5 THERMAL ENVIRONMENT

5.1 Introduction

Buildings need to be healthy and comfortable. If we are to build a sustainable future then new buildings must also use much less energy than they have done in the past. To achieve one objective without the other is a failure on the part of the designer. Both objectives are achievable, but the designer needs to appreciate the factors that affect comfort and be able to determine the energy needed to keep people comfortable in buildings.

5.2 Thermal comfort

We are all aware of some of our responses to the thermal environment. If we are hot we tend to feel somewhat lethargic and unenthusiastic about performing arduous tasks. If we are cool we tend to want to be active and moving around; if forced to stand still we might even find ourselves shivering.

We have probably also noticed that we can go outside in Winter and be comfortable so long as the sun is shining, and that if it is a humid day we feel overpowered with heat and break into a sweat even when attempting quite small tasks.

These observations can all be explained quite easily once we are aware of the general biological mechanisms that determine thermal comfort. However, keep in mind the previous chapter and try to appreciate that the explanations are somewhat simplified. Even so, the framework presented here will allow you to understand the majority of circumstances that you will come across in your lifetime as a building designer.

5.2.1 The metabolic process

In Appendix A the metabolic process was described as:

“the process by which nourishment is extracted from food and then converted into various forms of work in the body.”

As you might expect, this process is not 100% efficient. In the example I gave of myself walking up Bathwick Hill, I suggested that only 15% of nutritional energy was converted into useful work. Much of the energy extracted from food is therefore not expended directly on useful work but is converted into heat. This heat must be dissipated if it is not to raise my core body temperature: essential for my continued health.

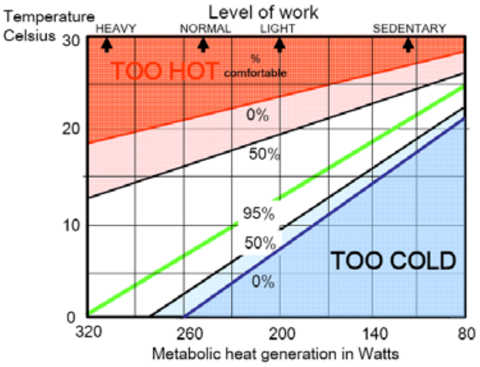


Figure 5.1 Metabolic Heat

Figure 5.1 gives a simplified chart that shows the metabolic heat generated by the body at different levels of work. From this chart it can be seen that the metabolic heat varies from a minimum of about 80 Watts to a maximum of about 300 watts. These are general figures and the actual amount will vary depending upon the gender, age, size and fitness of a person.

Also on Figure 5.1, there are indicated the percentage of people that would feel comfortable at a particular temperature whilst producing a given metabolic output. This is a very simplified chart, but it conveys the essential fact that as people perform more arduous tasks then they generate more metabolic heat. This heat needs to be dissipated from the body. In this chart it is assumed that all the increased heat is lost by lowering the temperature of the air.

Also, Figure 5.1 indicates that what is felt as a comfortable temperature will vary between people. Quite wide variations in temperature will still result in 50% of people feeling comfortable.

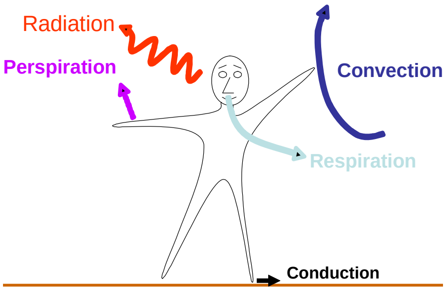


Figure 5.2 Ways of heat loss

5.2.2 Mechanisms of heat loss from body

There are five mechanisms that the body uses to lose heat:

i) Radiation,
ii) Conduction,
iii) Convection,
iv) Perspiration,
v) Respiration.

These are shown schematically in Figure 5.2. Each is briefly defined below, but more detailed information is given later in the notes.

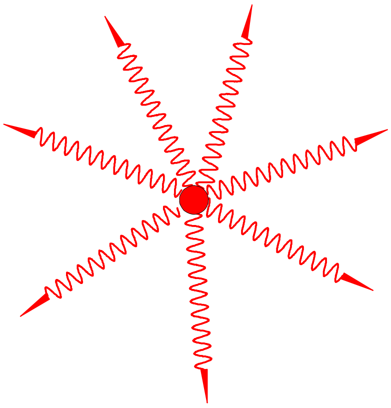


Figure 5.3 All objects radiate

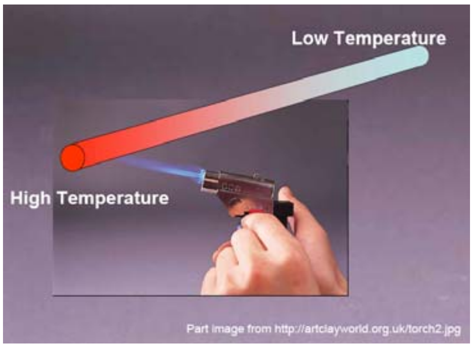
Radiation

As indicated in Figure 5.3, all objects emit energy or heat as radiation when they are above a temperature of -273°C i.e. absolute zero. The higher the temperature of an object the more heat or energy it radiates. We are able to feel the effects of radiation when there is a net difference between the radiation we emit and the radiation we receive from other surfaces.

If in Winter we sit next to a cold window then our skin temperature drops because we radiate more heat to the window than it emits to us. This drop in skin temperature will make us feel cold.

If we sit next to a hot radiator, then we will receive more heat from the radiator than we emit back to the radiator. There is therefore a net gain in heat and our skin increases in temperature and we feel the warmth from the radiator.

Conduction



Part image from http://artclayworld.org.uk/torch2.jpg

Figure 5.4 Conduction

If you take a bar as shown in Figure 5.4 and heat one end of it with a blow torch, then the temperature of the end of the bar will increase. Because one end of the bar is at a higher temperature than the other end of the bar, heat will flow from the hot end to the cold end. This process is known as conduction.

The rate at which heat flows from one end of the bar to the other depends upon the temperature gradient, the cross sectional area of the bar and the Thermal Conductivity of the material from which the bar is made:

$$\text{Heat Flow in Watts} = \frac{\text{temperature difference}}{\text{length of the bar}} \times \text{Area} \times \text{Thermal conductivity}$$

For there to be conduction between two separate objects, there must be direct contact between the two objects i.e. the objects must be touching one another.

Sensible Heat

If sufficiently high, the increased temperature of the bar will be seen because it will start radiating visible radiation. Heat from the blow torch is absorbed by the bar and this increases the temperature of the bar. The heat that is absorbed by the bar is called ‘sensible heat’, i.e. you can sense the increased temperature of the bar.

