3 Heat loss calculations

Learning objectives

Study of this chapter will enable the reader to:

1. identify and use the thermal conductivity and resistivity of building materials;
2. calculate the thermal resistance of a composite structure;
3. use building exposure categories;
4. use surface and cavity thermal resistance values;
5. identify high- and low-emissivity building materials;
6. calculate, or find, the thermal transmittance of walls, flat and pitched roofs, floors and windows;
7. use the proportional area method to calculate the average *U* value of a thermally bridged wall or other structure;
8. calculate the fabric and ventilation building heat loss components for a building;
9. calculate air and environmental temperatures produced in a room from a specified resultant temperature;
10. identify the use of admittance *Y* values;
11. hot-water storage boiler power requirements;
12. calculate total boiler power.

Key terms and concepts

boiler power 71; edge insulation 66; exposure: sheltered, normal and severe 63; hot-water heat load 71; intermittent heat load 70; proportion area method 64; steady-state heat loss 67; surface emissivity 63; surface resistance 63; thermal conductivity 61; thermal resistance 61; thermal storage of structure 67; thermal transmittance 64; *U* value 64; *Y* value 70.

Introduction

The terms and techniques for handling thermal properties of building materials are introduced to enable calculation of the thermal resistance *R*, thermal transmittance *U* and use of admittance

Y of composite building elements. Chartered Institution of Building Services Engineers data are used throughout and representative values are given. Calculation of building heat loss allows load estimation for heating equipment.

Thermal resistance of materials

The thermal resistance of a slab of homogeneous material is calculated by dividing its thickness by its thermal conductivity:

$$R = \frac{l}{\lambda}$$

where R is the thermal resistance (m^2K/W), l is the thickness of the slab (m) and λ is the thermal conductivity (W/mK). Resistance to heat flow by a material depends on its thickness, density, water content and temperature. The latter two parameters result from the material's location within the structure. Insulating materials are usually protected from moisture and the possibility of physical damage as they are of low density and strength. The thermal conductivity of masonry can be found from the bulk dry density and the moisture content, which depends on whether it is exposed to the climate or is in a protected position. Table 3.1 shows data for building materials taken from the *CIBSE Guide*, to which further reference can be made.

EXAMPLE 3.1

Find the thermal resistance of a 110 mm thickness of brickwork inner leaf.

From Table 3.1, $\lambda = 0.62$ W/mK and $l = 0.11$ m. Therefore:

$$R = \frac{0.110}{0.62}\ m^2K/W$$
$$= 0.1774\ m^2K/W$$

EXAMPLE 3.2

A designer wishes to replace 200 mm thick heavyweight concrete blocks in the design of a wall with fibreboard having the same thermal resistance. What thickness of fibreboard could be used?

The values of λ are 1.63 W/mK for the heavyweight concrete block and 0.06 W/mK for the fibreboard.

$$R\ (\text{concrete}) = \frac{0.200}{1.63}$$
$$R\ (\text{fibreboard}) = \frac{l}{0.06}$$

Table 3.1 Thermal conductivities of materials.

Material	*Density (kg/m^3)*	*Thermal conductivity λ (W/mK)*	*Specific heat capacity (J/kgK)*
Walls (external and internal)			
Asbestos cement sheet	700	0.36	1050
Asbestos cement decking	1500	0.36	1050
Brickwork (outer leaf)	1700	0.84	800
Brickwork (inner leaf)	1700	0.62	800
Cast concrete (dense)	2100	1.40	840
Cast concrete (lightweight)	1200	0.38	1000
Concrete block (heavyweight)	2300	1.63	1000
Concrete block (medium weight)	1400	0.51	1000
Concrete block (lightweight)	600	0.19	1000
Fibreboard	300	0.06	1000
Plasterboard	950	0.16	840
Tile hanging	1900	0.84	800
Surface finishes			
External rendering	1300	0.50	1000
Plaster (dense)	1300	0.50	1000
Plaster (lightweight)	600	0.16	1000
Roofs			
Aerated concrete slab	500	0.16	840
Asphalt	1700	0.50	1000
Felt–bitumen layers	1700	0.50	1000
Screed	1200	0.41	840
Stone chippings	1800	0.96	1000
Tile	1900	0.84	800
Wood–wool slab	500	0.10	1000
Floors			
Cast concrete	2000	1.13	1000
Metal tray	7800	50.00	480
Screed	1200	0.41	840
Timber flooring	650	0.14	1200
Wood blocks	650	0.14	1200
Insulation			
Expanded polystyrene (EPS) slab	25	0.035	1400
Glass fibre quilt	12	0.040	840
Glass fibre slab	25	0.035	1000
Mineral fibre slab	30	0.035	1000
Phenolic foam	30	0.040	1400
Polyurethane board	30	0.025	1400
Urea formaldehyde (UF) foam	10	0.040	1400

Therefore for the same resistance,

$$\frac{0.200}{1.63} = \frac{l}{0.06}$$

Hence,

$$l = 0.06 \times \frac{0.200}{1.63}\ \text{m} \times \frac{10^3\ \text{mm}}{1\ \text{m}}$$
$$= 7.4\ \text{mm}$$

Thermal transmittance (*U* value)

Thermal transmittance is found by adding the thermal resistances of adjacent material layers, boundary layers of air and air cavities, and then taking the reciprocal. Boundary layer or surface film thermal resistances result from the near-stationary air layer surrounding each part of a building, with an allowance for the radiant heat transfer at the surface. Heat transmission across cavities depends upon their width, ventilation and surface emissivities. The external surface resistance depends upon the building's exposure.

Sheltered: up to the third floor of buildings in city centres
Normal: most suburban and rural buildings; fourth to eighth floors of buildings in city centres
Severe: buildings on coastal or hill sites; floors above the fifth in suburban or rural districts; floors above the ninth in city centres.

Surface resistances are shown in Tables 3.2–3.5.

Table 3.2 Inside surface resistance R_{si}.

Building element	*Heat flow*	*R_{si} ($m^2 K/W$)*
Wall	Horizontal	0.12
Ceiling, floor	Upward	0.10
Ceiling, floor	Downward	0.14

Note: These values are for the high-emissivity surfaces ($E = 0.90$) common to most building components.

Table 3.3 Outside surface resistance R_{so}.

Builing element	*Surface emissivity*	*R_{so} ($m^2 K/W$)*		
		Sheltered	*Normal*	*Severe*
Wall	High	0.08	0.06	0.03
Wall	Low	0.11	0.07	0.03
Roof	High	0.07	0.04	0.02
Roof	Low	0.09	0.05	0.02

Table 3.4 Thermal resistance R_a of ventilated air spaces.

Air space of 25 mm or more	*R_a($m^2 K/W$)*
Loft space between flat plaster ceiling and pitched roof with tiles on felt	0.18
Air space behind tiles on tile hung wall	0.12
Air space in cavity wall	0.18
Air space between high- and low-emissivity surfaces	0.30

Table 3.5 Thermal resistances R_a for unventilated air spaces.

Air space thickness (mm)	*Surface emissivity*	*R_a($m^2 K/W$)*		
		Horizontal	*Upward*	*Downward*
5	High	0.10	0.10	0.10
5	Low	0.18	0.18	0.18
25 or more	High	0.18	0.17	0.22
25 or more	Low	0.35	0.35	1.06

Table 3.6 Data for Example 3.3.

