
aluminium–surfaced roofing	311	0.216
Brass		
hard–rolled, polished	294	0.038
polished	311–589	0.096
rolled–plate, natural surface	295	0.06
rubbed with coarse emery	295	0.20
dull plate	322–622	0.22
oxidised	472–872	0.61–0.59
Chromium–see Nickel alloys		
Copper		
polished electrolytic	353	0.018
commercial, emeried and polished	292	0.030
commercial, scraped shiny	295	0.072
polished	390	0.023
plate, covered with thick oxide	498	0.78
plate heated to 872 K	472–872	0.57–0.57
cuprous oxide	1072–1372	0.66–0.54
molten copper	1350–1550	0.16–0.13
Gold		
pure, highly polished	500–900	0.018–0.35
Iron and steel		
electrolytic iron, highly polished	450–500	0.052–0.064
polished iron	700–1300	0.144–0.377
freshly emeried iron	293	0.242
polished cast iron	473	0.21
wrought iron, highly polished	311–522	0.28
cast iron, newly turned	295	0.435
steel casting, polished	1044–1311	0.52–0.56
ground sheet steel	1211–1372	0.55–0.61
smooth sheet iron	1172–1311	0.55–0.60
cast iron, turned	1155–1261	0.60–0.70
oxidised surfaces		
iron plate, completely rusted	293	0.685
sheet steel, rolled and oxidised	295	0.657
iron	373	0.736
cast iron, oxidised at 872 K	472–872	0.64–0.78
steel, oxidised at 872 K	472–872	0.79–0.79
smooth electrolytic iron	500–800	0.78–0.82
iron oxide	772–1472	0.85–0.89
ingot iron, rough	1200–1390	0.87–0.95
sheet steel with rough oxide layer	297	0.80
cast iron, strongly oxidised	311–522	0.95
wrought iron, dull oxidised	294–633	0.94
steel plate, rough	311–644	0.94–0.97
molten metal		
cast iron	1572–1672	0.29–0.29
mild steel	1872–2070	0.28–0.28
Lead		
pure, unoxidised	400–500	0.057–0.075
grey, oxidised	297	0.281
oxidised at 472 K	472	0.03

(continued overleaf)

*From HOTTEL, H. C. and SAROFIM, A. F.: Radiation Heat Transfer (McGraw-Hill, New York, 1967)

Table 10.   (*continued*)

Surface	$T(K)$	Emissivity
Mercury	273–373	0.09–0.12
Molybdenum		
filament	1000–2866	0.096–0.292
Monel		
metal oxidised at 872 K	472–872	0.41–0.46
Nickel		
electroplated on polished iron and polished	296	0.045
techically pure, polished	500–600	0.07–0.087
electroplated on pickled iron, unpolished	293	0.11
wire	460–1280	0.096–0.186
plate, oxidised by heating to 872 K	472–872	0.37–0.48
nickel oxide	922–1527	0.59–0.86
nickel alloys		
chromonickel	325–1308	0.64–0.76
nickelin, grey oxidised	294	0.262
KA–28 alloy, rough brown, after heating	489–763	0.44–0.36
KA–28 alloy, after heating at 800 K	489–800	0.62–0.73
NCT 3 alloy, oxidised from service	489–800	0.90–0.97
NCT 6 alloy, oxidised from service	544–836	0.89–0.82
Platinum		
pure, polished plate	500–900	0.054–0.104
strip	1200–1900	0.12–0.17
filament	300–1600	0.036–0.192
wire	500–1600	0.073–0.182
Silver		
polished, pure	500–900	0.0198–0.0324
polished	310–644	0.0221–0.0312
Steel–see Iron		
Tantalum		
filament	1600–3272	0.194–0.31
Tin		
bright tinned iron sheet	298	0.043 and 0.064
Tungsten		
filament, aged	300–3588	0.032–0.35
filament	3588	0.39
Zinc		
commercially pure, polished	500–600	0.045–0.053
oxidised by heating to 672 K	672	0.11
galvanized sheet iron, fairly bright	301	0.228
galvanized sheet iron, grey oxidised	297	0.276
B. Refractories, building materials, paints etc.		
Asbestos		
board	297	0.96
paper	311–644	0.93–0.945
Brick		
red, rough	294	0.93
silica, unglazed	1275	0.80
silica, glazed, rough	1475	0.85
grog, glazed	1475	0.75
Carbon		
T–carbon	400–900	0.81–0.79
filament	1311–1677	0.526
candle soot	372–544	0.952
lampblack–water–glass coating	372–456	0.957–0.952
thin layer on iron plate	294	0.927
thick coat	293	0.967
lampblack, 0.08 mm or thicker	311–644	0.945

Table 10. (*continued*)

Surface	T (K)	Emissivity
Enamel		
white fused on iron	292	0.897
Glass		
smooth	295	0.937
Gypsum		
0.5 mm thick on blackened plate	294	0.903
Marble		
light grey, polished	295	0.931
Oak		
planed	294	0.895
Oil layers		
on polished nickel		
polished surface alone		0.045
0.025 mm oil		0.27
0.050 mm oil		0.46
0.125 mm oil		0.72
thick oil layer		0.82
on aluminium foil		
aluminium foil alone	373	0.087
1 coat of oil	373	0.561
2 coats of oil	373	0.574
Paints, lacquers, varnishes		
snow white enamel on rough iron plate	296	0.906
black, shiny lacquer sprayed on iron	298	0.875
black, shiny shellac on tinned iron sheet	294	0.821
black matt shellac	350–420	0.91
black laquer	311–366	0.80–0.95
matt black lacquer	311–366	0.96–0.98
white lacquer	311–366	0.80–0.95
oil paints	373	0.92–0.96
aluminium paint	373	0.27–0.67
after heating to 600 K	422–622	0.35
aluminium lacquer	294	0.39
Paper, thin		
pasted on tinned iron plate	292	0.924
pasted on rough iron plate	292	0.929
pasted on black lacquered plate	292	0.944
roofing	294	0.91
Plaster, lime, rough	283–361	0.91
Porcellain, glazed	295	0.924
Quartz, rough, fused	294	0.932
Refractory materials		
poor radiators	872–1272	0.65–0.75
good radiators	872–1272	0.80–0.90
Rubber		
hard, glossy plate	296	0.945
soft, grey, rough	298	0.859
Serpentine, polished	296	0.900
Water	273–373	0.95–0.963