The actual rise in temperature will depend upon the material from which the bar is made. Different materials absorb different amounts of heat for a given rise in temperature and this property is called Specific Heat. The total sensible heat that is absorbed by the bar will be given by:

$$\text{Heat Absorbed in Watts} = \text{Rise in Temperature} \times \text{mass} \times \text{Specific heat}$$

It is also the case that the term Sensible Heat implies that there is no change to the molecular organisation of the material. Molecules will be excited by the heat and tend to vibrate more, but one molecule will keep its place in relation to other molecules.

Latent Heat

This is not the case with Latent Heat. Taking water from the tap you may put it in a kettle and heat it up to make a cup of tea. When the water in the kettle gets to 100°C it starts to boil i.e. it changes its physical state from being that of a liquid to that of a gaseous form or vapour. The vapour is still at 100°C, only now the water molecules have broken free of the attraction they have for each other. This attraction is only broken by the molecules absorbing energy or heat, and this heat is known as the ‘Latent heat of vaporisation’ .

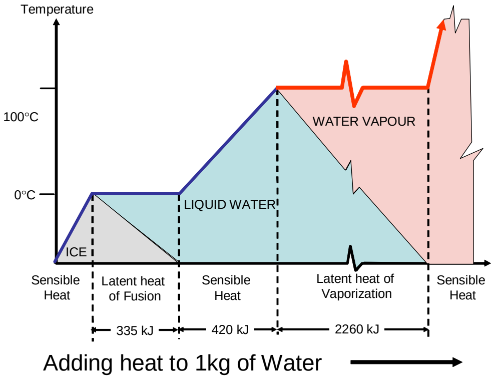


Figure 5.5 Sensible & latent heat

Similarly, if you put some water in the frost compartment of your refrigerator, then after a period of time the temperature of the water will drop to 0°C. As more heat is extracted the temperature will stay at 0°C but the water will change to ice. Energy or heat is extracted from the liquid and as the energy is lost the molecules fall into a rigid structure or solid. If the process is reversed then the same heat put into ice at 0°C will melt the ice into water at 0°C. The heat required to do this is known as the Latent Heat of Fusion.

Figure 5.5 shows the process of adding heat to 1kg of ice. The grey part under the curve represents the portion of solid ice, the blue represents the portion of liquid water and the pink represents the portion of water vapour. The break zigzag in the water vapour region is there to draw attention to the break in the horizontal axis of heat input. This is needed because of the very different energies associated with the different regions:

335 kJ Latent heat of fusion to melt 1 kg of ice,
420 kJ Sensible heat to raise the temperature of 1kg of water by 100°C,
2260 kJ Latent heat of vaporization to evaporate 1 kg of liquid water.

Convection

This is the process whereby heat is transported through the movement of a liquid or gas. When a liquid is heated it will usually expand and this results in it becoming less dense.

The density of a liquid or gas is its mass per unit volume. Therefore for water at 20°C, 1 kg of water occupies a volume of 1 litre or 1000cc. There are 1000 litres in 1 m^3 and therefore:

Density of water at 20°C = 1000 kg/m^3

And for comparison,

Density of water at 80°C = 974 kg/m^3 .

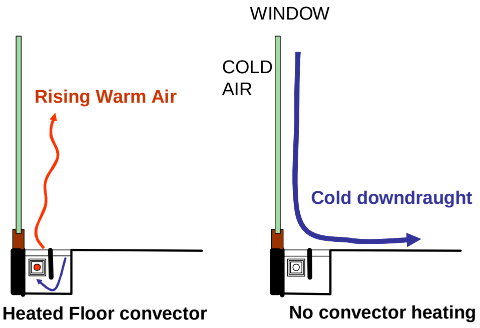


Figure 5.6 Rising hot air,
falling cold air.

A less dense liquid will float on top of a denser liquid, just like oil will float on water. Therefore, a warm liquid will float above a cooler and denser liquid. The denser cooler liquid is described as 'displacing' the warmer less dense liquid.

If you put your hand some way above a hot convector you can feel the warm air rising. Similarly, you can feel cold air falling down the inside of a window as heat is lost from the air next to the window. These situations can cause people to be uncomfortable. If sat above a warm plume of air you can become dry and parched, whilst if sat next to a window you may experience an uncomfortably cold draught around your ankles shown in Figure 5.6.

The greater the difference in temperature between a plume of warm air and its cooler surroundings, the greater are differences in density and forces driving the convection. These are often termed buoyancy forces. Where only buoyancy forces drive the air movement then the convection is termed 'Natural Convection' as opposed to 'Forced Convection' where air movement is driven by a fan.

Perspiration

We perspire or sweat through cells in the skin. Moisture exudes from cells and this moisture evaporates. The latent heat of evaporation is provided by the body which in consequence loses heat. This can be a most effective way of losing heat from the body. However, if the air is humid then the high relative humidity will inhibit the evaporation of water and we may be left with beads of sweat on our skin as shown in Figure 5.7. In such circumstances we lose the benefit of the evaporative cooling and we may need to encourage evaporation by increasing the movement of air over our skin. In much the same way as one cools down a cup of tea by blowing across the surface of the tea to encourage evaporation.

Figure 5.7 Beads of sweat

Respiration

When we breathe we draw in air that generally has a quite low relative humidity. However, the exhausted air exhaled from our lungs has a much higher relative humidity. Thus by breathing in and out we transfer moisture from our body to the air outside. This cools the body because we drink in water and then use our body heat to evaporate some of it and then expel that moisture from our lungs.

Some animals use this as the primary mechanism for cooling the body and anyone who has a pet dog will be familiar with the dog panting to cool down in hot weather or after strenuous exercise as in Figure 5.8.

Figure 5.8 Panting Dog

5.2.3 Relative importance of different mechanisms

Figure 5.9 gives a simplified picture of the different heat loss mechanisms used by the body to lose heat. The two principal features to note are that at a temperature of about 20°C, i.e. normal room temperature, nearly all the heat lost from the body is by convection and radiation. As the temperature of the surroundings increase above 20°C then the proportion of heat lost this way gradually decreases and evaporation i.e. perspiration and respiration, become increasingly important. At temperatures near to our core body temperature, 37°C, then evaporation becomes the principal mechanism for heat loss.

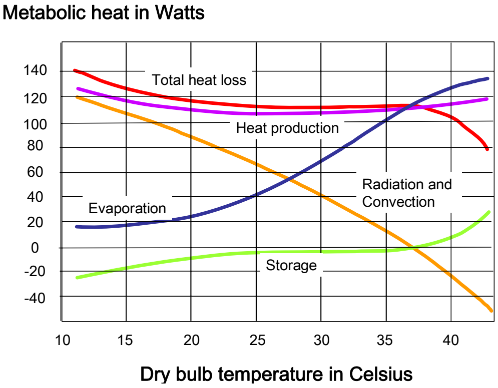


Figure 5.9 Heat loss from body

One consequence of this is the difficulty of cooling the body in hot, humid climates. High humidity limits the evaporation of moisture from the body and as this is the principal mechanism of heat loss in hot surroundings, it limits the heat loss from the body. Thus a most important method of keeping comfortable in hot humid climates is to encourage evaporation by encouraging air movement over the skin.