Element	*Length l (m)*	*λ (W/mK)*	*R (m^2K/W)*
R_{so}			0.030
Brick	0.105	0.84	0.125
R_a			0.180
Brick	0.105	0.84	0.125
Plaster	0.013	0.5	0.026
R_{si}			0.120
			$\sum R = 0.606$

EXAMPLE 3.3

An external wall consisting of 105 mm brick, 50 mm unventilated cavity, 105 mm brick and 13 mm dense plaster has a severe exposure. Find its *U* value.

The calculation of $\sum R$ is shown in Table 3.6. The thermal transmittance *U* is calculated as follows:

$$U = \frac{1}{\sum R}$$
$$= \frac{1}{0.606} \text{ W/m}^2\text{K}$$
$$= 1.65 \text{ W/m}^2\text{K}$$

EXAMPLE 3.4

Calculate the thermal transmittance of the wall in Example 3.3 if the cavity is filled with urea formaldehyde (UF).

The calculation of $\sum R$ is shown in Table 3.7. Then the new value of *U* is 0.6 W/m^2K.

Elements of buildings that are bridged by a material of noticeably different thermal conductivity, such as a dense concrete or steel lintel in a lightweight concrete wall, can be handled by combining the *U* values of the two constructions using the proportional area method. If U_1 and P_1 are the thermal transmittance and the unbridged proportion respectively of the gross wall area, and U_2 and P_2 are the same parameters for the bridging material, the overall *U* value is given by

$$U = P_1U_1 + P_2U_2$$

Table 3.7 Data for Example 3.4.

Element	*Length l (m)*	*λ (W/mK)*	*R (m^2K/W)*
Previous $\sum R$			0.606
Less R_a			−0.180
Net			0.426
UF foam	0.050	0.040	1.250
			$\sum R = 1.676$

EXAMPLE 3.5

In a concrete-framed commercial building the external walling of brick has a *U* value of 1.8 W/m^2K. The building has a gross perimeter of 180 m and is 3.6 m high. Thirty dense concrete pillars 180 mm wide penetrate the walling from inside to outside. The exposure is normal and the wall thickness is 300 mm.

Find the overall *U* value.

Thermal conductivity of the concrete pillar $\lambda = 1.40$ W/mK.
For the concrete pillar:

$$U_2 = \frac{1}{R_{si} + (l/\lambda) + R_{so}}$$

$$= \frac{1}{0.12 + (0.30/1.40) + 0.06} \text{ W/m}^2\text{K}$$

$$= 2.54 \text{ W/m}^2\text{K}$$

$$\text{surface area of pillars} = 30 \times 0.180 \times 3.6 \text{ m}^2$$

$$= 19.44 \text{ m}^2$$

$$\text{gross wall area} = 180 \times 3.6 \text{ m}^2$$

$$= 648 \text{ m}^2$$

$$P_2 \text{ (pillars)} = \frac{19.44}{648} = 0.03$$

$$P_2 \text{ (walling)} = \frac{648 - 19.44}{648} = 0.97$$

Thus the overall value of *U* is given by:

$$U = (0.97 \times 1.8) + (0.03 \times 2.54) \text{ W/m}^2\text{K}$$

$$= 1.82 \text{ W/m}^2\text{K}$$

Where only one leaf of a structure containing a cavity is bridged, the resistance of each leaf is calculated separately using the proportional areas as appropriate and then the resistances can be added. The centre line of the cavity can be chosen as the dividing line between the two leaves and half the air space resistance added into each side of the structure. Heat bridges are thermal routes having a lower resistance than the surrounding material that cause distortions to the otherwise uniform temperature gradients. Precise calculation of overall thermal transmittance may require the use of a finite-element computer program that investigates the two- or three-dimensional heat conduction process taking place.

The thermal transmittance of a flat roof is calculated in the manner outlined for walls, but attention must be paid to tapered components. For a pitched roof:

$$U = \frac{1}{R_A \cos \beta + R_R + R_B}$$

where R_A is the combined resistance of the materials in the pitched part of the roof including the outside surface resistance (m^2K/W), β is the pitch angle of the roof (degrees), R_R is the resistance of the roof void (m^2K/W) and R_B is the combined resistance of the materials in the fiat part of the ceiling including the inside surface resistance (m^2K/W).

Heat flow through solid ground floors in contact with the earth depends on the thermal resistance of the floor slab and the ground which, in turn, is largely determined by its moisture content. The thermal conductivity of the earth can vary from 0.70 to 2.10 W/mK depending upon the moisture content. Table 3.8 was evaluated for $\lambda = 1.40$ W/mK, which is about the same as for a concrete slab, and so the *U* values given can be used for floors of any thickness. Dense floor-finishing materials will not influence the quoted *U* values.

The thermal resistance of insulation placed under the screed of a solid floor, or on netting between the joists of a suspended timber floor, can be added to the reciprocal of the *U* value of the uninsulated floor and the new thermal transmittance can be calculated. An insulation material placed vertically around the edge of a concrete floor slab which has a thermal resistance of at least 0.25 m^2K/W and a depth of 1 m, for example, a 10 mm thickness of expanded polystyrene, will reduce the *U* value of the floor by the percentages shown in Table 3.9.

The thermal transmittance of windows depends on glazing and frame types and exposure. If a low-emissivity reflective metallic film is applied to the inside surface of the glass, then the internal

Table 3.8 *U* values for solid and suspended floors.

Length (m)	*Breadth (m)*	*U (W/m²K)*		
		Four exposed edges	*Two perpendicular exposed edges*	*Suspended floor*
100	100	0.10	0.05	0.11
40	40	0.21	0.12	0.22
20	20	0.36	0.21	0.37
10	10	0.62	0.36	0.59
10	4	0.90	0.54	0.83
4	4	1.22	0.73	0.96

Table 3.9 Corrections to U values of solid floors with edge insulation.

Length (m)	*Breadth (m)*	*Reduction in U value (%)*
100	100	16
40	40	18
20	20	19
10	10	22
10	4	25
4	4	28

Table 3.10 U values for typical windows.

Windows	*U (W/m²K)*		
	Sheltered	*Normal*	*Severe*
Single frame			
Wood frame	4.7	5.3	6.3
Aluminium frame	5.3	6.0	7.1
Aluminium frame with thermal break	5.1	5.7	6.7
Double glazing			
Wood frame	2.8	3.0	3.2
Aluminium frame	3.3	3.6	4.1
Aluminium frame with thermal break	3.1	3.3	3.7

surface resistance value can be significantly increased, resulting in a lower U value and reduced heat and light transmission from outside. Glass and metal window frames, in themselves, offer negligible resistance to heat flow, but when resistive materials are used the overall U value can be found using the proportional area method. Table 3.10 shows window U values assuming that the frame takes up 10% of the gross opening in the wall.

Heat loss from buildings

Heat loss occurs by convection and radiation from the outside of the building, and by infiltration of outdoor air. Heating equipment is sized on the basis of steady-state heat flows through the building fabric, with an estimation of the effect of non-steady influences relating to the thermal storage capacity of the structure, adventitious heat gains from people, lighting and machines, and the intermittency of heating system operation.

The steady-state heat loss Q_u through the building fabric is:

$$Q_u = \sum (AU)(t_{ei} - t_{ao}) \text{ W}$$

where $\sum(AU)$ is the sum of the products of the area and thermal transmittance of each room surface. Heat flows to adjacent rooms that are warmer than the outdoor air are found by using the appropriate temperature difference between them.

