10 Condensation in buildings

Learning objectives

Study of this chapter will enable the reader to:

1. identify the moisture content of humid air by its vapour pressure;
2. understand dew-point temperature;
3. identify the sources of moisture within a building;
4. understand the flow and storage characteristics of moisture flows found in habitable building;
5. explain the causes of condensation;
6. discuss the damage which can be caused by condensation;
7. calculate vapour diffusion resistance;
8. calculate vapour flow;
9. calculate air vapour pressure;
10. calculate air dew-point temperature;
11. understand atmospheric pressure terms;
12. use the e^x calculator function;
13. use the $\log_e$ calculator function;
14. be able to convert from e^x to $\log_e$ forms;
15. calculate and draw thermal temperature gradients through structures;
16. calculate and draw dew-point temperature gradients through structures;
17. identify condensation zones within structures;
18. discuss surface and interstitial condensation;
19. understand where to install thermal insulation and vapour barriers in relation to condensation risk and thermal and structural integrity requirements.

Key terms and concepts

atmospheric pressure 240; change of phase 240; condensation 240; dew-point 240; dew-point temperature gradient 251; diffusion 242; dry- and wet-bulb air temperatures 240; exponential and logarithmic functions 244; moisture flow 242; moisture production 240;

mould growth 242; partial pressure 240; psychrometric chart 241; saturated air 240; storage of moisture 240; surface and interstitial condensation 242; thermal temperature gradient 247; vapour barrier 254; vapour diffusion 242; vapour pressure 240; vapour resistance 242; vapour resistivity 242; ventilation 242; warm- and cold-deck roofing 255; water vapour 240.

Introduction

Condensation risk is analysed during design of a building, when retrofit measures such as additional thermal insulation, double glazing or ventilation control are being considered or where damage from condensation has been discovered. Anti-condensation measures are linked to temperature control systems and ventilation provision in that they determine the size of plant and resulting operating costs.

The fundamentals of air and water vapour mixtures are introduced and then the moisture diffusion properties of building materials are analysed. A convenient form of equation to enable the air dew-point temperature to be found using a student's scientific calculator is derived and this saves the need to refer to charts or tables.

Thermal and dew-point temperature gradients are calculated, allowing moisture flow rate to be found. The rate of moisture deposition within the structure can then be assessed for its damage potential.

Sources of moisture

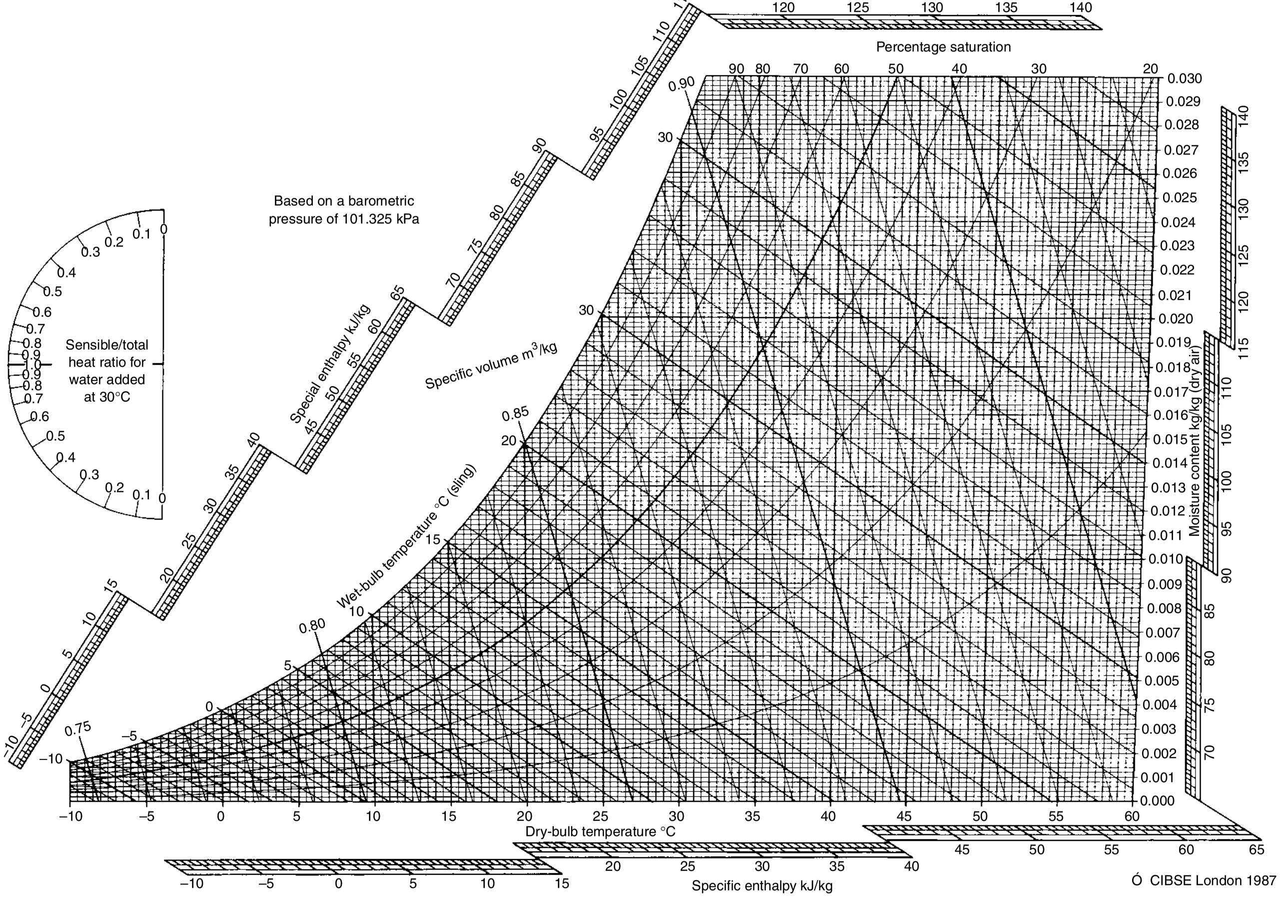
Air is a mixture of dry gases and water vapour. The water vapour exists in the form of finely divided particles of superheated steam at the air dry-bulb temperature. Total atmospheric pressure consists of the sum of the partial pressures of the two main constituents.