A2. STEAM TABLES

Tables 11A, 11B, 11C and 11D are adapted from the
Abridged Callendar Steam Tables
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Table 11A. Properties of saturated steam (S.I. units)

Absolute pressure (kN/m²)	Temperature		Enthalpy per unit mass (H_s) (kJ/kg)			Entropy per unit mass (S_s) (kJ/kg K)			Specific volume (v) (m³/kg)	
	(°C) θ_s	(K) T_s	water	latent	steam	water	latent	steam	water	steam
Datum: Triple point of water										
0.611	0.01	273.16	0.0	2501.6	2501.6	0	9.1575	9.1575	0.0010002	206.16
1.0	6.98	280.13	29.3	2485.0	2514.4	0.1060	8.8706	8.9767	0.001000	129.21
2.0	17.51	290.66	73.5	2460.2	2533.6	0.2606	8.4640	8.7246	0.001001	67.01
3.0	24.10	297.25	101.0	2444.6	2545.6	0.3543	8.2242	8.5785	0.001003	45.67
4.0	28.98	302.13	121.4	2433.1	2554.5	0.4225	8.0530	8.4755	0.001004	34.80
5.0	32.90	306.05	137.8	2423.8	2561.6	0.4763	7.9197	8.3960	0.001005	28.19
6.0	36.18	309.33	151.5	2416.0	2567.5	0.5209	7.8103	8.3312	0.001006	23.74
7.0	39.03	312.18	163.4	2409.2	2572.6	0.5591	7.7176	8.2767	0.001007	20.53
8.0	41.54	314.69	173.9	2403.2	2577.1	0.5926	7.6370	8.2295	0.001008	18.10
9.0	43.79	316.94	183.3	2397.9	2581.1	0.6224	7.5657	8.1881	0.001009	16.20
10.0	45.83	318.98	191.8	2392.9	2584.8	0.6493	7.5018	8.1511	0.001010	14.67
12.0	49.45	322.60	206.9	2384.2	2591.2	0.6964	7.3908	8.0872	0.001012	12.36
14.0	52.58	325.73	220.0	2376.7	2596.7	0.7367	7.2966	8.0333	0.001013	10.69
16.0	55.34	328.49	231.6	2370.0	2601.6	0.7721	7.2148	7.9868	0.001015	9.43
18.0	57.83	330.98	242.0	2363.9	2605.9	0.8036	7.1423	7.9459	0.001016	8.45
20.0	60.09	333.24	251.5	2358.4	2609.9	0.8321	7.0773	7.9094	0.001017	7.65
25.0	64.99	338.14	272.0	2346.4	2618.3	0.8933	6.9390	7.8323	0.001020	6.20
30.0	69.13	342.28	289.3	2336.1	2625.4	0.9441	6.8254	7.7695	0.001022	5.23
35.0	72.71	345.86	304.3	2327.2	2631.5	0.9878	6.7288	7.7166	0.001025	4.53
40.0	75.89	349.04	317.7	2319.2	2636.9	1.0261	6.6448	7.6709	0.001027	3.99
45.0	78.74	351.89	329.6	2312.0	2641.7	1.0603	6.5703	7.6306	0.001028	3.58
50.0	81.35	354.50	340.6	2305.4	2646.0	1.0912	6.5035	7.5947	0.001030	3.24
60.0	85.95	359.10	359.9	2293.6	2653.6	1.1455	6.3872	7.5327	0.001033	2.73
70.0	89.96	363.11	376.8	2283.3	2660.1	1.1921	6.2883	7.4804	0.001036	2.37
80.0	93.51	366.66	391.7	2274.0	2665.8	1.2330	6.2022	7.4352	0.001039	2.09
90.0	96.71	369.86	405.2	2265.6	2670.9	1.2696	6.1258	7.3954	0.001041	1.87
100.0	99.63	372.78	417.5	2257.9	2675.4	1.3027	6.0571	7.3598	0.001043	1.69
101.325	100.00	373.15	419.1	2256.9	2676.0	1.3069	6.0485	7.3554	0.0010437	1.6730
105	101.00	374.15	423.3	2254.3	2677.6	1.3182	6.0252	7.3434	0.001045	1.618
110	102.32	375.47	428.8	2250.8	2679.6	1.3330	5.9947	7.3277	0.001046	1.549
115	103.59	376.74	434.2	2247.4	2681.6	1.3472	5.9655	7.3127	0.001047	1.486
120	104.81	377.96	439.4	2244.1	2683.4	1.3609	5.9375	7.2984	0.001048	1.428
125	105.99	379.14	444.4	2240.9	2685.2	1.3741	5.9106	7.2846	0.001049	1.375
130	107.13	380.28	449.2	2237.8	2687.0	1.3868	5.8847	7.2715	0.001050	1.325
135	108.24	381.39	453.9	2234.8	2688.7	1.3991	5.8597	7.2588	0.001050	1.279
140	109.32	382.47	458.4	2231.9	2690.3	1.4109	5.8356	7.2465	0.001051	1.236
145	110.36	383.51	462.8	2229.0	2691.8	1.4225	5.8123	7.2347	0.001052	1.196
150	111.37	384.52	467.1	2226.2	2693.4	1.4336	5.7897	7.2234	0.001053	1.159
155	112.36	385.51	471.3	2223.5	2694.8	1.4445	5.7679	7.2123	0.001054	1.124
160	113.32	386.47	475.4	2220.9	2696.2	1.4550	5.7467	7.2017	0.001055	1.091
165	114.26	387.41	479.4	2218.3	2697.6	1.4652	5.7261	7.1913	0.001056	1.060
170	115.17	388.32	483.2	2215.7	2699.0	1.4752	5.7061	7.1813	0.001056	1.031
175	116.06	389.21	487.0	2213.3	2700.3	1.4849	5.6867	7.1716	0.001057	1.003
180	116.93	390.08	490.7	2210.8	2701.5	1.4944	5.6677	7.1622	0.001058	0.977
185	117.79	390.94	494.3	2208.5	2702.8	1.5036	5.6493	7.1530	0.001059	0.952
190	118.62	391.77	497.9	2206.1	2704.0	1.5127	5.6313	7.1440	0.001059	0.929
195	119.43	392.58	501.3	2203.8	2705.1	1.5215	5.6138	7.1353	0.001060	0.907
200	120.23	393.38	504.7	2201.6	2706.3	1.5301	5.5967	7.1268	0.001061	0.885