5.2.4 Definitions of thermal comfort

There are many different definitions of thermal comfort and it is not important to go through them at the moment. Remember some of the basic ideas previously mentioned in relation to comfort. There are physiological or biological mechanisms that influence our state of comfort, but also psychological and emotional factors that are also important. These latter influences are not easy to quantify and predict and yet they may play a most crucial part in affecting people's comfort.

Comfort is not an easy concept to identify, and many authorities define comfort by defining it to be an 'absence of discomfort'. Therefore when someone is neither too hot nor too cold then they will be comfortable. Indeed, it might be suggested that a neutral sense of the thermal environment indicates that we are comfortable.

The principal physiological aspect of thermal comfort is that in order to be comfortable the body must be in thermal equilibrium i.e. the body loses heat at the same rate as it generates heat through metabolism.

In the previous section it was seen how different mechanisms of heat transfer could be used to lose heat. It is not that important which mechanism is losing the heat, just that there is a balance between the heat generated and the heat lost by the body. This means that there are many different thermal conditions that can be comfortable.

5.2.5 Factors in thermal comfort

Considering the physical heat balance mentioned in the previous section, we might consider the two sides of the sides of the equation.

Activity	Metabolic heat in Watts	
	Women	Men
Sleeping	70	80
Sitting	100	120
Level Walking at 5km/hr	264	320
Walking uphill	420	520
Gymnastics	290 - 380	350 - 460
Dancing	230 - 420	280 -510

After Markus & Morris, Buildings Climate and Energy

Figure 5.10 Metabolic heat

Heat generation

The level of physical activity will be the primary factor determining metabolic heat generation. As already mentioned this will be affected by gender, age, weight and fitness. Figure 5.1 gave a simplified view and Figure 5.10 gives a little more information. This is provided for information only and it is not information that I would expect anyone to learn at this stage.

Heat Loss

The heat loss mechanisms have already been considered. However, it is necessary to consider the way in which environmental conditions will interact with these different methods of heat transfer.

Heat transfer by Radiation

Room surfaces at elevated temperatures will transmit net radiation to the body and this heat will have to be lost by other methods of heat transfer. Similarly if we are outdoors in sunshine we will receive a good deal of heat from the sun's rays and this will need to be balanced by heat lost through one of the other heat transfer mechanisms. It might even be better to shade the body from the sunlight and dispense with the need for additional cooling.

Depressed room surface temperatures will be net receivers of radiation from the body and therefore help to cool the body down.

If there is a strong asymmetry to the surface temperatures around the body it might be found uncomfortable. Being sat next to a cold window can be uncomfortable and being sat under a radiant ceiling panel may also cause discomfort.

Conduction

Ordinarily direct conduction is not that important. However, when you put clothes on there is a barrier between the skin and the air that convects heat from the body.

Different clothes insulate the body by different amounts and can considerably affect how comfortable you are. Below in Figure 5.11 the relative insulation is given for a number of different forms of apparel.

Type of clothing	Relative Insulation
Nude	0
Shorts	0.1
Tropical, shorts, shirt, sandals	0.3 – 0.4
Light summer, light trousers + shirt	0.5
Men's business suit	1.0
Men's heavy business suit	1.5
Women's skirt, blouse and jumper	0.7 – 0.9
Heavy suit + overcoat	2.0 – 2.5

After Markus & Morris, Buildings Climate and Energy

Figure 5.11 Insulation of dress

Additionally, conduction is important for fitments to doors and windows. A cold metal window lever will conduct heat effectively from the hand and feel very cold. However, a less conductive wooden doorknob might not feel too uncomfortable even when it is at quite a low temperature.

Convection

Wearing clothes will directly affect the area of skin exposed to the air and therefore will affect the heat directly convected from the skin.

The sensible heat transferred by convection will be influenced by the temperature of the air and the velocity of the air over the skin. The greater the temperature difference the greater will be the heat transfer and the higher the velocity of air the greater the heat transfer.

Perspiration

The principal factors affecting the heat lost through perspiration will be, the area of skin exposed to the air, air temperature, relative humidity of the air and its velocity.

Where relative humidities are high then heat loss through perspiration should be encouraged by exposing as much skin as possible to the air and increasing the air movement over the body. Perspiration will cause loss of body fluids and salt and therefore care is needed to ensure sufficient water is drunk and lost salt is replaced.

Respiration

This is affected by breathing rate and the humidity of the air. There is a need to replace lost moisture.

Behavioural factors

There are a number of behavioural factors that can directly influence our state of comfort.

We can choose to do any of a great variety of actions in order to change our state of comfort:

i) to exercise more and generate metabolic heat if we are cool,
ii) to open a window and let in a cool air if we are too warm,
iii) to lower a blind or move into shade if we are too hot,
iv) to alter our clothing to appropriate dress,
v) to drink a cup of hot tea and therefore induce sweating.

Taken together with the fact that there is a band of conditions that most people will find comfortable, the best design is not necessarily one single environmental condition throughout a building. People's requirements differ and it might be worthwhile allowing people to modify their behaviour in order to accommodate their comfort preferences.

This however introduces an indirect effect of restricted behaviour. If it is the case that a dress code will not allow a person to change their state of dress, or that individuals are not allowed to open a window or feel so constrained that they are unable to do so, then this will introduce psychological effects into the sense of comfort.

An individual who is in a position to shade his desk may choose not do so until a quite high level of discomfort has been incurred. This person is in a position to exercise discretion and may even look forward to a degree of overheating to be followed by the definite relief afforded by lowering a shade. Someone else however, who feels constrained in their behaviour, will feel resentment that they are unable to affect their own conditions and be far less tolerant of even slight feelings of discomfort.

These indirect behavioural factors can be extremely important in rooms occupied by many individuals.

Acclimatisation

We do acclimatize over time to the prevailing environmental conditions. If it is a hot spell during the Summer season then indoor conditions that seem quite comfortable in Winter may be perceived as quite cool. Acclimatization will not be considered this year, other than you should recognise that it is appropriate to design for a range of environmental conditions rather than one single comfort condition.

5.2.6 Bioclimatic chart

Two early pioneers of using building design to accommodate different climatic conditions were Olgyay and Olgyay who published a book " " in 1970.

In this book there is a chart called the Bioclimatic chart which is shown in a modified form in Figure 5.12. Here, a central range of comfort conditions are shown and outside the boundaries of this zone are shown the climate requirements needed to keep people comfortable. Thus if the external temperature increases there will need to be wind available to provide for evaporative cooling or some means shading of sunlight. If external temperatures fall then sunlight will be needed to provide additional warmth. Although rather simplified this approach is still worth appreciating as it does draw clear attention to the way in which buildings should be designed to utilize the prevailing environmental conditions.