The ventilation heat Q_v required to warm the natural infiltration of outdoor air is:

$$Q_v = 0.33\, NV\, (t_{ai} - t_{ao})\ \text{W}$$

The total heat requirement for each room is:

$$Q_p = Q_u + Q_v$$

The values of environmental and air temperature used in the calculations depend upon the type of heating system employed, and the following temperature ratios are used:

$$F_1 = \frac{t_{ei} - t_{ao}}{t_c - t_{ao}}$$
$$F_2 = \frac{t_{ai} - t_{ao}}{t_c - t_{ao}}$$

These two ratios are substituted into the equations for heat requirements Q_u and Q_v. The total heat requirement Q_p then becomes:

$$Q_p = \left[F_1 \sum (AU) + 0.33 F_2 NV\right] (t_c - t_{ao})\ \text{W}$$

For buildings with average external U values in the range 0.60–3.0 W/m^{2}K, including openings, which covers the majority of habitable structures, the temperature ratios have the following values (with an accuracy to 5.0%):

$$F_1 = 1.00 \quad F_2 = 1.10$$

for panel radiator heating systems:

$$F_1 = 0.92 \quad F_2 = 1.23$$

for forced warm-air heating systems. Further values are tabulated in the *CIBSE Guide*.

To check the comfort conditions produced by the heating system in a room we use:

$$t_{ai} = F_2 (t_c - t_{ao}) + t_{ao}$$

where t_c is the dry resultant temperature specified for the centre of the room from consideration of the application and t_{ao} has been specified for the location. The environmental temperature produced in the room is given by:

$$t_{ei} = F_1 (t_c - t_{ao}) + t_{ao}$$

EXAMPLE 3.6

An office building 20 m long by 10 m wide and 3 m high is to have a hot-water panel radiator heating system that will maintain a dry resultant temperature of 21°C at the centre of the room at an external air temperature of −4°C. There are 10 windows each of area 2 m^2 and two doors each of area 4 m^2. The roof can be taken as being flat. Infiltration of outside air amounts to 1.0 air change/h. Thermal transmittances are as follows: windows, 5.7 W/m^2K; walls, 0.5 W/m^2K; doors, 5.7 W/m^2K; roof, 0.3 W/m^2K; floor, 0.6 W/m^2K. Find the total rate of heat loss from the building under steady-state conditions, the room air temperature and the environmental temperature.

The calculation of $\sum(AU)$ is given in Table 3.11.
Using $F_1 = 1.0, F_2 = 1.10, N = 1.0, V = 600\ m^3$, $t_c = 21°C$ and $t_{ao} = -4°C$

$$
\begin{aligned}
Q_p &= (1 \times 415.6 + 0.33 \times 1.1 \times 1.0 \times 600)(21 + 4) \\
&= 15\,835\ W \\
&= 15.835\ kW \\
t_{ai} &= 1.1[21 - (-4)] - 4°C \\
&= 23.5°C \\
t_{ei} &= 1[21 - (-4)] - 4°C \\
&= 21°C
\end{aligned}
$$

EXAMPLE 3.7

The air-conditioning system in a computer room breaks down, and it is thought that there would be a risk of condensation forming from the moisture in the air if the room air temperature were to fall below 10°C. Assess the likely room air temperature from the following information: room dimensions, 12 m × 9 m × 3.3 m high; dimensions of window in one long exterior wall, 2.5 m × 2.2 m; ventilation rate, 0.50 air changes/h. The adjacent rooms, those below and above, are all at $t_{ei} = 19°C$. The outside air temperature is −2°C. U values of the external wall, the window and the internal surfaces are 0.6, 2.8 and 1.6 W/m^2K respectively.

Table 3.11 Data for Example 3.6.

Surface	*Area A (m^2)*	*U (W/m^2K)*	*AU (W/K)*
Windows	20	5.7	114.0
Doors	8	5.7	45.6
Walls	152	0.5	76.0
Roof	200	0.3	60.0
Floor	200	0.6	120.0
			$\sum(AU) = 415.6$

The surrounding rooms will steadily transfer heat into the computer room and then this heat will escape through the one external wall and by natural ventilation. The air temperature of the computer room should stabilize at some value t_1 °C. A balance of heat flows into and out of the room can be made:

$$\text{heat flow in} = \text{heat flow out}$$

$$\sum (UA\ \Delta t) = \sum (UA\ \Delta t) + Q_v$$

We can assume that, initially, the computer room environmental temperature is the same as its air temperature. The internal partition, floor and ceiling surface area is 315 m^2, the window area is 5.5 $m^2$and the external wall area is 34.1 m^2. Then:

$$\begin{aligned}
\text{heat flow in} &= 1.6\ \frac{W}{m^2K} \times 315\ m^2 \times (19 - t_1)\ K \\
&= 504(19 - t_1)\ W \\
\text{heat flow out} &= 2.8 \frac{W}{m^2K} \times 5.5\ m^2 \times (t_1 + 2)\ K \\
&\quad + 0.6\ \frac{W}{m^2K} \times 34.1\ m^2 \times (t_1 + 2)\ K \\
&\quad + 0.33\ \frac{W}{m^3K} \times 0.5 \times 12 \times 9 \times 3.3\ m^3 \times (t_1 + 2)\ K \\
&= 15.4(t_1 + 2) + 20.46(t_1 + 2) + 58.8(t_1 + 2)\ W \\
&= 94.66(t_1 + 2)\ W
\end{aligned}$$

Therefore:

$$\begin{aligned}
504(19 - t_1) &= 94.66(t_1 + 2) \\
5.32(19 - t_1) &= t_1 + 2 \\
101 - 5.3t_1 &= t_1 + 2 \\
99 &= 6.3t_1
\end{aligned}$$

Hence:

$$t_1 = 15.7°C$$

Therefore condensation is unlikely.

Where a building is occupied only occasionally, for example, a traditional heavyweight stone church or a brick-built assembly hall, the heating system is used intermittently and steady-state heat loss calculations are inappropriate. Admittance factors are used to evaluate the heat flow into the thermal storage of the structure, rather than through it. The heat output required for the heating system is

$$Q_p = \left[F_1 \sum (AY) + 0.33F_2NV\right](t_c - t_{ao})\ W$$

The Y values given in Table 3.12 are for a 12 h on, 12 h off heating cycle. To obtain other cycle times, multiply the Y values by (12/cycle hours)$^{0.5}$. This gives higher heat input rates for shorter periods.

Table 3.12 Thermal transmittance and admittance factors for complete structural components with normal exposure.