(continued overleaf)

Table 11A. (continued)

Absolute pressure (kN/m²)	Temperature		Enthalpy per unit mass (H_s) (kJ/kg)			Entropy per unit mass (S_s) (kJ/kg K)			Specific volume (v) (m³/kg)	
	(°C)	(K)								
	θ_s	T_s	water	latent	steam	water	latent	steam	water	steam
210	121.78	394.93	511.3	2197.2	2708.5	1.5468	5.5637	7.1105	0.001062	0.846
220	123.27	396.42	517.6	2193.0	2710.6	1.5628	5.5321	7.0949	0.001064	0.810
230	124.71	397.86	523.7	2188.9	2712.6	1.5781	5.5018	7.0800	0.001065	0.777
240	126.09	399.24	529.6	2184.9	2714.5	1.5929	5.4728	7.0657	0.001066	0.746
250	127.43	400.58	535.4	2181.0	2716.4	1.6072	5.4448	7.0520	0.001068	0.718
260	128.73	401.88	540.9	2177.3	2718.2	1.6209	5.4179	7.0389	0.001069	0.692
270	129.99	403.14	546.2	2173.6	2719.9	1.6342	5.3920	7.0262	0.001070	0.668
280	131.21	404.36	551.5	2170.1	2721.5	1.6471	5.3669	7.0140	0.001071	0.646
290	132.39	405.54	556.5	2166.6	2723.1	1.6596	5.3427	7.0022	0.001072	0.625
300	133.54	406.69	561.4	2163.2	2724.7	1.6717	5.3192	6.9909	0.001074	0.606
320	135.76	408.91	570.9	2156.7	2727.6	1.6948	5.2744	6.9692	0.001076	0.570
340	137.86	411.01	579.9	2150.4	2730.3	1.7168	5.2321	6.9489	0.001078	0.538
360	139.87	413.02	588.5	2144.4	2732.9	1.7376	5.1921	6.9297	0.001080	0.510
380	141.79	414.94	596.8	2138.6	2735.3	1.7575	5.1541	6.9115	0.001082	0.485
400	143.63	416.78	604.7	2132.9	2737.6	1.7764	5.1179	6.8943	0.001084	0.462
420	145.39	418.54	612.3	2127.5	2739.8	1.7946	5.0833	6.8779	0.001086	0.442
440	147.09	420.24	619.6	2122.3	2741.9	1.8120	5.0503	6.8622	0.001088	0.423
460	148.73	421.88	626.7	2117.2	2743.9	1.8287	5.0186	6.8473	0.001089	0.405
480	150.31	423.46	633.5	2112.2	2745.7	1.8448	4.9881	6.8329	0.001091	0.389
500	151.85	425.00	640.1	2107.4	2747.5	1.8604	4.9588	6.8192	0.001093	0.375
520	153.33	426.48	646.5	2102.7	2749.3	1.8754	4.9305	6.8059	0.001095	0.361
540	154.77	427.92	652.8	2098.1	2750.9	1.8899	4.9033	6.7932	0.001096	0.348
560	156.16	429.31	658.8	2093.7	2752.5	1.9040	4.8769	6.7809	0.001098	0.337
580	157.52	430.67	664.7	2089.3	2754.0	1.9176	4.8514	6.7690	0.001100	0.326
600	158.84	431.99	670.4	2085.0	2755.5	1.9308	4.8267	6.7575	0.001101	0.316
620	160.12	433.27	676.0	2080.8	2756.9	1.9437	4.8027	6.7464	0.001102	0.306
640	161.38	434.53	681.5	2076.7	2758.2	1.9562	4.7794	6.7356	0.001104	0.297
660	162.60	435.75	686.8	2072.7	2759.5	1.9684	4.7568	6.7252	0.001105	0.288
680	163.79	436.94	692.0	2068.8	2760.8	1.9803	4.7348	6.7150	0.001107	0.280
700	164.96	438.11	697.1	2064.9	2762.0	1.9918	4.7134	6.7052	0.001108	0.272
720	166.10	439.25	702.0	2061.1	2763.2	2.0031	4.6925	6.6956	0.001109	0.266
740	167.21	440.36	706.9	2057.4	2764.3	2.0141	4.6721	6.6862	0.001110	0.258
760	168.30	441.45	711.7	2053.7	2765.4	2.0249	4.6522	6.6771	0.001112	0.252
780	169.37	442.52	716.3	2050.1	2766.4	2.0354	4.6328	6.6683	0.001114	0.246
800	170.41	443.56	720.9	2046.5	2767.5	2.0457	4.6139	6.6596	0.001115	0.240
820	171.44	444.59	725.4	2043.0	2768.5	2.0558	4.5953	6.6511	0.001116	0.235
840	172.45	445.60	729.9	2039.6	2769.4	2.0657	4.5772	6.6429	0.001118	0.229
860	173.43	446.58	734.2	2036.2	2770.4	2.0753	4.5595	6.6348	0.001119	0.224
880	174.40	447.55	738.5	2032.8	2771.3	2.0848	4.5421	6.6269	0.001120	0.220
900	175.36	448.51	742.6	2029.5	2772.1	2.0941	4.5251	6.6192	0.001121	0.215
920	176.29	449.44	746.8	2026.2	2773.0	2.1033	4.5084	6.6116	0.001123	0.210
940	177.21	450.36	750.8	2023.0	2773.8	2.1122	4.4920	6.6042	0.001124	0.206
960	178.12	451.27	754.8	2019.8	2774.6	2.1210	4.4759	6.5969	0.001125	0.202
980	179.01	452.16	758.7	2016.7	2775.4	2.1297	4.4602	6.5898	0.001126	0.198
1000	179.88	453.03	762.6	2013.6	2776.2	2.1382	4.4447	6.5828	0.001127	0.194
1100	184.06	457.21	781.1	1998.6	2779.7	2.1786	4.3712	6.5498	0.001133	0.177
1200	187.96	461.11	798.4	1984.3	2782.7	2.2160	4.3034	6.5194	0.001139	0.163
1300	191.60	464.75	814.7	1970.7	2785.4	2.2509	4.2404	6.4913	0.001144	0.151
1400	195.04	468.19	830.1	1957.7	2787.8	2.2836	4.1815	6.4651	0.001149	0.141
1500	198.28	471.43	844.6	1945.3	2789.9	2.3144	4.1262	6.4406	0.001154	0.132
1600	201.37	474.52	858.5	1933.2	2791.7	2.3436	4.0740	6.4176	0.001159	0.124