I have simplified the chart even more and plotted areas of comfort on a psychrometric chart in Figure 5.13. The central area shows a comfort zone. At temperatures above this comfort zone then air movement may be used to keep people comfortable. At temperatures below the comfort zone then sunlight may be used to keep people comfortable.

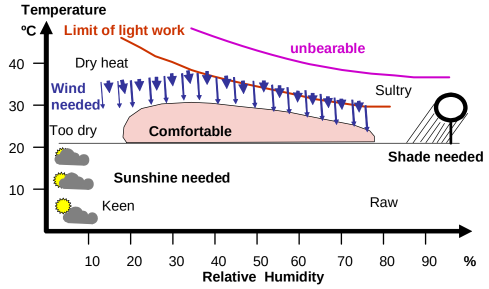


Figure 5.12 Bioclimatic chart

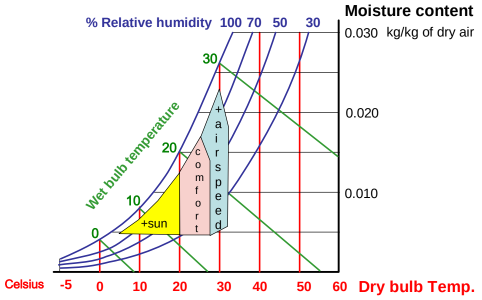


Figure 5.13 Simplified comfort

5.2.7 A Simplified comfort condition

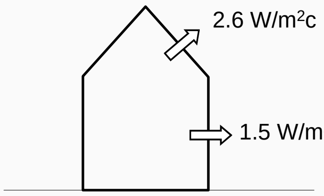
The forgoing can appear rather complicated and for many purposes a simplified approach is to be recommended. Particularly when we are mostly interested in the internal environment where the velocity of air is low and when we design for the United Kingdom where extreme relative humidity is uncommon. Therefore as long as the relative humidity is between 20% and 70% and the air velocity is below 0.1m/s then a measure known as the Dry Resultant Temperature may be used as a comfort temperature:

$$\text{Dry Resultant Temperature} = \frac{\text{Mean surface temperature}}{2} + \frac{\text{Dry bulb temperature}}{2}$$

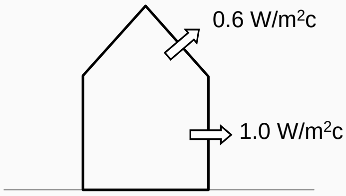
This means that if a comfort temperature of 20°C is chosen, then this might be achieved by combinations of dry bulb (db) and mean surface temperatures (mst) that together combine to give a Dry Resultant temperature of 20° C e.g. 18°C db + 22°C mst or 25°Cdb+15°C mst.

Additionally, the designer should avoid cold draughts or excessive air velocities and large temperature asymmetries.

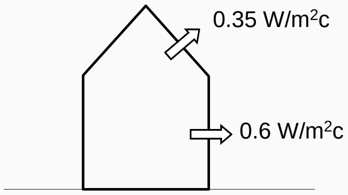
5.3 Heat loss and building design



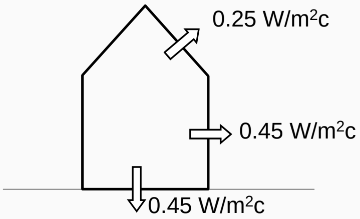
U–Values 1930's



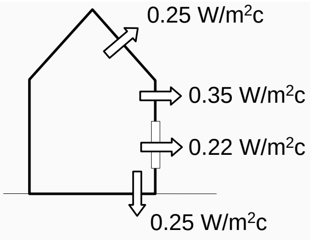
U–Values 1976 Building Regulation



U-Values 1982-5 Building Regulatio



U–Values 1990 Building Regulation



U–Values 2006 Building Regulations

Figure 5.14 – U-Values – Thermal transmittance

The large increase in the price of oil during the 1970's caused a re-appraisal of energy use throughout the world. In this country some measures taken to reduce energy expenditure were not enforced for many years, for instance, the 50mph speed limit imposed on road vehicles in order to reduce energy used in transport. Other measures have remained, and even been extended. Among these are the requirements for the Conservation of fuel and power in new buildings that are incorporated into the Building Regulations – Part 2L. Amongst other requirements these regulations limit the Thermal Transmittances allowed for various building elements e.g. walls, floors, roofs etc. The Thermal Transmittance of a building element is given the term U-value and states the degree to which heat is lost from for each square metre of surface for each degree in temperature difference between the inside and outside of the building.

U-values are therefore quoted in $W/m^2{}^\circ C$ or W/m^2K

Figure 5.14 shows the limits on U-values imposed at various times since the 1930's.

It is worth while noting that:

a) After the oil shock of the 1970's, the relative cost of energy had fallen until recently. The rationale for limiting heat loss from buildings was driven more by environmental considerations of global warming than the need to save money. Indeed, generally where the costs of wasting energy are low, the more important become regulations in limiting energy expenditure,

b) regulations are purposefully made simple so that they can be easily enforced. However, that very simplicity may act to restrict the originality of designs. Therefore designs are allowed, that exceed the limits imposed by the regulations, as long designers can show that those designs emit no more CO_2 throughout the year than a design that satisfies the regulations.

5.3.1 Limiting heat losses

Something of the order of 40% to 50% of the total amount CO_2 emitted in the United Kingdom is the result of heating, conditioning and lighting buildings. Therefore if CO_2 emissions are to be reduced, then attention must be directed to limiting CO_2 produced by buildings. As well as the market pressures imposed through the price of energy additional incentives are needed to encourage energy saving. In buildings this is partly achieved through the Building Regulations already mentioned. As well as specifying the maximum thermal transmittance for constructional elements, limits are placed on the permeability of the building envelope in order to limit heat loss through infiltration and also limits are placed upon the percentage of glazing in walls in order to limit the degree to which buildings overheat in Summer.