Typically, one standard atmosphere exerts a pressure of 1013.25 mb at sea level. When the air conditions are 25°C d.b. and 20°C w.b., the standard atmosphere is made up of 993.08 mb dry gas and 20.17 mb water vapour pressure. If this air is allowed to come into contact with a surface at a temperature of 17.6°C, the air becomes saturated with moisture and can no longer support all the water in its vapour state. This temperature is known as the air dew-point t_{dp}, and is shown on a sketch of the CIBSE psychrometric chart in Fig. 5.4. Further data on the properties of humid air can be obtained from the *CIBSE Guide* (CIBSE, 1986). Figure 10.1 is a reduced psychrometric chart that may be used to find data. It is reproduced by permission of the Chartered Institution of Building Services Engineers.

The sources of water vapour in an occupied building are as follows:

1. people, upwards of 0.7 kg per 24 h;
2. cooking;
3. washing, bathrooms, drying clothes;
4. humidifiers and open water surfaces;
5. animals (dogs exhale more moisture than people produce overall);
6. combustion of paraffin (the complete combustion of 1 kg of C_9H_{20} produces 1.41 kg of water vapour).

Porous structural surfaces, furniture and fabrics within the building absorb moisture and then release it into the internal atmosphere when the temperature and humidity allow this. Some moisture travels through the structure and evaporates externally unless it is prevented from doing so by an impervious layer or vapour barrier. The majority of internally produced humidity is removed by ventilation.



10.1 Psychrometric chart (reproduced by courtesy of the Chartered Institution of Building Services Engineers).

The warm internal atmosphere is able to hold more moisture than the cooler external air; thus the partial pressure of the vapour, that is, the vapour pressure p_s, is higher inside than outside. This vapour pressure difference causes mass transfer of moisture out of the building through the porous structure and by the ventilation air flow. When dense materials such as precast concrete or impervious barriers form a major part of the construction, moisture removal from the normal habitation is slow and condensation occurs on cold surfaces. Brickwork or masonry that is already saturated has the same effect.

Condensation and mould growth

Condensation and mould may readily form on window sills and in the corners of rooms, where the surface temperatures are lower compared with large areas. Gloss paint stops the absorption of moisture into an otherwise porous plaster or wooden component and water droplets form on the surface. The production of surface condensation in heated rooms is generally avoided in structures with a *U* value lower than 1.4 W/m^2K.

Dampness in the timber of roofs, not caused by the ingress of rain, may be due to condensation on low-temperature surfaces. A well-insulated flat plaster ceiling may produce these low-temperature conditions in the roof construction. Natural ventilation through gaps between the tiles and roofing felt is normally sufficient to stop rot and damp patches on the plasterboard. Well-sealed roofs, with boarding under the felt, should have their ventilation increased by means of openings in the soffit of the eaves after extra thermal insulation. Humid air enters the roof space through gaps in the fiat plaster ceiling around access hatches and pipes. Sealing these substantially reduces condensation risk. Roof insulation should stop at the wall head and not be pushed into the eaves, or ventilation will be restricted (Saunders, 1981).

Condensation forms within a structure or inside a solid material wherever the temperature falls below the dew-point of the moist air at that location. This is known as interstitial condensation. Vapour diffusion through building materials is calculated in a similar manner to the calculation of heat flow.

Vapour diffusion

The flow of water vapour through a porous building material or composite slab is analogous to the flow of heat through the structure. Convection currents transfer heat and moisture at the fluid–solid boundary. Conduction heat transfer is similar to vapour diffusion through a porous material, and its resistance to moisture flow varies with density, as does thermal resistance but in the opposite sense.

The mass flow rate of moisture through a composite structure consisting of a number of plane slabs and surfaces in series is

$$G = \frac{p_{s1} - p_{s2}}{R_v}$$

where G is the mass flow rate of vapour (kg/m^2s), R_v is the vapour resistance of the structure (Ns/kg) and P_{s1} and P_{s2} are the vapour pressures on surfaces 1 and 2 on each side of the slab (N/m^2 or Pa). The total vapour resistance R_v is given by

$$R_v = r_v \times l$$

where R_v is the total vapour resistance of a slab of homogeneous material (GN s/kg), r_v is the vapour resistivity of a material (GN s/kgm), and l is the thickness of material (m). Surface films and air cavities have only slight resistance to the flow of vapour and they are not normally included. Some typical values of vapour resistivity are given in Table 10.1. The complete resistance to the flow of vapour through some typical vapour barrier films is given in Table 10.2.

Further data are available in the reference source and in BRE Digest 369, February 1992, Building Research Establishment. Note that the values quoted in BRE Digest 369 are in MN s/g m (mega newton seconds per gram metre) for vapour resistivity and MN s/g for the vapour resistance of films. These units of measurement are the same as GN s/kgm (giga newton seconds per kilogram metre) and GN s/kg as both the numerator and denominator have been reduced by 1000 times.

Values of vapour pressure are available in CIBSE (1986) but can be calculated with sufficient accuracy from the following curve fit to the saturation conditions data:

$$p = 600.245 \exp(0.0684\, t_{dp}) \text{ Pa}$$

where t_{dp} is the air dew-point temperature from the psychrometric chart (°C) and $\exp(x) = e^x$ where $e = 2.71828$ is the exponential operator. Tabulated vapour pressures are in millibars (mb), and since 1 bar = 100 000 N/m^2 = 100 000 Pa, 1 mb = 100 N/m^2 = 100 Pa.