Table 11A. *(continued)*

Absolute pressure (kN/m²)	Temperature		Enthalpy per unit mass (H_s) (kJ/kg)			Entropy per unit mass (S_s) (kJ/kg K)			Specific volume (v) (m³/kg)	
	(°C)	(K)	water	latent	steam	water	latent	steam	water	steam
	θ_s	T_s								
1700	204.30	477.45	871.8	1921.6	2793.4	2.3712	4.0246	6.3958	0.001163	0.117
1800	207.11	480.26	884.5	1910.3	2794.8	2.3976	3.9776	6.3751	0.001168	0.110
1900	209.79	482.94	896.8	1899.3	2796.1	2.4227	3.9327	6.3555	0.001172	0.105
2000	212.37	485.52	908.6	1888.7	2797.2	2.4468	3.8899	6.3367	0.001177	0.0996
2200	217.24	490.39	930.9	1868.1	2799.1	2.4921	3.8094	6.3015	0.001185	0.0907
2400	221.78	494.93	951.9	1848.5	2800.4	2.5342	3.7348	6.2690	0.001193	0.0832
2600	226.03	499.18	971.7	1829.7	2801.4	2.5736	3.6652	6.2388	0.001201	0.0769
3000	233.84	506.99	1008.3	1794.0	2802.3	2.6455	3.5383	6.1838	0.001216	0.0666
3500	242.54	515.69	1049.7	1752.2	2802.0	2.7252	3.3976	6.1229	0.001235	0.0570
4000	250.33	523.48	1087.4	1712.9	2800.3	2.7965	3.2720	6.0685	0.001252	0.0498
4500	257.41	530.56	1122.1	1675.6	2797.7	2.8612	3.1579	6.0191	0.001269	0.0440
5000	263.92	537.07	1154.5	1639.7	2794.2	2.9207	3.0528	5.9735	0.001286	0.0394
6000	275.56	548.71	1213.7	1571.3	2785.0	3.0274	2.8633	5.8907	0.001319	0.0324
7000	285.80	558.95	1267.5	1506.0	2773.4	3.1220	2.6541	5.8161	0.001351	0.0274
8000	294.98	568.13	1317.2	1442.7	2759.9	3.2077	2.5393	5.7470	0.001384	0.0235
9000	303.31	576.46	1363.8	1380.8	2744.6	3.2867	2.3952	5.6820	0.001418	0.0205
10000	310.96	584.11	1408.1	1319.7	2727.7	3.3606	2.2592	5.6198	0.001453	0.0180
11000	318.04	591.19	1450.6	1258.8	2709.3	3.4304	2.1292	5.5596	0.001489	0.0160
12000	324.64	597.79	1491.7	1197.5	2698.2	3.4971	2.0032	5.5003	0.001527	0.0143
14000	336.63	609.78	1571.5	1070.9	2642.4	3.6241	1.7564	5.3804	0.0016105	0.01150
16000	347.32	620.47	1650.4	934.5	2584.9	3.7470	1.5063	5.2533	0.0017102	0.00931
18000	356.96	630.11	1734.8	779.0	2513.9	3.8766	1.2362	5.1127	0.0018399	0.007497
20000	365.71	638.86	1826.6	591.6	2418.2	4.0151	0.9259	4.9410	0.0020374	0.005875
22000	373.68	646.83	2010.3	186.3	2196.6	4.2934	0.2881	4.5814	0.0026675	0.003735
22120	374.15	647.30	2107.4	0	2107.4	4.4429	0	4.4429	0.0031700	0.003170