Construction	*U* (W/m^{2}K)	*Y* (W/m^{2}K)
Walls		
220 mm brick, 13 mm light plaster	1.90	3.6
220 mm brick, 25 mm cavity, 10 mm plasterboard on dabs	1.50	2.5
220 mm brick, 25 mm cavity, 10 mm foil-backed plasterboard on dabs	1.20	1.8
220 mm brick, 20 mm glass fibre quilt, 10 mm plasterboard	1.00	1.4
220 mm brick, 25 mm polyurethane slab, 10 mm plasterboard	0.66	1.0
19 mm render, 40 mm expanded polystyrene slab, 200 mm lightweight concrete block, 13 mm light plaster	0.40	2.2
10 mm tile hanging, 25 mm air gap, 100 mm glass fibre quilt, 10 mm plasterboard	0.36	0.67
105 mm brick, 25 mm cavity, 105 mm brick, 13 mm dense plaster	1.50	4.4
105 mm brick, 50 mm UF foam, 105 mm brick, 13 mm light plaster	0.55	3.6
105 mm brick, 25 mm cavity, 100 mm lightweight concrete block, 13 mm light plaster	0.92	2.2
100 mm lightweight concrete block, 75 mm glass fibre, 100 mm lightweight concrete block, 13 mm lightweight plaster	0.29	2.4
Roof		
5 mm asbestos cement sheet	6.5	6.5
10 mm tile, loft space, 10 mm plasterboard	2.6	2.6
10 mm tile, loft space, 100 mm glass fibre quilt, 10 mm plasterboard	0.34	0.66
19 mm asphalt, 25 mm stone chippings, 150 mm heavyweight concrete block	2.3	5.2
19 mm asphalt, 13 mm fibreboard, 25 mm air gap, 75 mm glass fibre quilt, 10 mm plasterboard	0.40	0.69
Floor		
Concrete	—	6.0
Concrete, carpet or woodblock	—	3.0
Suspended timber and carpet	—	1.5
Partitions		
Heavyweight partition walls	—	3.0
Windows		
Single-glazed	—	5.6
Double-glazed	—	3.2

Boiler power

The boiler power required for a building is found from the sum of the following:

1. peak heat input rate $(Q_f + Q_v)$ W to the heating system;
2. heat loss from the distribution pipe or duct system, which can initially be taken as 10% of $(Q_f + Q_v)$ W and refined later when pipe sizes and lengths are known;
3. rate of energy supply Q_{HWS} W to the hot-water services system where this is supplied from the same boiler plant.

Then:

$$Q_{HWS} = \frac{\text{mass of stored water kg}}{\text{heating period}} \times 4.186\ \frac{\text{kJ}}{\text{kg K}} \times (t_{HWS} - 10)\ \text{K}$$

The specific heat capacity of water is 4.186 kJ/kg K and the temperature of mains cold water is normally about 10°C. The mass of stored hot water at 65°C either will be 135 l for a small domestic residence or can be found from the number of occupants *N* and the expected daily hot-water usage per person, which will vary from 4 l/person for an office or shop to 70 l/person for a hotel. The time period to raise the storage cylinder contents to the desired temperature can be varied to suit the site conditions; 3 h is acceptable for housing.

EXAMPLE 3.8

Calculate the boiler power required for a commercial building having a peak heat loss of 900 kW, a low-pressure hot-water radiator heating system, 450 occupants and a 3 h heating period for the hot-water storage cylinder. Water is to be stored at 65°C and daily consumption is expected to be 65 l/person. One litre of water weighs 1 kg.

$$
\begin{aligned}
Q_{\mathrm{HWS}} &= \frac{450\ \text{people}}{3\ \mathrm{h}} \times 65\ \frac{\mathrm{l}}{\text{person}} \times \frac{1\ \mathrm{kg}}{1\ \mathrm{l}} \times 4.186\ \frac{\mathrm{kJ}}{\mathrm{kgK}} \times (65 - 10\ \mathrm{K}) \\
&\quad \times \frac{1\ \mathrm{h}}{3600\ \mathrm{s}} \times \frac{1\ \mathrm{kWs}}{1\ \mathrm{kJ}} \\
&= 624\ \mathrm{kW}
\end{aligned}
$$

The boiler power is obtained as follows:

$$
\begin{aligned}
\text{building heat loss } Q_f + Q_v &= 900\ \mathrm{kW} \\
10\%\ \text{distribution losses} &= 90\ \mathrm{kW} \\
Q_{\mathrm{HWS}} &= 624\ \mathrm{kW} \\
\text{boiler power} &= 1614\ \mathrm{kW}
\end{aligned}
$$

Thermal transmittance measurement

The current stock of buildings creates the need for the energy engineer to be able to discover the value of the thermal transmittance of existing structures. The building has design *U* values that were calculated in accordance with standard practice and regulations, but what is the reality of the designer's intentions? Does the design *U* value exist in the components that have been constructed? When the components of the building, such as walls, windows, corners of walls, and interfaces between walls and floors, are taken together as an integrated package, are the *U* values achieved? Has the process of construction destroyed the designer's work? Such possibilities have a lasting influence upon the energy consumption of the building.

A large proportion of the energy consumed in the UK is used to keep the inside of buildings warm. Monitoring the quality of in situ thermal insulation and for the retrofitting of additional insulation to existing structures is an important part of energy management. The built thermal transmittance (*U* value) of a structure can be calculated from measurements of air and surface temperatures from a thermocouple temperature instrument or multi-channel data logger (Figs 1.3, 1.11 and 1.12). It is not necessary to know the constructional details of the wall, roof, floor, door or window in order to discover its *U* value. The visiting surveyor will not wish to drill holes through brick, concrete and timber to measure the thickness of each material. Even if this is done, the quality of the materials remains largely unknown and assumptions about the water content and the integrity of each layer would have to be made. The constructional detail is unknown. There may be air spaces, vapour barriers and layers of thermal insulation in place, but these are hidden from view.

Figure 3.1 represents a cross-section through the unknown structure. It could be an external wall, internal wall, roof, floor, glazing or door. All that can be realistically assessed are the temperatures on either side, at nodes 1 and 4, and on the surfaces at nodes 2 and 3. A shielded surface-contact thermocouple probe can be used to measure each surface temperature. An exposed thermocouple junction or a sling psychrometer can be used to find the air temperatures. The values for the inside and outside surface film resistances, R_{si} and R_{so} m^2K/W, are assumed to be their normal, tabulated values for the appropriate applications. The heat transfer equations (Chapter 10) that describe the heat flow through the structure, Q W, are as follows.

For the whole structure:

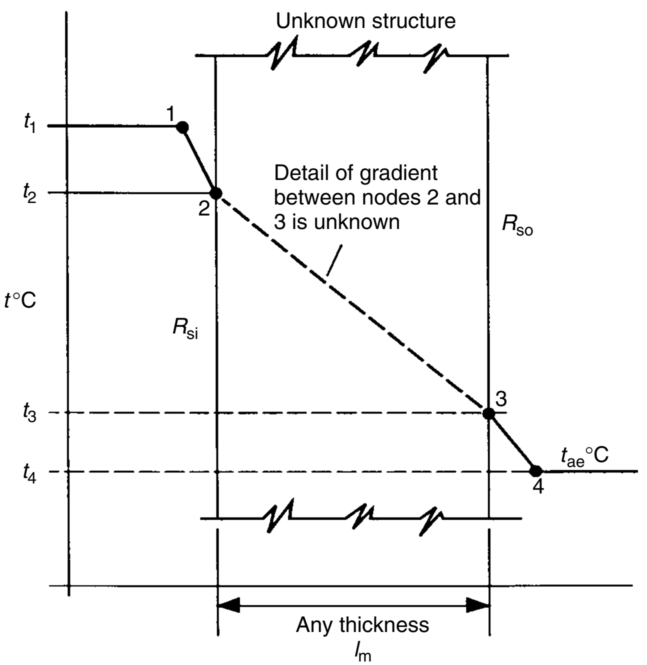
$$Q = U \frac{\text{W}}{\text{m}^2\text{K}} \times A\ \text{m}^2 (t_1 - t_4)\ \text{K}$$

For the interior film:

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

For the unknown structure:

$$Q = \frac{1}{R} \frac{\text{W}}{\text{m}^2\text{K}} \times A\ \text{m}^2 (t_2 - t_3)\ \text{K}$$



3.1 Temperature gradient through a structure.

where R m^{2}K/W is the resistance of the unknown parts of the construction. For the exterior film:

$$Q = \frac{1}{R_{so}} \frac{\text{W}}{\text{m}^2\text{K}} \times A \text{ m}^2 (t_3 - t_4) \text{ K}$$

The heat flow is considered to be under steady-state conditions: that is, it remains at a stable rate over several hours and certainly while the measurements are taken. This is the same assumption that is made for calculating thermal transmittances. It is also true that the daily cyclic variation in outdoor air temperature and solar heat gains, plus the intermittent cooling effects of wind and rain, cause unsteadiness in the flow of heat from the building. The analysis of such heat transfers requires dedicated software, weather data and a computer model of the whole building. An awareness of the overall problem is helpful, however.