Table 10.1 Vapour resistivity.

Material	*Vapour resistivity (GN s/kgm)*
Brickwork	40
Dense concrete	200
Aerated concrete	30
Glass fibre wool	10
Foamed urea formaldehyde	30
Foamed polyurethane, open cell	30
Foamed polyurethane, closed cell	1000
Foamed polystyrene	500
Hardboard	520
Insulating fibreboard	20
Mineral fibre wool	6
Plaster	50
Plywood	520
Wood wool/cement slab	15
Wood	50

Source: Reproduced from *CIBSE Guide* (CIBSE, 1986) by permission of the Chartered Institute of Building Services Engineers.

Table 10.2 Vapour resistances of films.

Material	*Vapour resistance (GN s/kg)*
Aluminium foil	Over 4000
Double layer Kraft paper	0.35
Gloss paint	8
Interior paint	3
Polythene film, 0.1 mm	200
Roofing felt	4 (and up to 100)

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EXAMPLE 10.1

State the vapour pressure for air at 25°C d.b., 20°C w.b. in Pascals.

The vapour pressure for air under these conditions is 20.17 mb. Thus:

$$p_S = 20.17\ \text{mb} \times \frac{100\ \text{Pa}}{1\ \text{mb}} = 2017\ \text{Pa}$$

EXAMPLE 10.2

Calculate the vapour pressure for saturated air at 25°C d.b., 20°C w.b. from the dew-point.

The dew-point is $t_{dp} = 17.6°\text{C}$. Therefore,

$$p_S = 600.245 \times \exp(0.0684 \times 17.6)\ \text{Pa}$$

Scientific calculators have an e^x function, and in this calculation,

$$x = 0.0684 \times 17.6 = 1.20384$$

Consequently,

$$p_S = 600.245 \times e^{1.20384}$$

Having left 1.20384 in the displayed x register, execute the e^x function, producing 3.33289, and multiply by 600.245 to obtain,

$$p_S = 2000.6\ \text{Pa}$$

This is less than 1% different from the tabulated vapour pressure and is of sufficient accuracy bearing in mind the other figures involved in the problem.

The dew-point temperature can be found from the saturation vapour pressure by rearranging the equation:

$$p_S = 600.245 \times \exp(0.0684\ t_{dp})\ \text{Pa}$$

to give,

$$\frac{p_S}{600.245} = \exp(0.0684\ t_{dp})$$

This is a logarithmic equation of the form:

$$y = e^x$$

where y is the number whose logarithm to base e is x. Logarithms to base e are called natural logarithms and are expressed as follows:

$$\log_e y = x \text{ or } \ln y = x$$

EXAMPLE 10.3

Compute the natural logarithm of 2 and then raise e to the power of this logarithm.

Enter 2 into the calculator x display and press the ln key; the answer is 0.6931. Therefore:

$$\ln 2 = 0.6931 \quad \text{or} \quad \log_e 2 = 0.6931$$

Now, as $x = 0.6931$ is displayed in the calculator, execute e^x. This results in

$$e^{0.6931} = 2$$

Thus it is seen that e^x is the antilogarithm of $\ln x$, and the two expressions $y = e^x$ and $\ln y = x$ are interchangeable to suit the problem. Thus for:

$$\frac{p_s}{600.245} = \exp(0.0684\, t_{dp})$$

we can write:

$$\ln\left(\frac{p_s}{600.245}\right) = 0.0684\, t_{dp}$$

and,

$$t_{dp} = \frac{1}{0.0684} \times \ln\left(\frac{p_s}{600.245}\right) {}^\circ\text{C}$$

EXAMPLE 10.4

Calculate the dew-point for saturated air with a vapour pressure of 2000.6 Pa.

$$\begin{aligned} t_{dp} &= \frac{1}{0.0684} \times \ln\left(\frac{2000.6}{600.245}\right) {}^\circ\text{C} \\ &= \frac{1}{0.0684} \times \ln 3.33 \\ &= 17.6^\circ\text{C} \end{aligned}$$

An alternative general equation is stated in BRE Digest 369 for the calculation of vapour pressure:

$$p_s = 0.6105 \times \exp\left(\frac{17.269 \times t_{dp}}{237.3 + t_{dp}}\right) \text{ kPa}$$

This is less convenient to use when a dew-point temperature is to be calculated from a known vapour pressure. The curve-fit equation that has been demonstrated here is of sufficient accuracy for most manual estimations of condensation risk.

Typical values of vapour pressure are given in Table 10.3. These will accommodate some applications without reference to tables or equations.

EXAMPLE 10.5

Calculate the total vapour resistance of a cavity wall constructed from 13 mm plaster, 100 mm aerated concrete, 40 mm mineral wool, 10 mm air space and 105 mm brickwork.

For each layer:

$$R_V = r_V \times l$$

For the whole structure:

$$\sum (R_V) = \sum (r_V \times l)$$

From Table 10.1 the vapour resistivities are plaster 50, aerated concrete 30, mineral wool 6, brickwork 40. The surface films and air space have no resistance to the flow of vapour. Material thicknesses are used in metres.

$$\begin{aligned}\sum (R_V) &= 50 \times 0.013 + 30 \times 0.1 + 6 \times 0.04 + 40 \times 0.105 \\ &= 8.09 \text{ GN s/kg}\end{aligned}$$

Table 10.3 Vapour pressures.

Air condition t_a (°C d.b.)	*% saturation*	*Dew-point t_{dp} (°C)*	*Vapour pressure (Pa)*
−5	100	−5	402
−3	80	−5.6	381
0	80	−2.7	489
1	80	−1.8	526
2	80	−0.9	565
5	80	1.9	699
10	80	6.7	984
14	60	6.5	965
15	60	7.4	1030
20	50	9.4	1182
22	50	11.3	1339

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EXAMPLE 10.6

The cavity wall in Example 10.5 is to be used for a dwelling exposed to an external environment of −1°C d.b., 80% saturation, where the heating system is designed to maintain the internal air at 22°C and 50% saturation. If the wall has a surface area of 110 m^2, find the moisture mass flow rate taking place through the wall.