Table 11B. Properties of saturated steam (Centigrade and Fahrenheit units)

Pressure		Temperature		Enthalpy per unit mass						Entropy (Btu/lb°F)		Specific volume (ft³/lb)
				Centigrade units (kcal/kg)			Fahrenheit units (Btu/lb)					
Absolute (lb/in.²)	Vacuum (in. Hg)	(°C)	(°F)	Water	Latent	Steam	Water	Latent	Steam	Water	Steam	Steam
0.5	28.99	26.42	79.6	26.45	582.50	608.95	47.6	1048.5	1096.1	0.0924	2.0367	643.0
0.6	28.79	29.57	85.3	29.58	580.76	610.34	53.2	1045.4	1098.6	0.1028	2.0214	540.6
0.7	28.58	32.28	90.1	32.28	579.27	611.55	58.1	1042.7	1100.8	0.1117	2.0082	466.6
0.8	28.38	34.67	94.4	34.66	577.95	612.61	62.4	1040.3	1102.7	0.1196	1.9970	411.7
0.9	28.17	36.80	98.2	36.80	576.74	613.54	66.2	1038.1	1104.3	0.1264	1.9871	368.7
1.0	27.97	38.74	101.7	38.74	575.60	614.34	69.7	1036.1	1105.8	0.1326	1.9783	334.0
1.1	27.76	40.52	104.9	40.52	574.57	615.09	72.9	1034.3	1107.2	0.1381	1.9702	305.2
1.2	27.56	42.17	107.9	42.17	573.63	615.80	75.9	1032.5	1108.4	0.1433	1.9630	281.1
1.3	27.35	43.70	110.7	43.70	572.75	616.45	78.7	1030.9	1109.6	0.1484	1.9563	260.5
1.4	27.15	45.14	113.3	45.12	571.94	617.06	81.3	1029.5	1110.8	0.1527	1.9501	243.0
1.5	26.95	46.49	115.7	46.45	571.16	617.61	83.7	1028.1	1111.8	0.1569	1.9442	228.0
1.6	26.74	47.77	118.0	47.73	570.41	618.14	86.0	1026.8	1112.8	0.1609	1.9387	214.3
1.7	26.54	48.98	120.2	48.94	569.71	618.65	88.2	1025.5	1113.7	0.1646	1.9336	202.5
1.8	26.33	50.13	122.2	50.08	569.06	619.14	90.2	1024.4	1114.6	0.1681	1.9288	191.8
1.9	26.13	51.22	124.2	51.16	568.47	619.63	92.1	1023.3	1115.4	0.1715	1.9243	182.3
2.0	25.92	52.27	126.1	52.22	567.89	620.11	94.0	1022.2	1116.2	0.1749	1.9200	173.7
3.0	23.88	60.83	141.5	60.78	562.89	623.67	109.4	1013.2	1122.6	0.2008	1.8869	118.7
4.0	21.84	67.23	153.0	67.20	559.29	626.49	121.0	1006.7	1127.7	0.2199	1.8632	90.63
5.0	19.80	72.38	162.3	72.36	556.24	628.60	130.2	1001.6	1131.8	0.2348	1.8449	73.52
6.0	17.76	76.72	170.1	76.71	553.62	630.33	138.1	996.6	1134.7	0.2473	1.8299	61.98
7.0	15.71	80.49	176.9	80.52	551.20	631.72	144.9	992.2	1137.1	0.2582	1.8176	53.64
8.0	13.67	83.84	182.9	83.89	549.16	633.05	151.0	988.5	1139.5	0.2676	1.8065	47.35
9.0	11.63	86.84	188.3	86.88	547.42	634.30	156.5	985.2	1141.7	0.2762	1.7968	42.40
10.0	9.59	89.58	193.2	89.61	545.82	635.43	161.3	982.5	1143.8	0.2836	1.7884	38.42
11.0	7.55	92.10	197.8	92.15	544.26	636.41	165.9	979.6	1145.5	0.2906	1.7807	35.14
12.0	5.50	94.44	202.0	94.50	542.75	637.25	170.1	976.9	1147.0	0.2970	1.7735	32.40
13.0	3.46	96.62	205.9	96.69	541.34	638.03	173.9	974.6	1148.5	0.3029	1.7672	30.05
14.0	1.42	98.65	209.6	98.73	540.06	638.79	177.7	972.2	1149.9	0.3086	1.7613	28.03
14.696	Gauge (lb/in.²)	100.00	212.0	100.06	539.22	639.28	180.1	970.6	1150.7	0.3122	1.7574	26.80
15	0.3	100.57	213.0	100.65	538.9	639.5	181.2	970.0	1151.2	0.3137	1.7556	26.28
16	1.3	102.40	216.3	102.51	537.7	640.2	184.5	967.9	1152.4	0.3187	1.7505	24.74
17	2.3	104.13	219.5	104.27	536.5	640.8	187.6	965.9	1153.5	0.3231	1.7456	23.38
18	3.3	105.78	222.4	105.94	535.5	641.4	190.6	964.0	1154.6	0.3276	1.7411	22.17
19	4.3	107.36	225.2	107.53	534.5	642.0	193.5	962.2	1155.7	0.3319	1.7368	21.07
20	5.3	108.87	228.0	109.05	533.6	642.6	196.3	960.4	1156.7	0.3358	1.7327	20.09
21	6.3	110.32	230.6	110.53	532.6	643.1	198.9	958.8	1157.7	0.3396	1.7287	19.19
22	7.3	111.71	233.1	111.94	531.7	643.6	201.4	957.2	1158.6	0.3433	1.7250	18.38
23	8.3	113.05	235.5	113.30	530.8	644.1	203.9	955.6	1159.5	0.3468	1.7215	17.63
24	9.3	114.34	237.8	114.61	530.0	644.6	206.3	954.0	1160.3	0.3502	1.7181	16.94
25	10.3	115.59	240.1	115.87	529.2	645.1	208.6	952.5	1161.1	0.3534	1.7148	16.30
26	11.3	116.80	242.2	117.11	528.4	645.5	210.8	951.1	1161.9	0.3565	1.7118	15.72
27	12.3	117.97	244.4	118.31	527.6	645.9	212.9	949.7	1162.6	0.3595	1.7089	15.17
28	13.3	119.11	246.4	119.47	526.8	646.3	215.0	948.3	1163.3	0.3625	1.7060	14.67
29	14.3	120.21	248.4	120.58	526.1	646.7	217.0	947.0	1164.0	0.3654	1.7032	14.19
30	15.3	121.3	250.3	121.7	525.4	647.1	219.0	945.6	1164.6	0.3682	1.7004	13.73
32	17.3	123.3	254.0	123.8	524.1	647.9	222.7	943.1	1165.8	0.3735	1.6952	12.93
34	19.3	125.3	257.6	125.8	522.8	648.6	226.3	940.7	1167.0	0.3785	1.6905	12.21