There needs to be as large a temperature difference between indoors and outdoors as reasonably practical on the day of test. This is to minimize the effect of any errors in the measurement of the temperatures. When the indoor and external air temperatures are 20°C and 10°C, an error of 0.5°C in one of the temperatures will be $100 \times 0.5/(20 - 10)\%$, 5% of the difference. If overall inaccuracies can be kept within 5%, a reasonably reliable outcome can be obtained. The heating system and weather should also be functioning under steady conditions during the test period. Take the values of R_{si} and R_{so} to be 0.12 and 0.06 m^{2}K/W, as they would be for walls with normal exposure. Use other values if necessary. If, on a test, the temperatures t_1, t_2, t_3 and t_4 are 21°C, 17°C, 0°C and −2°C the rate of heat flow Q, thermal transmittance U and resistance R of the structure can be calculated by using the R_{si} or R_{so} equations:

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

The surface area A m^2 is taken as 1 m^2:

$$Q = \frac{1}{0.12} \times (21 - 17) \text{ W}$$
$$= 33.33 \text{ W}$$

The same answer results from the use of R_{so}:

$$Q = \frac{1}{R_{so}} \frac{\text{W}}{\text{m}^2\text{K}} \times A \text{ m}^2 (t_3 - t_4) \text{ K}$$
$$Q = \frac{1}{0.06} \times [0 - (-2)] \text{ W}$$
$$= 33.33 \text{ W}$$

Find the U value from:

$$Q = U \frac{\text{W}}{\text{m}^2\text{K}} \times A \text{ m}^2 (t_1 - t_4) \text{ K}$$
$$33.33 = U \frac{\text{W}}{\text{m}^2\text{K}} \times 1 \text{ m}^2 \times [21 - (-2)] \text{ K}$$

$$U = \frac{33.33}{[21-(-2)]}\ \text{W/m}^2\text{K}$$
$$= 1.45\ \text{W/m}^2\text{K}$$

This is an elderly wall, which has a higher thermal transmittance than for modern standards. Consideration can be given as to how much additional thermal insulation is possible. The thermal resistance of the existing structure, without the surface film resistances, can be found from:

$$Q = \frac{1}{R}\ \frac{\text{W}}{\text{m}^2\text{K}} \times A\ \text{m}^2 (t_2 - t_3)\ \text{K}$$
$$33.33 = \frac{1}{R}\ \frac{\text{W}}{\text{m}^2\text{K}} \times 1\ \text{m}^2 \times (17-0)\ \text{K}$$
$$R = \frac{(17-0)}{33.33}\ \text{m}^2\text{K/W}$$
$$= 0.51\ \text{m}^2\text{K/W}$$

When the thermal transmittance is known from design calculations or in situ measurements, the thickness of additional thermal insulation that is needed to reduce heat loss can be calculated. This may be desirable in order to align the building with current regulations and improve its energy-using efficiency. Outdated building designs will be less attractive to potential users than new or recently refurbished, low-energy consumption residential, commercial and industrial alternative sites.

The wall U value that was considered here could be lowered from 1.45 to, say, 0.4 W/m^{2}K by the addition of thermal insulation. If the insulation can be injected into the wall cavity no further constructional measures are needed. Where there is no cavity, or if rainwater penetration could result, then an additional internal or exterior layer of material is required. Thermal insulation may not be structurally rigid and it often does not provide a hard-wearing or weatherproof surface. Adding layers to either side of a wall necessitates architectural changes, particularly to fenestration and doorways. If polyurethane board and an internal surface finish of 10 mm plasterboard can be fitted to the interior surfaces, the necessary thickness of insulation can be calculated as follows.

From Table 3.1, the thermal conductivities are:

plasterboard: $\lambda = 0.16$ W/mK

polyurethane board: $\lambda = 0.025$ W/mK

$$\text{new thermal resistance of whole structure } R_n = \frac{1}{U_n}\ \frac{\text{m}^2\text{K}}{\text{W}}$$
$$= \frac{1}{0.4}\ \frac{\text{m}^2\text{K}}{\text{W}}$$
$$= 2.5\ \text{m}^2\text{K/W}$$
$$\text{resistance of plasterboard} = \frac{0.01}{0.16}\ \frac{\text{mK}}{\text{W}}$$
$$= 0.0625\ \text{m}^2\text{K/W}$$
$$\text{resistance of existing wall} = \frac{1}{1.45}\ \frac{\text{m}^2\text{K}}{\text{W}}$$
$$= 0.69\ \text{m}^2\text{K/W}$$

The additional thermal insulation that is needed is found by subtracting the existing thermal resistance, and that for the new surface finish, from the target thermal resistance:

$$\text{additional resistance needed} = (2.5 - 0.69 - 0.0625)\ \text{m}^2\text{K/W}$$
$$= 1.748\ \text{m}^2\text{K/W}$$
$$\text{insulation resistance} = \frac{l\ \text{mm}}{\lambda}\frac{\text{mK}}{\text{W}} \times \frac{1\ \text{m}}{10^3\ \text{mm}}$$
$$1.748 = \frac{l\ \text{mm}}{0.025}\frac{\text{mK}}{\text{W}} \times \frac{1\ \text{m}}{10^3\ \text{mm}}$$
$$\text{insulation thickness } l\ \text{mm} = 1.748\ \frac{\text{m}^2\text{K}}{\text{W}} \times 0.025\frac{\text{W}}{\text{mK}} \times \frac{10^3\ \text{mm}}{1\ \text{m}}$$
$$= 43.7\ \text{mm}$$