From the CIBSE psychrometric chart, the internal and external air dew-point temperatures are found to be:

$$\text{internal } t_{dp} = 11.5°\text{C}$$

$$\text{external } t_{dp} = -3.5°\text{C}$$

The internal air vapour pressure is:

$$\begin{aligned} p_{s1} &= 600.245 \times \exp(0.0684 \times 11.5)\ \text{Pa} \\ &= 1318.09\ \text{Pa} \end{aligned}$$

and the external air pressure is,

$$\begin{aligned} p_{s2} &= 600.245 \times \exp[0.0684 \times (-3.5)]\ \text{Pa} \\ &= 472.45\ \text{Pa} \end{aligned}$$

Using $R_v = 8.09$ GN s/kg from Example 10.5, we obtain the moisture mass flow rate through the wall as:

$$\begin{aligned} G &= \frac{p_{s1} - p_{s2}}{R_v}\ \text{kg/m}^2\text{s} \\ &= (1318.09 - 472.45)\ \frac{\text{N}}{\text{m}^2} \times \frac{\text{kg}}{8.09\ \text{GN s}} \times \frac{1\ \text{GN}}{10^9\ \text{N}} \\ &= 1.045 \times 10^{-7}\ \text{kg/m}^2\text{s} \end{aligned}$$

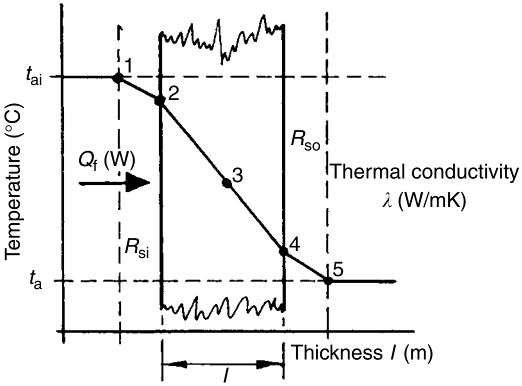
Temperature gradient

Heat flows through a structure from an area of high temperature to one of lower temperature. Homogeneous materials have a linear temperature gradient through their thickness, as shown in Fig. 10.2. Temperature drops 1–2 and 3–4 are caused by the internal and external surface film resistances. To determine the surface and intermediate temperatures, the overall rate of heat flow through the whole structure is equated with the individual heat flows in each slab:

$$Q_f\ \text{W} = U\ \frac{\text{W}}{\text{m}^2\text{K}} \times A\ \text{m}^2 \times (t_1 - t_5)\ \text{K}$$

This same rate of heat flow Q_f also passes through the internal surface film, the concrete and the external surface film. Therefore:

$$Q_f = \frac{1}{R_{si}}\ \frac{\text{W}}{\text{m}^2\text{K}} \times A\ \text{m}^2 \times (t_1 - t_2)\ \text{K}$$



10.2 Temperature gradient through a solid construction.

and,

$$Q_f = \frac{\lambda}{l}\,\frac{\mathrm{W}}{\mathrm{m^2K}} \times A\ \mathrm{m}^2 \times (t_2 - t_4)\ \mathrm{K}$$

and,

$$Q_f = \frac{1}{R_{so}}\,\frac{\mathrm{W}}{\mathrm{m^2K}} \times A\ \mathrm{m}^2 \times (t_4 - t_5)\ \mathrm{K}$$

The heat flow rate Q_f can easily be evaluated from U, t_{ai} and t_{ao}. The only unknowns in the other equations are the second temperatures t_2 and t_4. An intermediate temperature t_3 can be calculated at half the concrete thickness by using $l/2$:

$$Q_f = \frac{2\lambda}{l}\,\frac{\mathrm{W}}{\mathrm{m^2K}} \times A\ \mathrm{m}^2 \times (t_2 - t_3)\ \mathrm{K}$$

If the wall area is taken as 1 m^2, then:

$$Q_f = \frac{1}{R_{si}}(t_1 - t_2)$$

and,

$$t_2 = t_1 - Q_f\,R_{si}$$

Similarly:

$$Q_f = \frac{\lambda}{l}(t_2 - t_4)$$

and,

$$t_4 - t_2 - \frac{l}{\lambda}Q_f$$

Also:

$$Q_f = \frac{1}{R_{so}}(t_4 - t_5)$$

and,

$$t_5 = t_4 - Q_f \, R_{so}$$

Calculating the outdoor air temperature t_5 is a check on the accuracy of the calculations and method. It should agree with the original value used in finding Q_f to within ±1%.

To find t_3 use:

$$Q_f = \frac{2\lambda}{l}(t_2 - t_3)$$

Hence:

$$t_3 = t_2 - \left(\frac{l}{2\lambda} Q_f\right)$$

EXAMPLE 10.7

Calculate the temperature gradient through a medium-weight concrete block wall 100 mm thick. The internal and external air temperatures are 20°C d.b. and −1°C d.b.