Table 11B. (*continued*)

Pressure		Temperature		Enthalpy per unit mass						Entropy (Btu/lb°F)		Specific volume (ft³/lb)
				Centigrade units (kcal/kg)			Fahrenheit units (Btu/lb)					
Absolute (lb/in.²)	Vacuum (in. Hg)	(°C)	(°F)	Water	Latent	Steam	Water	Latent	Steam	Water	Steam	Steam
36	21.3	127.2	260.9	127.7	521.5	649.2	229.7	938.5	1168.2	0.3833	1.6860	11.58
38	23.3	128.9	264.1	129.5	520.3	649.8	233.0	936.4	1169.4	0.3879	1.6817	11.02
40	25.3	130.7	267.2	131.2	519.2	650.4	236.1	934.4	1170.5	0.3923	1.6776	10.50
42	27.3	132.3	270.3	132.9	518.0	650.9	239.1	932.3	1171.4	0.3964	1.6737	10.30
44	29.3	133.9	273.1	134.5	516.9	651.4	242.0	930.3	1172.3	0.4003	1.6700	9.600
46	31.3	135.4	275.8	136.0	515.9	651.9	244.9	928.3	1173.2	0.4041	1.6664	9.209
48	33.3	136.9	278.5	137.5	514.8	652.3	247.6	926.4	1174.0	0.4077	1.6630	8.848
50	35.3	138.3	281.0	139.0	513.8	652.8	250.2	924.6	1174.8	0.4112	1.6597	8.516
52	37.3	139.7	283.5	140.4	512.8	653.2	252.7	922.9	1175.6	0.4146	1.6566	8.208
54	39.3	141.0	285.9	141.8	511.8	653.6	255.2	921.1	1176.3	0.4179	1.6536	7.922
56	41.3	142.3	288.3	143.1	510.9	654.0	257.6	919.4	1177.0	0.4211	1.6507	7.656
58	43.3	143.6	290.5	144.4	510.0	654.4	259.9	917.8	1177.7	0.4242	1.6478	7.407
60	45.3	144.9	292.7	145.6	509.2	654.8	262.2	916.2	1178.4	0.4272	1.6450	7.175
62	47.3	146.1	294.9	146.8	508.4	655.2	264.4	914.6	1179.0	0.4302	1.6423	6.957
64	49.3	147.3	296.9	148.0	507.6	655.6	266.5	913.1	1179.6	0.4331	1.6398	6.752
66	51.3	148.4	299.0	149.2	506.7	655.9	268.6	911.6	1180.2	0.4359	1.6374	6.560
68	53.3	149.5	301.0	150.3	505.9	656.2	270.7	910.1	1180.8	0.4386	1.6350	6.378
70	55.3	150.6	302.9	151.5	505.0	656.5	272.7	908.7	1181.4	0.4412	1.6327	6.206
72	57.3	151.6	304.8	152.6	504.2	656.8	274.6	907.4	1182.0	0.4437	1.6304	6.044
74	59.3	152.6	306.7	153.6	503.4	657.0	276.5	906.0	1182.5	0.4462	1.6282	5.890
76	61.3	153.6	308.5	154.7	502.6	657.3	278.4	904.6	1183.0	0.4486	1.6261	5.743
78	63.3	154.6	310.3	155.7	501.8	657.5	280.3	903.2	1183.5	0.4510	1.6240	5.604
80	65.3	155.6	312.0	156.7	501.1	657.8	282.1	901.9	1184.0	0.4533	1.6219	5.472
82	67.3	156.5	313.7	157.7	500.3	658.0	283.9	900.6	1184.5	0.4556	1.6199	5.346
84	69.3	157.5	315.4	158.6	499.6	658.2	285.6	899.4	1185.0	0.4579	1.6180	5.226
86	71.3	158.4	317.1	159.6	498.9	658.5	287.3	898.1	1185.4	0.4601	1.6161	5.110
88	73.3	159.4	318.7	160.5	498.3	658.8	289.0	896.8	1185.8	0.4622	1.6142	5.000
90	75.3	160.3	320.3	161.5	497.6	659.1	290.7	895.5	1186.2	0.4643	1.6124	4.896
92	77.3	161.2	321.9	162.4	496.9	659.3	292.3	894.3	1186.6	0.4664	1.6106	4.796
94	79.3	162.0	323.3	163.3	496.3	659.6	293.9	893.1	1187.0	0.4684	1.6088	4.699
96	81.3	162.8	324.8	164.1	495.7	659.8	295.5	891.9	1187.4	0.4704	1.6071	4.607
98	83.3	163.6	326.6	165.0	495.0	660.0	297.0	890.8	1187.8	0.4723	1.6054	4.519
100	85.3	164.4	327.8	165.8	494.3	660.1	298.5	889.7	1188.2	0.4742	1.6038	4.434
105	90.3	166.4	331.3	167.9	492.7	660.6	302.2	886.9	1189.1	0.4789	1.6000	4.230
110	95.3	168.2	334.8	169.8	491.2	661.0	305.7	884.2	1189.9	0.4833	1.5963	4.046
115	100.3	170.0	338.1	171.7	489.8	661.5	309.2	881.5	1190.7	0.4876	1.5927	3.880
120	105.3	171.8	341.3	173.6	488.3	661.9	312.5	878.9	1191.4	0.4918	1.5891	3.729
125	110.3	173.5	344.4	175.4	486.9	662.3	315.7	876.4	1192.1	0.4958	1.5856	3.587
130	115.3	175.2	347.3	177.1	485.6	662.7	318.8	874.0	1192.8	0.4997	1.5823	3.456
135	120.3	176.8	350.2	178.8	484.2	663.0	321.9	871.5	1193.4	0.5035	1.5792	3.335
140	125.3	178.3	353.0	180.5	482.9	663.4	324.9	869.1	1194.0	0.5071	1.5763	3.222
145	130.3	179.8	355.8	182.1	481.6	663.7	327.8	866.8	1194.6	0.5106	1.5733	3.116
150	135.3	181.3	358.4	183.7	480.3	664.0	330.6	864.5	1195.1	0.5140	1.5705	3.015