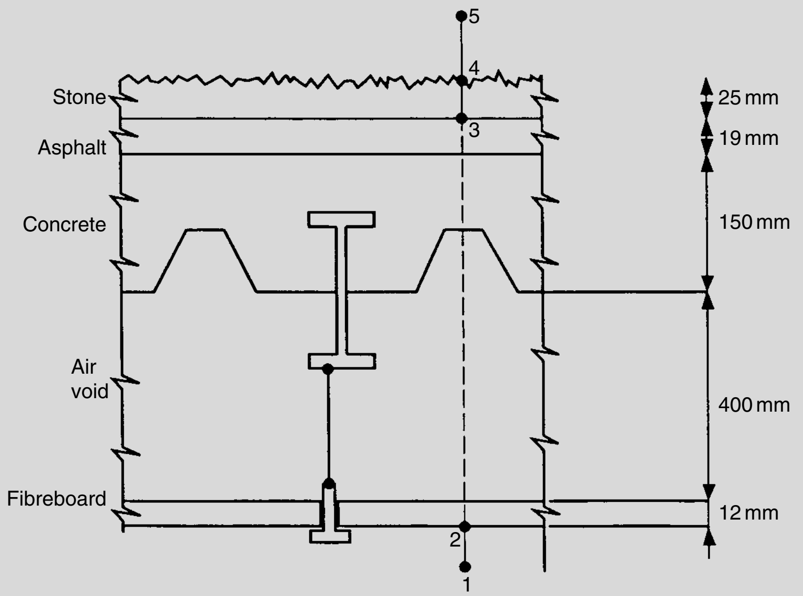
Materials are available in standard dimensions. The thickness to be used will be the next larger size, 50 mm. Check that the additional insulation calculations have been correctly made and find the real new U value:

$$R_\text{n} = \frac{1}{1.45} + \frac{0.01}{0.16} + \frac{0.05}{0.025}\ \frac{\text{m}^2\text{K}}{\text{W}}$$
$$= 0.69 + 0.0625 + 2.0\ \text{m}^2\text{K/W}$$
$$= 2.752\ \text{m}^2\text{K/W}$$
$$U_\text{n} = \frac{1}{R_\text{n}}\ \frac{\text{W}}{\text{m}^2\text{K}}$$
$$= \frac{1}{2.752}\ \frac{\text{W}}{\text{m}^2\text{K}}$$
$$= 0.36\ \text{W/m}^2\text{K}$$

The new thermal transmittance does not exceed the desired value of 0.4 W/m^2K and is suitable. If the wall has an air cavity between the inner and outer surfaces, it may be possible to inject urea formaldehyde or phenolic foam, or blown rock wool, and achieve the desired result without architectural effects. Another possibility is the addition of insulation and a protective layer to the exterior surface.

EXAMPLE 3.9

A 20-year-old 150 mm thick ribbed concrete flat roof over an office is supported on a structural steel frame. A typical cross-section through the roof is shown in Fig. 3.2. The concrete is waterproofed with 19 mm asphalt that is topped with 25 mm of white stone chippings. Beneath the concrete, there is a 400 mm deep unventilated air space for service cables and pipes. The ceiling riles are 12 mm thick fibreboard supported on a lightweight galvanized steel frame. The ceiling tile frame is suspended from the structural steel by galvanized wires and self-tapping screws. All the lighting, electrical and other services that are within the ceiling space are supported by hangers from the roof structural steel frame. The roof has normal exposure and its thermal transmittance is to be reduced to 0.25 W/m^2K. Thermocouple temperature sensors were used to assess the average thermal



3.2 Roof construction for Example 3.9.

transmittance of the roof structure. On the day of test, the temperatures t_1, t_2 and t_5 were 19°C, 17.6°C and 5°C. The temperature at node 4 could not be measured owing to the roughness of the surface. The temperature at node 3 could be measured but it is not needed. Describe the features of two methods that could be used to insulate the roof. Decide which materials would be suitable and find the correct thickness for the insulation.

From Tables 3.2, 3.3 and 3.5, $R_{si} = 0.1$ m^{2}K/W, $R_{so} = 0.05$ m^{2}K/W (low emissivity), $R_a = 0.17$ m^{2}K/W (high emissivity).

From Table 3.1, the thermal conductivities of the materials are:

cast concrete, lightweight	$\lambda = 0.38$ W/mK
asphalt	$\lambda = 0.5$ W/mK
stone chippings	$\lambda = 0.96$ W/mK
glass fibre quilt	$\lambda = 0.06$ W/mK
polyurethane board	$\lambda = 0.025$ W/mK

The options to be tried are as follows:

(a) Remove some ceiling tiles and lay a lightweight blanket, such as glass fibre, on top of the tiles. This depends on whether the fibreboard tiles, support wires and screws are able to hold the additional weight. Extra support rods may be needed. There will be considerable disturbance to the room usage. This may preclude installation work during normal working hours. Removing the tiles will disturb dust and debris from the void and necessitate a cleaning operation in the room. Indoor scaffolding will be needed. Care must be taken not to lay the insulation on top of luminaires and electrical cables, to avoid the overheating of lamps and wiring.

$$Q = \frac{1}{R_{si}} \frac{\text{W}}{\text{m}^2\text{K}} \times A \text{ m}^2 \times (t_1 - t_2) \text{ K}$$
$$= \frac{1}{0.1} \times (19 - 17.6) \text{ W}$$
$$= 14 \text{ W}$$
$$14 \text{ W} = U \frac{\text{W}}{\text{m}^2\text{K}} \times 1 \text{ m}^2 \times (19 - 5) \text{ K}$$
$$U = \frac{14}{19 - 5} \text{ W/m}^2\text{K}$$
$$= 1 \text{ W/m}^2\text{K}$$
$$R_n = \frac{1}{0.25} \frac{\text{m}^2\text{K}}{\text{W}}$$
$$= 4 \text{ m}^2\text{W/K}$$
$$\text{resistance of the existing roof} = \frac{1}{1} \frac{\text{m}^2\text{K}}{\text{W}}$$
$$= 1 \text{ m}^2\text{K/W}$$
$$\text{insulation resistance} = (4 - 1) \text{ m}^2\text{K/W}$$
$$= 3 \text{ m}^2\text{K/W}$$
$$\text{glass fibre thickness } l \text{ mm} = 3 \frac{\text{m}^2\text{K}}{\text{W}} \times 0.04 \frac{\text{W}}{\text{mK}} \times \frac{10^3 \text{ mm}}{1 \text{ mm}}$$
$$= 120 \text{ mm}$$

Glass fibre thickness to be used will be 150 mm.

$$R_n = \frac{1}{1} + \frac{0.15}{0.04} \frac{\text{m}^2\text{K}}{\text{W}}$$
$$= 4.75 \text{ m}^2\text{K/W}$$
$$U_n = \frac{1}{4.75} \frac{\text{W}}{\text{m}^2\text{K}}$$
$$= 0.21 \text{ W/m}^2\text{K}$$

The new thermal transmittance is below the desired value of 0.25 W/m^{2}K and is suitable. Check that the new U value is correct:

$$R_n = 0.1 + \frac{0.012}{0.06} + \frac{0.15}{0.04} + 0.17 + \frac{0.015}{0.38} + \frac{0.019}{0.5} + \frac{0.025}{0.96} + 0.05 \frac{\text{m}^2\text{K}}{\text{W}}$$
$$= 4.73 \text{ m}^2\text{K/W}$$

$$U_n = \frac{1}{4.73}\ \frac{W}{m^2K}$$
$$= 0.21\ W/m^2K$$

(b) Remove the stone chippings from the roof and lay sheets of rigid polyurethane or phenolic foam. An adhesive can be used to hold the sheets in place. The stone chippings are then placed on top of the foam. The foam is water-repellent and rot-resistant. Installation on the outer surface of the roof will not cause disturbance indoors. The roof will become a warm-deck type (Chapter 10) and will gain the benefit of improved thermal storage capacity: that is, the building will remain warmed for longer periods. In summer, the concrete will be insulated from the solar heat gains and hot outdoor air, and will remain relatively cool:

$$\text{polyurethane thickness } l \text{ mm} = 3\ \frac{m^2K}{W} \times 0.025\ \frac{W}{mK} \times \frac{10^3\ mm}{1\ mm}$$
$$= 75\ mm$$

Polyurethane thickness to be used will be 100 mm and the new U value will be 0.2 W/m^{2}K.