From Table 3.1 thermal conductivity $\lambda = 0.51$ W/mK, from Table 3.2 $R_{si} = 0.12$ m^{2}K/W and from Table 3.3 $R_{so} = 0.06$ m^{2}K/W. Then the thermal transmittance is given by:

$$\begin{aligned} U &= \frac{1}{R_{si} + (l/\lambda) + R_{so}} \\ &= \frac{1}{0.12 + (0.1/0.51) + 0.06} \text{ W/m}^2\text{K} \\ &= 2.66 \text{ W/m}^2\text{K} \end{aligned}$$

For a wall area of 1 m^2:

$$\begin{aligned} Q_2 &= 2.66 \times [22 - (-1)] \text{ W} \\ &= 61.16 \text{ W} \end{aligned}$$

Using the numbered locations in Fig. 10.2:

$$t_1 = 22°\text{C}, t_5 = -1°\text{C}$$

$$t_2 = 22 - 61.16 \times 0.12 = 14.66°\text{C}$$

$$t_4 = 14.66 - \frac{0.1}{0.51} \times 61.16 = 2.67°\text{C}$$

and,

$$t_5 = 2.67 - 61.16 \times 0.06 = -1°\text{C}$$

which agrees with the input data. Also,

$$t_3 = 14.66 - \left(\frac{0.1}{2 \times 0.51} \times 61.16\right) = 8.66°\text{C}$$

which should be the temperature midway between t_2 and t_4 that is (14.66 ± 2.67)/2 = 8.67°C, which it is.

EXAMPLE 10.8

Calculate the temperature gradient through a cavity wall consisting of 13 mm lightweight plaster, 100 mm lightweight concrete block, 40 mm mineral fibre slab, 10 mm air space and 105 mm brickwork. Internal and external air temperatures are 22°C and 0°C.

From Table 3.1, the thermal conductivities are as follows: plaster, $\lambda_1 = 0.16$ W/mK; concrete, $\lambda_2 = 0.19$ W/mK; mineral fibre, $\lambda_3 = 0.035$ W/mK; brickwork, $\lambda_4 = 0.84$ W/mK. From Tables 3.2, 3.3 and 3.4, $R_{si} = 0.12$ m^{2}K/W, $R_{so} = 0.06$ m^{2}K/W and $R_a = 0.18$ m^{2}K/W. Then

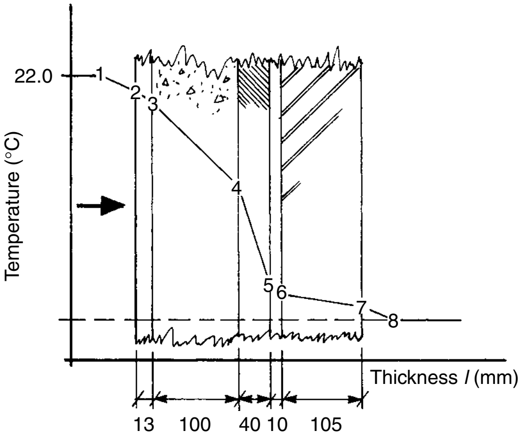
$$\begin{aligned} U &= \left(R_{si} + \frac{l_1}{\lambda_1} + \frac{l_2}{\lambda_2} + \frac{l_3}{\lambda_3} + R_a + \frac{l_4}{\lambda_4} + R_{so}\right)^{-1} \\ &= \left(0.12 + \frac{0.013}{0.16} + \frac{0.10}{0.19} + \frac{0.04}{0.035} + 0.18 + \frac{0.105}{0.84} + 0.06\right)^{-1} \text{ W/m}^2\text{K} \\ &= 0.45 \text{ W/m}^2\text{K} \end{aligned}$$

For a wall area of 1 m^2:

$$Q_f = 0.45 \times (0.22 - 0) = 9.9 \text{ W}$$

Using the notation from Fig. 10.3, temperatures are calculated as follows:

$$\begin{aligned} t_2 &= 22 - (0.12 \times 9.9) = 20.81°\text{C} \\ t_3 &= 20.81 - \left(\frac{0.013}{0.16} \times 9.9\right) = 20.01°\text{C} \\ t_4 &= 20.01 - \left(\frac{0.01}{0.19} \times 9.9\right) = 14.8°\text{C} \\ t_5 &= 14.8 - \left(\frac{0.04}{0.035} \times 9.9\right) = 3.49°\text{C} \\ t_6 &= 3.49 - (0.18 \times 9.9) = 1.71°\text{C} \\ t_7 &= 1.71 - \left(\frac{0.105}{0.84} \times 9.9\right) = 0.47°\text{C} \\ t_8 &= 0.47 - (0.06 \times 9.9) = 0.12°\text{C} \end{aligned}$$



10.3 Temperature notation for Example 10.8.

A slight error of 0.55% has occurred as a result of rounding all the results to two decimal places. Notice the larger temperature drops across the two main insulating materials.

Dew-point temperature gradient

Moist air passing through the structure from the high internal air vapour pressure to the lower external air vapour pressure will form a gradient of vapour pressures. The vapour pressure at any location is calculated from the mass flow rate of vapour *G* and vapour resistances in the same manner as for the thermal gradient.

The moist air dew-point temperature is calculated for each of these vapour pressures and another temperature gradient is drawn on the structural cross-section. If the thermally produced structure temperature equals or falls below the local air dew-point, then condensation will commence at that location. This information is used to decide whether a wall or roof will remain dry and whether a vapour barrier should be installed. The vapour barrier is fitted on the warm side of any zone of interstitial condensation.

Once the internal and external air vapour pressures, total vapour resistance and mass flow rate of vapour are known, the equation:

$$G = \frac{p_{si} - p_{s2}}{R_v}$$

can be written as,

$$p_{s2} = p_{s1} - R_v G$$

Note that this is of the same form as:

$$t_2 = t_1 - RQ_f$$

Surface air films and cavities offer negligible resistance to the flow of moisture.

EXAMPLE 10.9

Calculate the dew-point gradient for the cavity wall in Example 10.8. Determine whether surface or interstitial condensation will take place. Internal and external percentage saturations are 50 and 100 respectively.