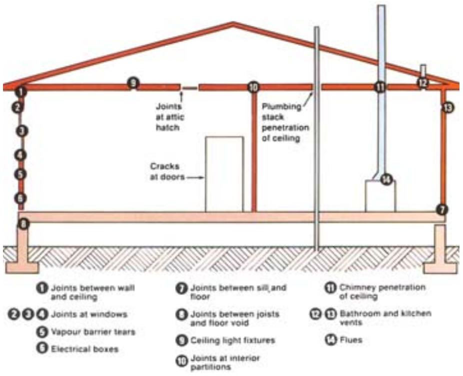


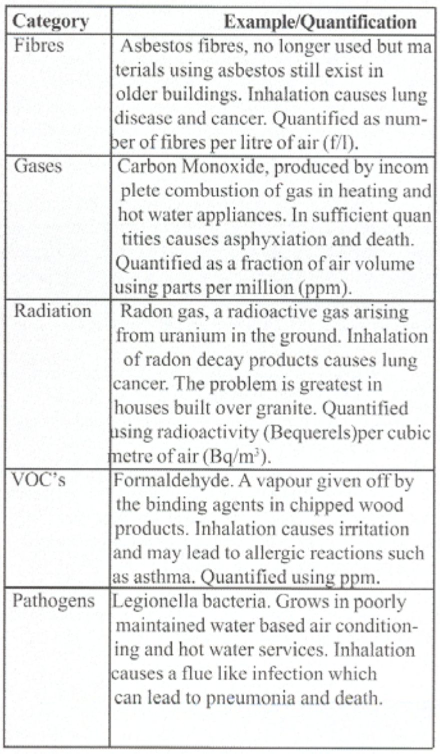
Figure 5.15 – Contaminants in air

If the limiting thermal transmittances in Figure 5.14 are compared, it can be seen that the maximum allowable U-Value has been considerably lowered over the years.

Even so, it is still noticeable that the U-value of a window is considerably higher than other building elements. Indeed the maximum allowable U-value of the window has only been halved over the last thirty years whilst that of the opaque elements has been reduced by 75%.

Thus windows are still the weak link in the façade and the heat loss through windows is a major part of heat loss through the fabric of the building. This fact led some designers in the 1970's to reduce heat losses by limiting the areas of glazing. Unfortunately, this resulted in some buildings being rather gloomy inside and to users increasing their use of electric lighting. Also, limiting the area of glazing meant that insufficient use was made of the heat from sunlight and the contribution it could make to the heating a building.

Locating windows on particular facades and using different areas of glazing affect energy use in complex ways. It is not easy to achieve the optimal balance between maximizing useful solar gains, limiting unwanted heat losses and ensuring useful amounts of light.



Category	Example/Quantification
Fibres	Asbestos fibres, no longer used but materials using asbestos still exist in older buildings. Inhalation causes lung disease and cancer. Quantified as number of fibres per litre of air (f/l).
Gases	Carbon Monoxide, produced by incomplete combustion of gas in heating and hot water appliances. In sufficient quantities causes asphyxiation and death. Quantified as a fraction of air volume using parts per million (ppm).
Radiation	Radon gas, a radioactive gas arising from uranium in the ground. Inhalation of radon decay products causes lung cancer. The problem is greatest in houses built over granite. Quantified using radioactivity (Bequerels)per cubic metre of air (Bq/m^3).
VOC's	Formaldehyde. A vapour given off by the binding agents in chipped wood products. Inhalation causes irritation and may lead to allergic reactions such as asthma. Quantified using ppm.
Pathogens	Legionella bacteria. Grows in poorly maintained water based air conditioning and hot water services. Inhalation causes a flue like infection which can lead to pneumonia and death.

Figure 5.16 – Contaminants in air

5.3.2 Infiltration

Reduced U-values have reduced considerably the heat loss through the fabric of the building. This has meant that the heat needed to warm the infiltrating fresh air has become a much more significant part of the total heat loss from the building.

It is necessary here to distinguish between the unplanned infiltration of air into the building and planned ventilation. Infiltration occurs fortuitously and as such is best eliminated as much as possible. This can be done by making the building airtight: reducing the gaps between building elements; sealing the gaps around pipes etc. that penetrate through the façade and making building elements less permeable. Figure 5.15 shows where infiltration can occur.

In design projects undertaken within the course this year, the principal methods of preventing excessive infiltration will be to limit the number of entrances and exits in your buildings, and to ensure a degree of compartmentalisation within the interior. Increased compartmentalisation means that when opening a front door, the warm air in the hallway is lost, but that in other rooms is retained behind closed doors.

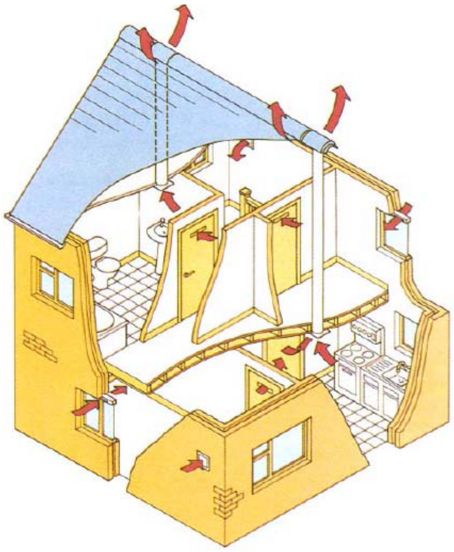


Figure 5.17 –Domestic ventilation

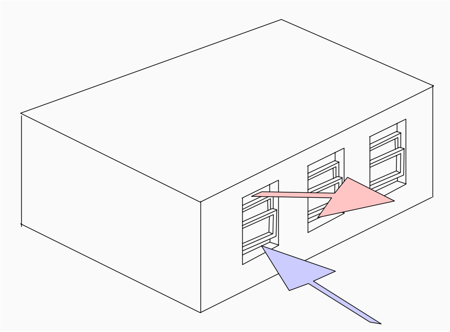


Figure 5.18 –Sash windows

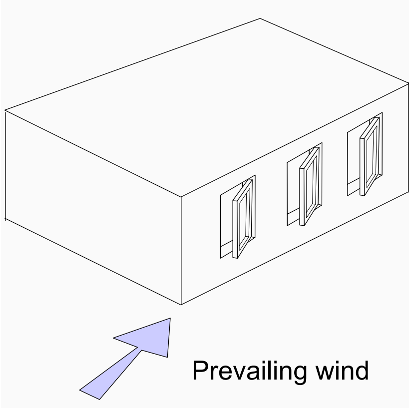


Figure 5.19 –Casement windows

Accurately predicting the level of infiltration into a building can be quite difficult and depends upon many factors;

- the standard of construction
- type of construction and detailing of joints
- length and size of cracks in construction
- wind direction and speed
- building height
- number of separated compartments in the building
- number of windows
- air tightness of windows

5.3.3 Planned Ventilation

Eliminating or reducing infiltration makes it essential that the building designer ensures that there is sufficient planned ventilation.

Planned ventilation ensures:

- an adequate supply of oxygen
- dilution of body odours and smells
- control of relative humidity of air
- dilution of toxic chemicals such as Volatile Organic Compounds
- introduce fresh air that is uncontaminated with pathogens

It has been found that one of the principal factors involved in reducing the incidence of Sick Building Syndrome is improving the quality of air breathed by occupants. Figure 5.16 lists some of the contaminants in buildings.

Fresh air directly from the cold outdoors may cause draughts and therefore it must be introduced carefully into a room or pre-heated. Once introduced the air needs to be distributed about the room so that stagnant pockets of air are eliminated.

In domestic scale buildings this can be achieved by incorporating trickle ventilators within the window frames and providing paths for air to be ventilated at the ridge as is shown in Figure 5.17.