The installation can be validated by measuring the three temperatures when steady-state conditions have been re-established. Calculate the ceiling surface temperature with the glass fibre insulation in place on a day when the indoor and outdoor air temperatures are 21°C and 3°C:

$$Q = 0.21\ \frac{W}{m^2K} \times 1\ m^2 \times (21 - 3)\ K$$
$$= 3.78\ W$$
$$Q = \frac{1}{R_{si}}\ \frac{W}{m^2K} \times A\ m^2 \times (t_1 - t_2)\ K$$
$$3.78 = \frac{1}{0.1} \times (21 - t_2)\ K$$
$$t_2 = 21 - 3.78 \times 0.1°C$$
$$= 20.6°C$$

Questions

1. State what is meant by the following terms:

   (a) thermal resistance;
   (b) thermal conductivity;
   (c) thermal resistivity;
   (d) specific heat capacity;
   (e) thermal transmittance;
   (f) orientation and exposure;
   (g) surface resistance;
   (h) cavity resistance;
   (i) emissivity;
   (j) admittance factor;
   (k) heavyweight and lightweight structures.

2. The following materials are being considered for the internal skin of a cavity wall:

    (a) 105 mm brickwork;
    (b) 200 mm heavyweight concrete block;
    (c) 150 mm lightweight concrete block;
    (d) 75 mm expanded polystyrene slab;
    (e) 100 mm mineral fibre slab and 15 mm plasterboard;
    (f) 40 mm glass fibre slab, 150 mm lightweight concrete block and 15 mm lightweight plaster.

    Compare their thermal resistances and comment upon their suitability for a residence.
3. Calculate the thermal transmittances of the following:

    (a) single-glazed window, severe exposure;
    (b) double-glazed window, sheltered exposure;
    (c) 220 mm brick wall and 13 mm lightweight plaster;
    (d) 220 mm brick wall, 50 mm glass fibre quilt and 10 mm plasterboard;
    (e) 105 mm brick wall, 10 mm air space, 40 mm glass fibre slab and 100 mm lightweight concrete block;
    (f) 40° pitched roof, 10 mm tile, roofing felt and 10 mm flat plaster ceiling with 100 mm glass fibre quilt laid between the joists;
    (g) 19 mm asphalt flat roof, 13 mm fibreboard, 25 mm air space, 100 mm mineral wool quilt and 10 mm plasterboard.

    All exposures are normal unless otherwise specified.
4. A lounge 7 m long × 4 m wide × 2.8 m high is maintained at a resultant temperature of 21°C and has 1.5 air changes/h of outside air at −2°C. There are two double-glazed wood-framed windows of dimensions 2 m × 1.5 m and an aluminium framed double-glazed door of dimensions 1 m × 2 m. Exposure is normal. One long and one short wall are external and constructed of 105 mm brick, 10 mm air space, 40 mm polyurethane board, 150 mm lightweight concrete block and 13 mm lightweight plaster. The internal walls are of 100 mm lightweight concrete block and are plastered. There is a solid ground floor with edge insulation. The roof has a thermal transmittance of 0.34 W/m^{2}K. Adjacent rooms are at a resultant temperature of 18°C. Calculate the steady-state heat loss from the room for a convective heating system.
5. A single-storey community building of dimensions 20 m × 15 m × 3 m high has low-temperature hot-water radiant panel heaters. There are 10 windows of dimensions 2.5 m × 2 m. Natural infiltration amounts to 1 air change/h. Internal and external design temperatures are 20°C and −1°C. Thermal transmittances are as follows: walls, 0.6 W/m^{2}K; windows, 5.3 W/m^{2}K; floor, 0.5 W/m^{2}K; roof, 0.4 W/m^{2}K. Calculate the steady-state heat loss.
6. Calculate the environmental temperature produced in an unheated room within an occupied building, using the following information: room dimensions, 5 m × 4 m × 2.6 m high; a window of dimensions 2.5 m × 1.25 m in one long external wall; 0.5 air changes/h; external air temperature, 3°C; solid ground floor; surrounding rooms are all at an environmental temperature of 20°C. The thermal transmittances are as follows: external wall, 1 W/m^{2}K; window, 5.3 W/m^{2}K; floor, 0.7 W/m^{2}K; internal walls, 1.2 W/m^{2}K; ceiling, 1 W/m^{2}K. Assume that the room environmental temperature is equal to the air temperature.
7. A single-storey factory is allowed to have 35% of its wall area as single glazing and 20% of its roof area as single-glazed roof-lights. Wall and roof U values are not to exceed 0.6 W/m^{2}K. An architect proposes a building of dimensions 50 m × 30 m × 4 m high with a wall U value

of 0.4 W/m^{2}K, a roof *U* value of 0.32 W/m^{2}K, 20 double-glazed windows each of area 16 m^2 having a *U* value of 3.3 W/m^{2}K and 35 roof-lights each of area 10 m^2 having a *U* value of 5.3 W/m^{2}K. Does the proposal meet the allowed heat loss limit?

8. Calculate the boiler power required for a building with a heat loss of 50 kW and an indirect hot-water storage system for 20 people, each using 50 l of hot-water at 65°C per day. The cylinder is to be heated from 10°C in 2.5 h. Add 10% for pipe and cylinder heat losses.
9. A single-storey building has dimensions 40 m × 20 m × 4 m high with windows of area 80 m^{2}and a door of area 9 m^2. It is to be maintained at a resultant temperature of 20°C when the outside is at −1°C and natural ventilation amounts to 1 air change/h. Thermal transmittances are as follows: walls, 1.8 W/m^{2}K; windows, 5.3 W/m^{2}K; door, 5 W/m^{2}K; floor, 0.6 W/m^{2}K; roof, 1.8 W/m^{2}K. A convective heating system is used. It is proposed to reduce the *U* values of the walls and roof to 0.4 and 0.3 W/m^{2}K respectively. Calculate the percentage reduction in heater power that would be produced.
10. List the ways in which existing residential, commercial and industrial buildings can have their thermal insulation improved. Discuss the practical measures that are needed to protect the insulation from deterioration.
11. Review the published journals and find examples of buildings where the existing thermal insulation has been upgraded. Prepare an illustrated presentation or article on a comparison of the outcomes from the cases found.
12. Write a technical report on the argument in favour of adding thermal insulation to existing buildings. Support your case by referring to government encouragement, global energy resources, atmospheric pollution, legislation, cost to the building user and the profitability of the user's company.
13. A flat roof over a bedroom causes intermittent condensation during sub-zero outdoor air temperatures. The roof has normal exposure. The owners want to eliminate the condensation and reduce the thermal transmittance to 0.15 W/m^{2}K. Thermocouple temperature sensors were used to assess the average thermal transmittance of the roof structure. On the day of test, the indoor air, ceiling surface and outdoor air temperatures were 16°C, 11°C and −2°C. Calculate the existing thermal transmittance of the roof and the thickness of expanded polystyrene slab that would be needed.
14. An external solid brick wall is to be insulated with phenolic foam slabs held on to the exterior brickwork with UPVC hangers. Expanded metal is to be fixed onto the outside of the foam and then cement rendered to a thickness of 12 mm. The wall has a sheltered exposure. The intention is to reduce the thermal transmittance to 0.3 W/m^{2}K. Thermocouple temperature sensors were used to assess the average thermal transmittance of the wall prior to the design work. On the day of test, the indoor air, interior wall surface and outdoor air temperatures were 15°C, 12.7°C and 6°C. Calculate the existing thermal transmittance of the wall and the thickness of phenolic foam that would be needed. If the foam is only available in multiple thicknesses of 10 mm, state the thermal transmittance that will be achieved for the wall. Calculate the internal surface temperature that should be found on the wall for a day when the indoor and outdoor air temperatures are 18°C and 0°C.
15. The roof over a car-manufacturing area consists of 4 mm profiled aluminium sheets on steel trusses. Wood wool slabs, 25 mm, are fitted below the roof sheets. The roof trusses remain uninsulated as they protrude through the wood wool. The trusses cause condensation to precipitate onto the vehicle bodies during cold weather. The roof is to be insulated with polyurethane board, which will be secured to the underside of the roof trusses. The roof has a normal exposure. The intention is to reduce the thermal transmittance to 0.25 W/m^{2}K. Thermocouple temperature sensors were used to assess the average thermal transmittance of the roof prior to the insulation. On the day of test, the indoor air under the roof was 13°C,