Referring to Fig. 10.2,

$$p_{s1} = p_{s2}$$
$$p_{s5} = p_{s6}$$
$$p_{s7} = p_{s8}$$

Thus,

$$p_{s3} = p_{s1} - (\text{vapour resistance of plater} \times G)$$

where p_{s3} and p_{s1} are the vapour pressures on each side of the plaster and,

$$\text{vapour resistance of plaster} = r_v \times l$$

Similar equations are written for the other materials, with appropriate resistivities r_v and thicknesses l. The resistivities are plaster 50, concrete 30, mineral wool 6 and brickwork 40. From the CIBSE psychrometric chart, for internal air at 22°C d.b., 50% saturation, $t_{dp} = 11.5°\text{C}$, and for external air at 0°C d.b., 100% saturation, $t_{dp} = 0°\text{C}$. Then,

$$p_{s1} = 600.245 \times \exp(0.0684 \times 11.5)\ \text{Pa}$$
$$= 1318.09\ \text{Pa}$$
$$p_{s8} = 600.245 \times \exp(0.0684 \times 0)\ \text{Pa}$$
$$= 600.245\ \text{Pa, because } (e^0 = 1)$$

The vapour resistance R_v for this wall was calculated in Example 10.5:

$$R_v = 8.09\ \text{GN s/kg}$$

The mass flow of vapour per m^2 of wall area is:

$$G = (1318.09 - 600.245)\ \frac{\text{N}}{\text{m}^2} \times \frac{\text{kg}}{8.09\ \text{GN s}} \times \frac{1\ \text{GN}}{10^9\ \text{N}}$$
$$= 88.7 \times 10^{-9}\ \text{kg/m}^2\text{s}$$

The vapour pressure and corresponding dew-point temperature can now be calculated for each numbered point through the wall:

$$p_{s3} = 1318.09\ \frac{N}{\mathrm{m}^2} 50 \times 0.013\ \frac{\mathrm{GN\ s}}{\mathrm{kg}} \times \frac{10^9\ \mathrm{N}}{1\ \mathrm{GN}} \times \frac{88.7}{10^9}\ \frac{\mathrm{kg}}{\mathrm{m^2 s}}$$

$$= (1318.09 - 57.7)\ \mathrm{N/m^2}$$

$$= 1260.4\ \mathrm{Pa}$$

$$t_{dp3} = \frac{1}{0.0684} \times \ln\left(\frac{p_{s3}}{600.245}\right)^{\circ}\mathrm{C}$$

$$= \frac{1}{0.0684} \times \ln\left(\frac{1260.4}{600.245}\right)^{\circ}\mathrm{C}$$

$$= 10.85^{\circ}\mathrm{C}$$

$$p_{s4} = 1260.4 - 30 \times 0.1 \times 88.7\ \mathrm{Pa}$$

$$= 994.3\ \mathrm{Pa}$$

$$t_{dp4} = \frac{1}{0.0684} \times \ln\left(\frac{994.3}{600.245}\right)^{\circ}\mathrm{C}$$

$$= 7.38^{\circ}\mathrm{C}$$

$$p_{s5} = 994.3 - 6 \times 0.04 \times 88.7\ \mathrm{Pa}$$

$$= 973\ \mathrm{Pa}$$

$$t_{dp5} = \frac{1}{0.0684} \times \ln\left(\frac{973}{600.245}\right)^{\circ}\mathrm{C}$$

$$= 7.06^{\circ}\mathrm{C}$$

$$p_{s7} = 973 - 40 \times 0.105 \times 88.7^{\circ}\mathrm{C}$$

$$= 600.5^{\circ}\mathrm{C}$$

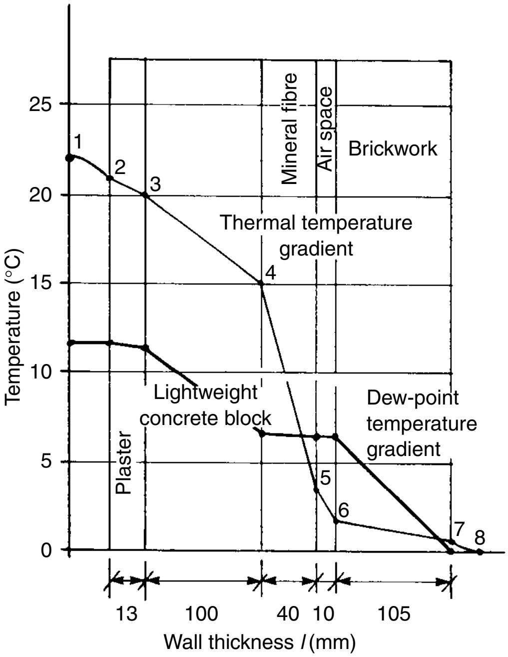
$$t_{dp7} = \frac{1}{0.0684} \times \ln\left(\frac{600.5}{600.245}\right)^{\circ}\mathrm{C}$$

$$= 0.006^{\circ}\mathrm{C}\ \text{shows small calculation inaccuracy}$$

$$= 0^{\circ}\mathrm{C}\ \text{the significant value}$$

The dew-point temperature gradient ends with the input data and is superimposed upon a scale drawing of the thermally induced gradient shown in Fig. 10.4.

Owing to the high thermal resistance and very low vapour resistance of the mineral fibre slabs fixed in the cavity, under the design conditions as stated the material temperature drops below the moist air dew-point temperature midway through its thickness. Interstitial condensation will occur within the mineral fibre, air space and external brickwork. Ventilation of the remaining wall cavity allows evaporative removal of the droplets. Variation of internal and external air conditions will limit the duration of such temperature gradients. Periods of condensation will be very intermittent. Solar heat gains to the external brickwork will raise the temperature of the structure and help to reduce condensation periods. The walls most at risk are those always shaded from direct sunlight and having reduced wind exposure due to the proximity of nearby buildings.