Without ventilation, air in an occupied room may become fuggy and more humid. This may lead to condensation on cold surfaces that can lead to unsightly mould growth and unhealthy damp living conditions. Humid conditions may also lead to the deterioration of building materials.

Other ways of ensuring adequate ventilation in domestic scale buildings will be to:

- **ensure that buildings are not too deep,**
- **to use sash windows if windows are only on one wall**
- **casement windows to catch the prevailing wind,**
- **use cross ventilation where ever possible.**

5.3.4 Mechanisms driving natural ventilation

There are two mechanisms that drive natural ventilation.

Pressure differences across the building

Pressure differences across the building are caused by the flow of air around the building. In your course on structural engineering you have learnt that these pressure differences are one of the loads imposed upon building surfaces. Wind driving onto the face of a building will create a positive pressure on that facade. In the lee of the wind, suction will be created on the facade. The combination of a positive pressure on one facade and suction on the opposite facade will create a pressure difference across the building, and this will force air into and out of the building. The pressures will depend upon the speed of the wind and the C_p – co-efficient of pressure. The value of C_p will be determined by many factors, the direction of the wind, the location of surrounding buildings, the shape and form of the building being considered and the proximity of some notable feature such as a corner or some angular projection from the facade.

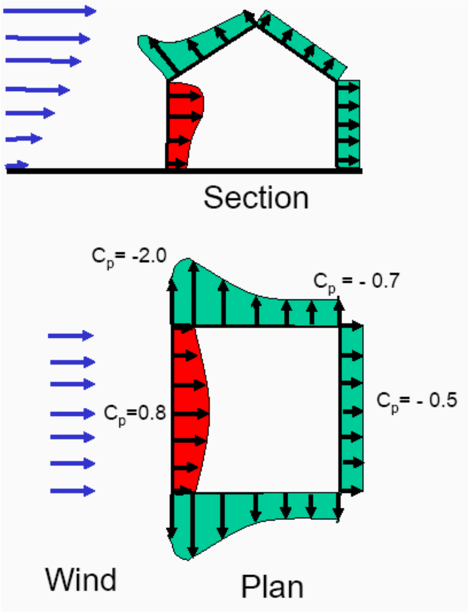


Figure 5.20– Pressure co-efficients

Ventilation rates also depend upon the resistance that there is to air flow through the windows and other air paths through the building. The resistance to air flow through a window is measured by its Co-efficient of Discharge, C_d.

The rather complicated way in which air flows around real buildings makes it difficult to accurately predict rates of ventilation. Reasonable approximations can be calculated if the building form is simple and the characteristics of the openings in the building are known.

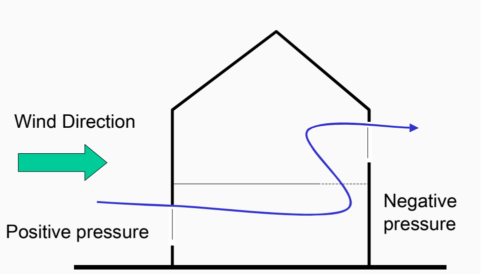


Figure 5.21 – Pressure driven

Buoyancy driven Stack Effect

The Stack Effect describes the effect of warm air rising above cold air. Warm air expands and so it becomes less dense and floats above colder more dense air. The effect is the same as that seen in an open fire with a chimney, where the hot air rises in the chimney, exits at high level and draws cold air into the room. The higher the temperature of the air and the greater the height of the chimney, then the greater is the pressure differential driving the flow of air.

The stack effect is a function of Δ(temperature) and Δ(height).

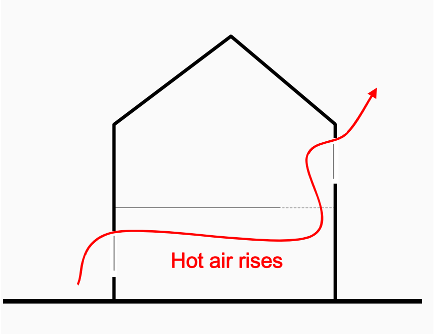


Figure 5.22 – Buoyancy driven

The two effects may either work together to increase ventilation or fight against each other. Because modern well sealed structures have reduced infiltration it means that much more attention needs to be given to ventilation. Unfortunately, estimating natural ventilation over the many different conditions throughout the year is not simple. However in the small buildings encountered in first year, constant volume trickle ventilators can provide for the minimum ventilation.

5.4 Estimating heat losses

The heat lost from a building is of two parts, that lost through ventilation and that lost through the fabric of the structure.

$$\Phi_{TOTAL} = \Phi_{VENT} + \Phi_{FABRIC} \quad \text{Watt}$$

5.4.1 Heat lost through infiltration and ventilation

The heat transfer rate needed to heat up the infiltration air is given by,

$$\Phi_{VENT} = \frac{NV}{3} \times \left(t_{ai} - t_{ao}\right) \quad \text{W}$$

Where:

N is the number of air changes per hour,

V is the volume of the building or room.

The above formula gives the heat needed to heat up the outside air to that of the inside of the building if the air change rate is known. Values of typical infiltration rates are given in Figure 11.

This formula comes from calculating the heat needed to heat up a given mass flow rate of air,

$$\Phi = \dot{m} c \left(t_1 - t_2\right) \quad \text{W}$$

Where,

Φ = heat flow rate in kW, i.e J/s

$\dot{m}$ = mass flow rate in kg/s

c = specific heat of air, 1000 J/kgK

t_1 -t_2 = temperature rise of substance.

The mass flow rate of the air $\dot{m} = \rho\, \dot{v}$ kg/s

where ρ is the density of air, 1.2 kg/m^3 kg/m^3

and $\dot{v}$ is the volume flow rate in m^3/s.

If the total volume of the room is V m^3 and there are N air changes per hour, then, $\dot{v} = \dfrac{V \times N}{3600}$ m^3/s

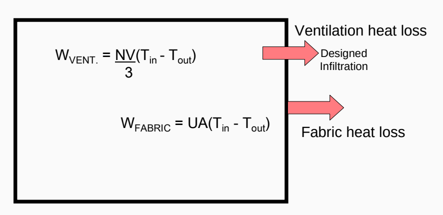
And,

$$\Phi_{VENT} = \dot{m} c \left(t_1 - t_2\right) = \rho \dot{v} c \left(t_1 - t_2\right) = 1.2 \times \frac{V \times N}{3600} \times 1000 \times \left(t_1 - t_2\right)$$

$$\Phi_{VENT} = \frac{V \times N}{3} \times \left(t_1 - t_2\right) \quad \text{W}$$