internal roof surface temperature was 11°C and the outdoor air temperature was 2°C. Calculate the existing thermal transmittance of the roof and the thickness of polyurethane that would be needed. The insulation is only available in multiple thicknesses of 10 mm. State the thermal transmittance that will be achieved for the roof. Calculate the internal surface temperature that should be found on the newly insulated roof for a day when the indoor and outdoor air temperatures are 16°C and −5°C.

16. Which of these buildings have a slow response, several hours, to variations in weather? More than one correct answer.
    1. Concrete- and steel-framed 20-storey offices.
    2. Traditional stone churches.
    3. London underground railway stations.
    4. Large volume single-storey industrial buildings having lightweight thermal insulation to corrugated sheet steel wall and roof cladding, for example, aircraft hanger, car factory.
    5. Small prefabricated building, transportable, temporary site accommodation, caravan, tent and marquee.
17. Which of these is correct?
    1. Thermal resistivity is the fire resistance property of a material.
    2. Thermal resistance is the total resistance to flow of water through a heating system circulation.
    3. Thermal conductivity is used in calculating the resistance of an electrical heating wiring system.
    4. Thermal resistance is a material component property and is measured in m^2K/W.
    5. Thermal resistance is how many hours electrical cable insulation resists fire in the building.
18. Which of these is correct?
    1. The sheet of glass in a window provides a significant thermal resistance.
    2. Thermal conductivity of window glass is around 1 W/mK.
    3. Thermal conductivity of window glass is around 1 mK/W.
    4. Window glass is only used to keep wind out of the building.
    5. Windows create no thermal resistance to heat flow.
19. Which is the correct unit?
    1. Thermal conductivity m^2K/W.
    2. Thermal transmittance W/m^3K.
    3. Thermal conductivity mK/kJ.
    4. Thermal resistivity W/mK.
    5. Thermal resistivity mK/W.
20. What does $\sum (UA\ \Delta t)$ mean?
    1. Something in Greek language.
    2. Universal ASHRAE temperature difference used for building heat gain calculation.
    3. Integration of *U* values and areas during a time interval.
    4. Summation of thermal transmittance, surface area and indoor–outdoor air temperature difference of each external element of the building.
    5. All the *U* values, surface area and temperature differences added together for the whole building.

21. What does $0.33NV\Delta t$ mean?
    1. One-third of the volumetric air change rate multiplied by daily degree days above base temperature.
    2. 33% of normal building volume per degree temperature difference to calculate energy usage cost.
    3. A design guide to the plant room floor area likely to be required for air-handling units.
    4. A fraction of the nominal building volume multiplied by air temperature difference.
    5. Volumetric specific heat capacity of air, times number of air changes per hour, times room volume, times indoor–outdoor air temperature difference, calculates natural ventilation rate of heat loss for a heating system.
22. What are admittance values?
    1. Solar heat gain factors for windows and opaque structures.
    2. The opposite if resistance values.
    3. Number of people who can pass through the buildings' entry and transportation systems at peak flow periods.
    4. Always twice the thermal transmittance value.
    5. Thermal factors evaluating heat flows into thermal storage of the structure.
23. Which does not apply to admittance values?
    1. Y W/m^{2}K.
    2. Reciprocal of U value.
    3. Used instead of thermal transmittance in certain circumstances.
    4. Expresses heat flow inwards to a heavy mass structural component.
    5. Used for highly intermittently heated buildings.
24. Which explanation of thermal conductivity is correct?
    1. Ability of a material to conduct electricity.
    2. Property evaluating materials' ability to pass heat.
    3. Equal to resistivity multiplied by thickness.
    4. Units are W/m^{3}K.
    5. Units are W/m^{2}K.
25. Which is correct about thermal resistance?
    1. Calculated from data tables and computer programs.
    2. Calculated from material thickness divided by thermal conductivity.
    3. Calculated by dividing material thickness in metres by thermal resistivity in mK/W.
    4. Units are kJ/m^{2}K.
    5. Units are W/mK.
26. Which of these calculated values of thermal resistance is not correct?
    1. 110 mm of brickwork is 0.13.
    2. 150 mm of fibreglass roof insulation is 3.75.
    3. 100 mm concrete having a thermal conductivity of 2.0 W/mK is 0.05.
    4. A metal window frame 20 mm thickness has a thermal conductivity of 50.0 W/mK and has a thermal resistance of virtually zero.
    5. A low-energy building wall has 1.0 m thickness of phenolic foam having a thermal conductivity of 0.04 W/mK making a thermal resistance of 25.0 m^{2}K/W.

27. Which of these calculated values of thermal resistance is not correct?

    1. 110 mm of brickwork is 0.13.
    2. 150 mm of fibreglass roof insulation is 3.75.
    3. 100 mm concrete having a thermal conductivity of 2.0 W/mK is 0.05.
    4. A metal window frame 20 mm thickness has a thermal conductivity of 50.0 W/mK and has a thermal resistance of virtually zero.
    5. A low-energy building wall has 1.0 m thickness of phenolic foam having a thermal conductivity of 0.04 W/mK making a thermal resistance of 25.0 m^2K/W.

28. Which of these is correct?

    1. *U* value is the sum of all thermal resistivities in a structure.
    2. *R* value is the sum of all thermal resistivities in a structure.
    3. *Y* value is the sum of all thermal resistivities in a structure.
    4. *U* value is the sum of all thermal resistances in a structure.
    5. *R* value is the sum of all thermal resistances in a structure.

29. Which is the correct description of a thermal transmittance exposure location?

    1. Sheltered is only for below-ground structures.
    2. Normal exposure means the surface faces the prevailing wind direction.
    3. Severe exposure applies to fifth floors anywhere.
    4. Severe exposure applies to floors above fifth floor in suburban districts.
    5. Sheltered exposure means the building is surrounded by trees.

30. Which is correct about an existing structure's thermal transmittance?

    1. Can only be calculated from design information.
    2. Cannot be measured in situ.
    3. Measurement requires a thermal imaging camera.
    4. Measure structural temperatures to calculate *U* value.
    5. Thermocouple temperature sensors have to be buried into drilled holes through the structure.