10.4 Temperature gradients in the wall in Example 10.9.

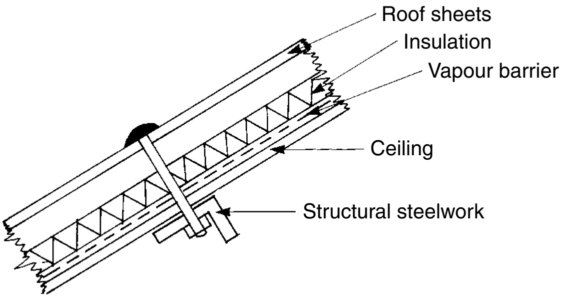
When condensation takes place, a change of phase occurs as the water vapour turns into liquid. The calculations of water vapour transfer end at this discontinuity. The reason for undertaking the calculations was to establish if and where condensation is formed. The whole thickness of the layer where liquid forms is likely to be dampened owing to capillary attraction within porous solid material. The quantity of condensation that may be formed during a 60-day winter period can be assessed from the expected average air conditions. This aids the prediction of the physical damage that may be caused.

Installation note

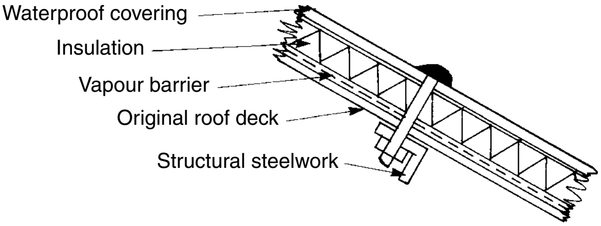
Added thermal insulation can cause conditions where condensation will take place owing to the lowered structural temperatures. The installation of a vapour barrier raises the overall vapour resistance and may be able to keep the dew-point gradient below the thermally produced temperatures.

1. Materials with a low thermal resistance but a high vapour resistance, such as aluminium foil, sheet plastic, roofing felt and gloss paint, are placed on the warm side of the structure.
2. Materials of high thermal and vapour resistance can be placed anywhere.
3. Materials of moderate vapour resistance but high thermal resistance should be placed on the cold side of the structure. Such materials will require the addition of a weather-resistant coating when applied to the outside of a building.

Thermal or acoustic insulation applied to industrial roofs can increase the possibility of the occurrence of condensation. Alternative schemes are shown in Figs 10.5 and 10.6 (Saunders, 1981).



10.5 Cold-deck roof.



10.6 Warm-deck roof.

In the cold-deck design, the roofing sheets remain at little more than the external air temperature. Ventilation through gaps at the eaves, junctions where the sheets overlap and holes around steel supports provides passageways for the ingress of moist air. Condensation on the underside of the cold deck will cause water to run down the steelwork and wet the ceiling. It is unlikely that a tight seal can be made between the vapour barrier and the steel supports to avoid this happening. Before insulation of an existing roof, its underside is maintained at above the local dew-point except during severe weather or when the heating plant is off.

The warm-deck design improves the weather resistance of the roof and raises the original underside surface temperature even further. Interstitial condensation is unlikely because of the vapour barriers.

EXAMPLE 10.10

Calculate the external air temperature that will cause condensation to form on the underside of a factory roof constructed from 10 mm corrugated asbestos cement sheet. Internal air conditions near the roof are 23°C d.b., 30% saturation. The thermal conductivity of asbestos cement sheet is 0.4 W/mK. The roof has a severe exposure.

From the CIBSE psychrometric chart, the internal air dew-point is 5°C. From Tables 3.2 and 3.3, $R_{si} = 0.1$ m^{2}K/W and $R_{so} = 0.02$ m^{2}K/W. Let the unknown external air temperature be t_o. Then for a roof area of 1 m^2:

$$Q_f = U\,(23 - t_o)\ \text{W/m}^2$$

For the external surface film:

$$\begin{aligned}Q_\mathrm{f} &= \frac{1}{R_\mathrm{si}}(23 - 5)\ \mathrm{W/m^2}\\ &= \frac{1}{0.1} \times 18\ \mathrm{W/m^2}\\ &= 180\ \mathrm{W/m^2}\end{aligned}$$

For the roof:

$$\begin{aligned}U &= \frac{1}{R_\mathrm{si} + (l/\lambda) + R_\mathrm{so}}\\ &= \frac{1}{0.1 + (0.01/0.4) + 0.02}\\ &= 6.9\ \mathrm{W/m^2}\end{aligned}$$

Now, rate of heat flow through roof sheets = rate of heat flow through internal surface film.

$$6.9\ \frac{\mathrm{W}}{\mathrm{m^2\ K}} \times (23 - t_\mathrm{o})\ \mathrm{K} = 180\ \frac{\mathrm{W}}{\mathrm{m^2}}$$

$$26.0 = 23 - t_\mathrm{o}$$

$$t_\mathrm{o} = -3.09°\mathrm{C}$$

Questions

1. Describe how the following forms of condensation occur: temporary, permanent and interstitial.
2. List the sources of moisture in buildings.
3. What is the purpose of installing a vapour barrier and what effect does it have on the dew-point temperatures within a structure?
4. Discuss the use of thermal insulation in reducing the likelihood of condensation in walls and roofs.
5. State examples of thermal insulation increasing the risk that condensation occurs.
6. List the actions that could be taken to reduce the water vapour input to a dwelling.
7. Discuss the use of heating and ventilation in combating condensation problems.
8. Why might prefabricated concrete buildings suffer more from condensation than other constructions?
9. What sources of moisture would you look for when consulted about mould growth on a building?
10. Describe the constituent parts of the atmospheric pressure.
11. What drives water vapour from one area to another?
12. Describe the way in which moisture is alternatively stored and released by porous building materials.
13. What is the flow of vapour through a composite structure analogous to?
14. State the conditions under which water vapour will condense on or within a construction.
15. Calculate the temperature gradients through the following structures. Internal and external air temperatures are to be taken as 21°C d.b. and −1°C d.b. Assume that $t_\mathrm{a} = t_\mathrm{e}$. The answers should be expressed as the surface or interface temperatures in descending order

from the warm side. Outside surfaces are taken as having a high emissivity and normal exposure. All air spaces are ventilated. The thermal conductivity of glass is 1.05 W/mK.