Note Figure 12 gives Ventilation rates in l/s per person and as there are 1000 litres in one m^3 then the ventilation heat loss will be given by,

$$\Phi_{VENT} = \frac{(x\, litres/\text{sec})}{1000} \times 1.2 \times 1000 \times \Delta T = (x\, litres/\text{sec}) \times 1.2 \times \Delta T \quad \text{Watt}$$



Type of construction	Infiltration rate in Air changes per hour
Well sealed building	0.25
Good quality build	0.5
Poor quality build	> 2.0

Figure 5.23 – Fabric and ventilation

Circumstance	Ventilation in litres/second
Minimum -no contaminants	7.5
General	10.0
Maximum – contamination	15.0

Figure 5.24 – Ventilation rates

Speed of air in m/s	Occupant response
< 0.25	Unnoticed
0.25 – 0.5	Pleasant
0.5 – 1.0	Aware of air movement
1.0 – 1.5	Draughty
>1.5	Unacceptable

Figure 5.25 – Effects of air

5.4.2 Heat loss through building Fabric

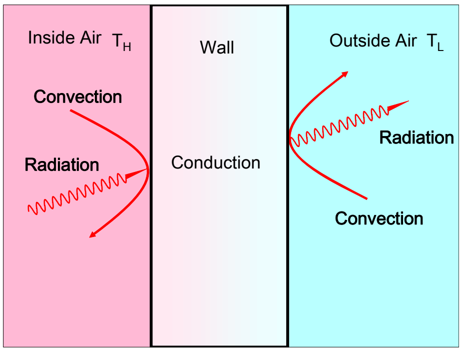


Figure 5.26 – Modes of heat transfer

Under steady state conditions the heat transmitted through a building element can be estimated using the Thermal Transmittance or U-Value of the element. The U-Value takes into account the three modes of heat transfer as shown in Figure 5.26;

- Radiation transfer between surroundings and surfaces
- Convection between air and surfaces of the element
- Conduction through the structural elements

Φ_{Fabric}, the heat lost through the whole fabric of the building is given by summing the heat losses through all the individual building elements as indicated in Figure 5.27, and the equation,

$$\Phi_{FABRIC} = \sum_{n=1}^{n=N} U_n A_n (t_{ai} - t_{ao}) \quad \text{Watts}$$

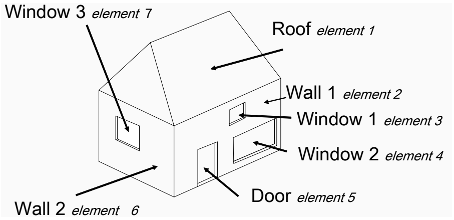


Figure 5.27 – Summing all elements

where;

Σ = Sum the effects of the N different building elements
U_n = U value of $n^{th.}$ building element in W/m²K
A_n = Area of $n^{th.}$ surface in m²
t_{ai} = inside air temperature in ºC
t_{ao} = outside air temperature in ºC.
N = total number of building elements

The total resistance to heat flow through a particular building element is given summing the resistance of all the layers that comprise the building element as indicated in Figure 5.28 and the equation,

$$R_{Total} = \sum_{i=1}^{i=I} R_i \quad \text{m}^2\,\text{K/W}$$

where,
R_{Total} = Sum of the thermal resistances,
Σ = Sum the effects of the I layers in a building element,
R_i = Thermal resistance of the $i^{th.}$ layer of building element.

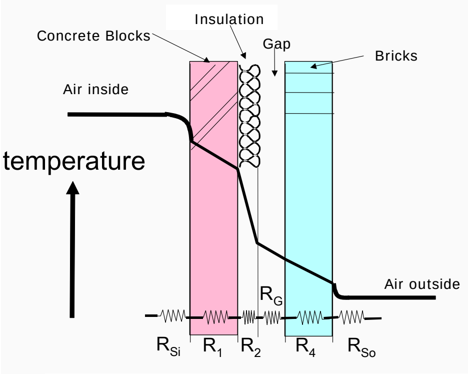


Figure 5.28 – Summing all layers

The U-value of the building element is then simply found by taking the reciprocal of the total thermal resistance,

$$U = \frac{1}{R_{Total}} = \frac{1}{\sum_{i=1}^{i=I} R_i} \quad \text{W/m}^2\text{K}$$

Heat flow through a single layer

The heat flow through a single layer of material is described by Fourier's law of conduction,

$$\text{Heat Flow} = -\frac{\text{Thermal conductivity} \times \text{Area} \times \text{Temperature difference}}{\text{Thickness of Layer}}$$

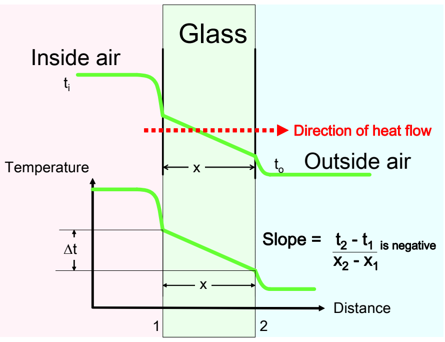


Figure 5.29 – Temperature across a layer

Typical thermal conductivities W/mK	
Aluminium	170
Glass	1.0
Brick	0.7
Wood	0.15
Glass fibre	0.05
Stationary air	0.026
Wet Earth	2.1
Dry Earth	0.7

Figure 5.30 – Thermal Conductivities

The negative sign indicates that heat flows in the opposite direction to the positive temperature gradient as can be seen in Figure 5.29. The various quantities are represented by the following symbols,

Φ is the heat flow through the layer in Watts
λ is the thermal conductivity of the material in W/mK
A is the surface area in m^2
x is the thickness of the layer in m
t_1 is the high temperature
t_2 is the low temperature

Using the symbols above, Fourier's law can be written as,

$$\Phi = -\lambda A_1 \frac{(t_2 - t_1)}{x_1} \qquad W,$$

And this may be rewritten as,

$$\Phi = \lambda A_1 \frac{(t_1 - t_2)}{x_1}. \qquad W$$

or,

$$\Phi = \lambda\, A_1 \frac{(t_{in} - t_{out})}{x_1} \qquad W$$

Thus heat flow through a building element:

- increases the greater the temperature differences
- increases as the thermal conductivity of the layer increases
- decreases as the thickness of the layer is increased

The table in Figure 5.30 gives a representative range of thermal conductivities for various building materials.