Table 11C. Enthalpy of superheated steam, H (kJ/kg)

Pressure P (kN/m^2)	Saturation T_s (K)	Saturation S_s (kJ/kg)	Temperature, θ (°C) / T(K) — 100 / 373.15	200 / 473.15	300 / 573.15	400 / 673.15	500 / 773.15	600 / 873.15	700 / 973.15	800 / 1073.15
100	372.78	2675.4	2676.0	2875.4	3074.6	3278.0	3488.0	3705.0	3928.0	4159.0
200	393.38	2706.3		2870.4	3072.0	3276.4	3487.0	3704.0	3927.0	4158.0
300	406.69	2724.7		2866.0	3069.7	3275.0	3486.0	3703.1	3927.0	4158.0
400	416.78	2737.6		2861.3	3067.0	3273.5	3485.0	3702.0	3926.0	4157.0
500	425.00	2747.5		2856.0	3064.8	3272.1	3484.0	3701.2	3926.0	4156.8
600	431.99	2755.5		2850.7	3062.0	3270.0	3483.0	3701.0	3925.0	4156.2
700	438.11	2762.0		2845.5	3059.5	3269.0	3482.6	3700.2	3924.0	4156.0
800	443.56	2767.5		2839.7	3057.0	3266.8	3480.4	3699.0	3923.8	4155.0
900	448.56	2772.1		2834.0	3055.0	3266.2	3479.5	3698.6	3923.0	4155.0
1000	453.03	2776.2		2828.7	3051.7	3264.3	3478.0	3697.5	3922.8	4154.0
2000	485.59	2797.2			3024.8	3248.0	3467.0	3690.0	3916.0	4150.0
3000	506.98	2802.3			2994.8	3231.7	3456.0	3681.6	3910.4	4145.0
4000	523.49	2800.3			2962.0	3214.8	3445.0	3673.4	3904.0	4139.6
5000	537.09	2794.2			2926.0	3196.9	3433.8	3665.4	3898.0	4135.5
6000	548.71	2785.0			2886.0	3178.0	3421.7	3657.0	3891.8	4130.0
7000	558.95	2773.4			2840.0	3159.1	3410.0	3648.8	3886.0	4124.8
8000	568.13	2759.9			2785.0	3139.5	3398.0	3640.4	3880.8	4121.0
9000	576.46	2744.6				3119.0	3385.5	3632.0	3873.6	4116.0
10000	584.11	2727.7				3097.7	3373.6	3624.0	3867.2	4110.8
11000	591.19	2709.3				3075.6	3361.0	3615.5	3862.0	4106.0
12000	597.79	2698.2				3052.9	3349.0	3607.0	3855.3	4101.2