(a) 6 mm single-glazed window.
(b) 6 mm double-glazed window.
(c) Cavity wall of 15 mm dense plaster, 100 mm lightweight concrete block, air space and 105 mm brick.
(d) An industrial roof of 10 mm asbestos cement corrugated sheet which has been given an external coating of 50 mm phenolic foam. The thermal conductivity of asbestos sheet is 0.4 W/mK.

16. A shop window consists of 6 mm plate glass in an aluminium frame. The display area air temperature is expected to be 15°C d.b. and to have a dew-point of 7°C. Find the external air temperature that will start to produce condensation on the inside of the window. The window has normal exposure.
17. If a double-glazed window is to be fitted in the shop in Question 16, what could the external air temperature drop to before condensation starts?
18. A hospital ward is to be maintained at 24°C d.b. and 80% saturation. The air dew-point is 20.5°C. Thermal insulation is to be added to the inside of the existing wall to avoid surface condensation when the external air temperature falls to −5°C d.b. The *U* value of the original wall is 1.9 W/m^{2}K. Calculate the thickness of insulation material required if its thermal conductivity is 0.06 W/mK.
19. Calculate the thermal transmittance, temperature and dew-point gradients through a flat roof consisting of 25 mm stone chippings, 10 mm roofing felt, 150 mm aerated concrete, 75 mm wood wool/cement slabs, a ventilated 50 mm air space and 12 mm plasterboard. The roof has a sheltered exposure. Internal air conditions are 22°C d.b., 50% saturation. External conditions are 2°C d.b., 80% saturation. The stone chippings have a high emissivity when weathered and offer no resistance to the flow of water vapour. Plot a graph of the two temperature gradients and find if condensation is likely to occur.
20. Calculate the thermal transmittance, temperature and dew-point gradients through a wall consisting of 15 mm dense plaster, 100 mm medium-weight concrete blockwork, 40 mm glass fibre quilt, a ventilated 10 mm air space and 105 mm brickwork. The wall has a severe exposure. The average internal air conditions are 14°C d.b., 60% saturation when the external conditions are 1°C d.b., 80% saturation. Plot a graph of the two temperature gradients and find if condensation is likely to occur.
21. Where are indoor condensation problems most likely found?

    1. Hot dry ambient air locations.
    2. Hot humid ambient air locations.
    3. Temperate maritime climates, such as the UK, where outdoor air humidity remains high.
    4. Below zero ambient air locations.
    5. In any building anywhere.

22. Why does condensation occur within a building?

    1. Users leave taps running, baths full, water evaporates and deposits onto room surfaces, making air moist.
    2. Kettles, cooking, fish tanks and open bowls of water evaporate more water vapour into room than ventilation can remove.
    3. Porous building materials provide pathways for cold moisture to ingress a warm building and make indoor surfaces damp.

4. Evaporated water within the building meets surfaces at below dew-point temperature.
5. Cyclic variation of indoor surface temperatures always produces below dew-point locations.

23. What always combats condensation problems within occupied buildings?

    1. Thermal insulation.
    2. Impervious building materials.
    3. Removing open water surfaces.
    4. Air conditioning.
    5. Heating and ventilation.

24. From where does water vapour originate within a building?

    1. Atmospheric rain.
    2. Wind-driven atmospheric humidity.
    3. Occupants and their activities.
    4. Lack of sufficient natural and mechanical ventilation.
    5. Refrigeration systems and food storage.

25. What is the relationship of building materials to moisture mass transfer?

    1. There is none, building materials do not leak water.
    2. Good design and construction removes all moisture issues.
    3. Modern building materials have zero permeability.
    4. Porous structural materials absorb and pass moisture.
    5. Vapour barriers isolate brick, concrete and thermal insulation materials from moisture generated within a building.

26. What drives moisture flow through a structure?

    1. Vapour pressure difference in Pascals.
    2. Air temperature difference in °C d.b.
    3. Percentage saturation difference.
    4. Air moisture content difference in kg H_2O/kg dry air.
    5. Wet-bulb air temperature difference in °C w.b.

27. Which is correct about condensation and mould growth?

    1. Always occurs in buildings over 20 years old.
    2. Cannot happen with current design standards.
    3. Readily forms in the UK in room corners, on window sills, in cupboards on external walls and within structures having an overall thermal transmittance of over 1.4 W/m^2K.
    4. Must be removed, the surface gloss painted and outdoor air ventilation minimized.
    5. Impervious external surface materials need to be matched with an outdoor vapour barrier to stop moisture flowing into the wall, floor or roof structure.

28. Vapour diffusion into a structure that then condenses is called what type?

    1. Adiabatic.
    2. Complex.
    3. Leakage.
    4. Interstitial.
    5. Intermediate.

29. What is happening in a building during vapour diffusion?
    1. Odours and gases produced indoors slowly percolate through the building structure to outdoors.
    2. Steam from water boiling, cooking and hot-water washing become absorbed into furniture, furnishings, carpets and surface plaster unless removed by ventilation.
    3. Internally sourced water vapour migrates through porous building structures.
    4. Low indoor vapour pressure drives moisture towards higher outdoor moist air vapour pressure.
    5. Liquid water passes through the building structure.
30. In the context of condensation in building, what does r_V symbolize?
    1. Vapour resistivity of a material.
    2. Vapour resistivity of a structure.
    3. Resistance to vapour flow of a structure.
    4. Volumetric resistivity of a structure.
    5. Volumetric resistance of a material to moisture transfer.
31. Which is true?
    1. 10^3 kN s/gm = GN s/kgm.
    2. 10^3 N s/g = MN s/g.
    3. MN s/gm = GN s/kgm.
    4. 10^6 N s/kg = MN s/g.
    5. kN s/kg = MN s/g.
32. What is the vapour resistivity of a structural material measured in?
    1. kN/m^{2}s.
    2. MN s.
    3. kN s/kg.
    4. GN s/kg m.
    5. kN kg/m^{2}s.