Heat flow through multiple layers

When a building element comprises a number of layers of different materials then it is necessary to evaluate the resistance of each layer in order to sum the contribution made by each layer to the overall resistance of the building element. The resistance of the $i^{th.}$ layer may be found from its thermal conductivity and its thickness using the following relationship,

$$R_i = \frac{x_i}{\lambda_i} \quad m^2 K/W.$$

Where a layer is exposed to the air, there will be a surface resistance to the flow of heat flow $\mathbf{R_s}$ which is related to the surface heat transfer coefficient $\mathbf{h_s}$ by the following relationship,

$$R_s = \frac{1}{h_s} \quad m^2\, K/W,$$

The terms thermal conductance C, and thermal resistance R, are terms used to describe the properties of a given layer of a building element. The terms thermal conductivity λ, and thermal resistivity r, describe the properties of the layer material. The relationships between the various properties are shown in Figure 5.31.

$$\textit{Thermal Conductance} \quad C = \frac{\lambda}{\Delta x} \qquad in\ W/m^2K$$

$$\textit{Thermal Resistance} \quad R = \frac{1}{C} = \frac{\Delta x}{\lambda} \qquad in\ m^2K/W$$

$$\textit{Thermal Resistance} \quad R = r\,\Delta x$$

$$\textit{Where} \quad \textit{thermal resistivity} \quad r = \frac{1}{\lambda} \qquad in\ mK/W$$

Figure 5.31 – Thermal properties

The thermal properties of different building materials are often given in terms of their thermal conductivities and the surface properties of an element are often given in terms of their surface heat transfer co-efficients. The overall U-value of an element may therefore be conveniently written as,

$$U = \frac{1}{R_{total}} = \frac{1}{\sum R_i} = \frac{1}{\left(\frac{1}{h_{in}} + \sum_{i=1}^{i=I} \frac{x_i}{\lambda_i} + R_g + \frac{1}{h_{out}}\right)} \qquad \mathrm{W/m^2K}$$

It is most easily calculated if it is set out in a tabular form as shown below.

Layer	Material	Thickness	Conductivity	R
		x	λ	x/λ
1				
2				
3				
4				
5				
6				
7				
8				
Subtotal				
Inside Surface resistance		Orientation		
Internal Gap				
External surface resistance		Exposure		
		Orientation		
		Emissivity		
Total Thermal resistance of the element - R_T				

The surface heat transfer co-efficients depend upon the types of surface, whether they are internal or external surfaces, their orientation and the degree of exposure to which the external surfaces are subjected.

Figures 5.32 and 5.33 show the values tabulated for internal and external surfaces.

Internal surface resistance in m²K/W	
Wall	0.12
Ceiling	0.10
Floor	0.14
Cavity	0.18

Figure 5.32 – Internal surface resistances

External surface resistance in m²K/W				
	Emissivity	Exposure		
Surface	ε	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

Figure 5.33 – External surface resistances

It should be noted that in calculations involving U-values as set out above, it is assumed that all the heat travels in a parallel path across the element. Thus when considering the heat passing through adjacent elements it is assumed that no heat passes between the two touching surfaces. That this is a simplification can be seen by comparing the heat flows at the corner of a building as in Figure 5.34.

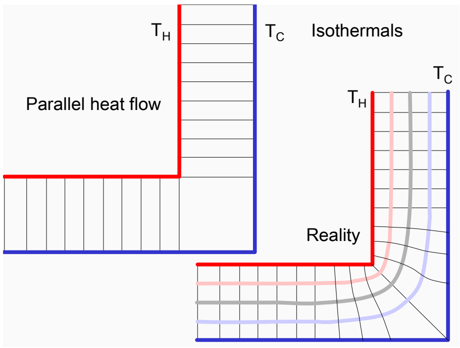
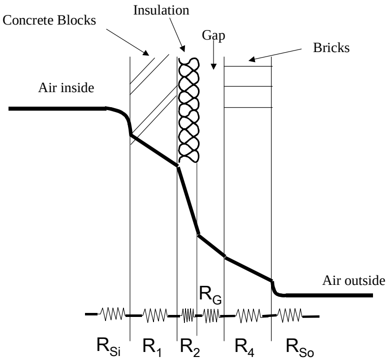


Figure 5.34 – Non parallel heat flow

5.4.3 Temperature profiles



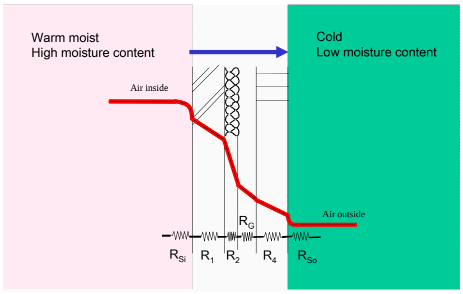
Writing the Fourier equation using the resistance of a layer leads to the heat loss through a single layer being given by,

$$\Phi = A_1 \frac{(t_1 - t_2)}{R_1} \text{ Watt} .$$

Where a construction is made up of a number of layers as shown in Figure 22, then at steady state there will be the same flow of heat passing through each layer and,

$$\frac{\Phi}{A} = \frac{(t_{ai} - t_1)}{R_{in}} = \frac{(t_1 - t_2)}{R_1} = \frac{(t_2 - t_3)}{R_2} = \frac{(t_3 - t_4)}{R_g} = \frac{(t_4 - t_5)}{R_4} = \frac{(t_5 - t_{ao})}{R_{out}}$$

where R_{in} is the internal surface resistance in $m^2 K / W$
R_{out} is the outside surface resistance in $m^2 K / W$
R_i is the resistance of $i^{th.}$ layer in $m^2 K / W$
R_g is the thermal resistance of the gap in $m^2 K/W$
t_{ao} is the outside air temperature in ºC
t_{ai} is the inside air temperature in ºC



But, the sum of all the temperature differences across the elements should equal the overall temperature difference between the inside and outside temperature,

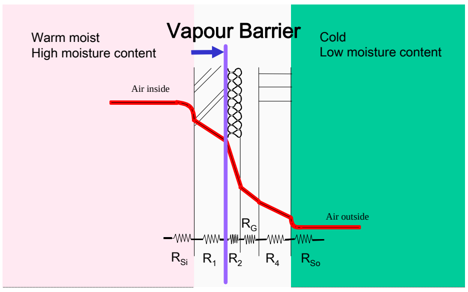
$$(t_{ai} - t_{ao}) = (t_{ai} - t_1) + (t_1 - t_2) + (t_2 - t_3) + (t_3 - t_4) + (t_4 - t_5) + (t_5 - t_{ao})$$

and so using the fact that the heat flow through each layer is the same,

$$\frac{\Phi}{A} = U\left(t_{ai} - t_{ao}\right) = \frac{\left(t_{ai} - t_{ao}\right)}{R_{TOTAL}} = \frac{\Delta t_n}{R_n}$$

or,

$$\frac{\left(t_{ai} - t_{ao}\right)}{\Delta t_n} = \frac{R_{TOTAL}}{R_n}$$



Where: Δt_n , is the temperature drop across the $n^{th.}$ layer,
R_{TOTAL} is the overall thermal resistance of the whole wall.

This is a useful relationship because it allows you to calculate temperatures across each element and examine the temperatures at each layer. This enables you to check that temperatures do not fall below the dew point temperature, for if this were to occur, then interstitial condensation would take place within the structure and this could cause damp patches, a loss of thermal insulation and even deterioration of the materials used in construction.