Table 11D. Entropy of superheated steam, S (kJ/kg K)

| Pressure P (kN/m^2)	Saturation T_s (K)	Saturation H_s (kJ/kg)	Temperature, θ (°C) / T(K) — 100 / 373.15	200 / 473.15	300 / 573.15	400 / 673.15	500 / 773.15	600 / 873.15	700 / 973.15	800 / 1073.15
100	372.78	7.3598	7.362	7.834	8.216	8.544	8.834	9.100	9.344	9.565
200	393.38	7.1268		7.507	7.892	8.222	8.513	8.778	9.020	9.246
300	406.69	6.9909		7.312	7.702	8.033	8.325	8.591	8.833	9.057
400	416.78	6.8943		7.172	7.566	7.898	8.191	8.455	8.700	8.925
500	425.00	6.8192		7.060	7.460	7.794	8.087	8.352	8.596	8.820
600	431.99	6.7575		6.968	7.373	7.708	8.002	8.268	8.510	8.738
700	438.11	6.7052		6.888	7.298	7.635	7.930	8.195	8.438	8.665
800	443.56	6.6596		6.817	7.234	7.572	7.867	8.133	8.375	8.602
900	448.56	6.6192		6.753	7.176	7.515	7.812	8.077	8.321	8.550
1000	453.03	6.5828		6.695	7.124	7.465	7.762	8.028	8.272	8.502
2000	485.59	6.3367			6.768	7.128	7.431	7.702	7.950	8.176
3000	506.98	6.1838			6.541	6.922	7.233	7.508	7.756	7.985
4000	523.49	6.0685			6.364	6.770	7.090	7.368	7.620	7.850
5000	537.07	5.9735			6.211	6.647	6.977	7.258	7.510	7.744
6000	548.71	5.8907			6.060	6.542	6.880	7.166	7.422	7.655
7000	558.95	5.8161			5.933	6.450	6.798	7.088	7.345	7.581
8000	568.13	5.7470			5.792	6.365	6.724	7.020	7.280	7.515
9000	576.46	5.6820				6.288	6.659	6.958	7.220	7.457
10000	584.11	5.6198				6.215	6.598	6.902	7.166	7.405
11000	591.19	5.5596				6.145	6.540	6.850	7.117	7.357
12000	597.79	5.5003				6.077	6.488	6.802	7.072	7.312
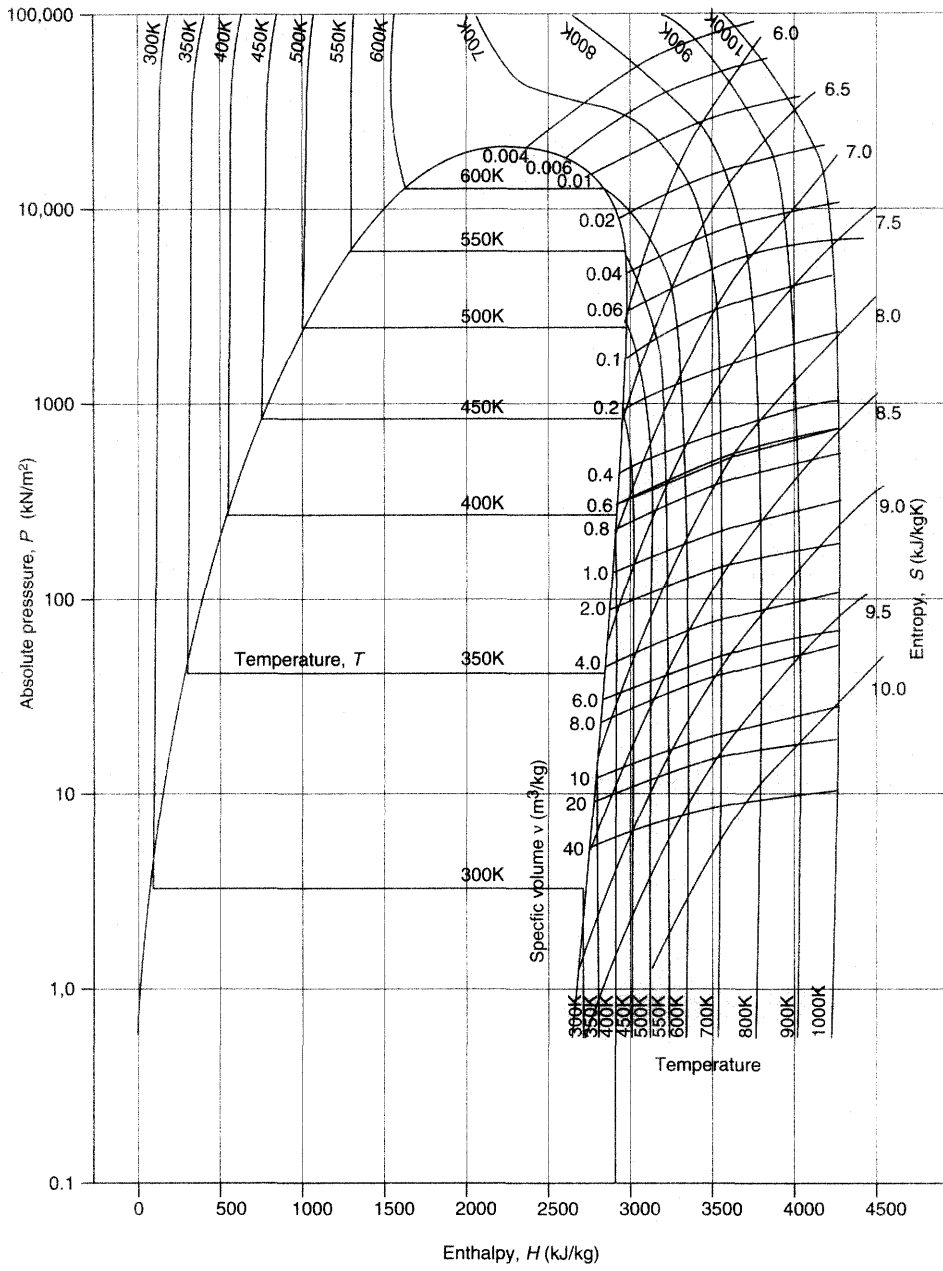
Figure 11A.   Pressure-enthalpy diagram for water and steam