Sustainable building

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The HQ of the UK Institute of Physics (IOP) applies physics principles to minimise its use of fossil fuels

Exam links

The terms in bold link to topics in the **AQA**, **Edexcel**, **OCR**, **WJEC** and **CCEA** A-level specifications, as well as the **IB**, **Pre-U** and **SQA** exam specifications.

The IOP building design incorporates **materials** with high **specific heat capacity** and uses heat pumps to transfer **energy** and control its **temperature**.

The Institute of Physics (IOP) is the professional body that represents physicists in the UK and around the world. The Institute has a new headquarters near King's Cross station in London, constructed inside the shell of a much older building. In planning the new HQ, it was decided that the building itself should demonstrate aspects of sustainable building design.

The general idea of *sustainability* is that we should not do things today that will leave problems (and hence costs) for future generations. Burning fossil fuels is an example of an unsustainable practice — today we have to cope with the effects of climate change arising from fossil fuels burned over the last two centuries. So, the IOP's HQ has important features that are intended to minimise the use of fossil fuels. Since, for most buildings, heating and cooling put the biggest demands on energy supplies, we will look at this aspect first.

Thermal modelling

For any building where people work, it is important to have rooms at a comfortable temperature, typically close to 20°C. The exterior temperature may drop below 0°C in winter and rise above 30°C in summer. There is also the day–night temperature cycle to take into account. Both heating and cooling are needed.

Once the architects had designed the building, a thermal modelling program was run to determine how much heating

The Institute of Physics has a new HQ in London

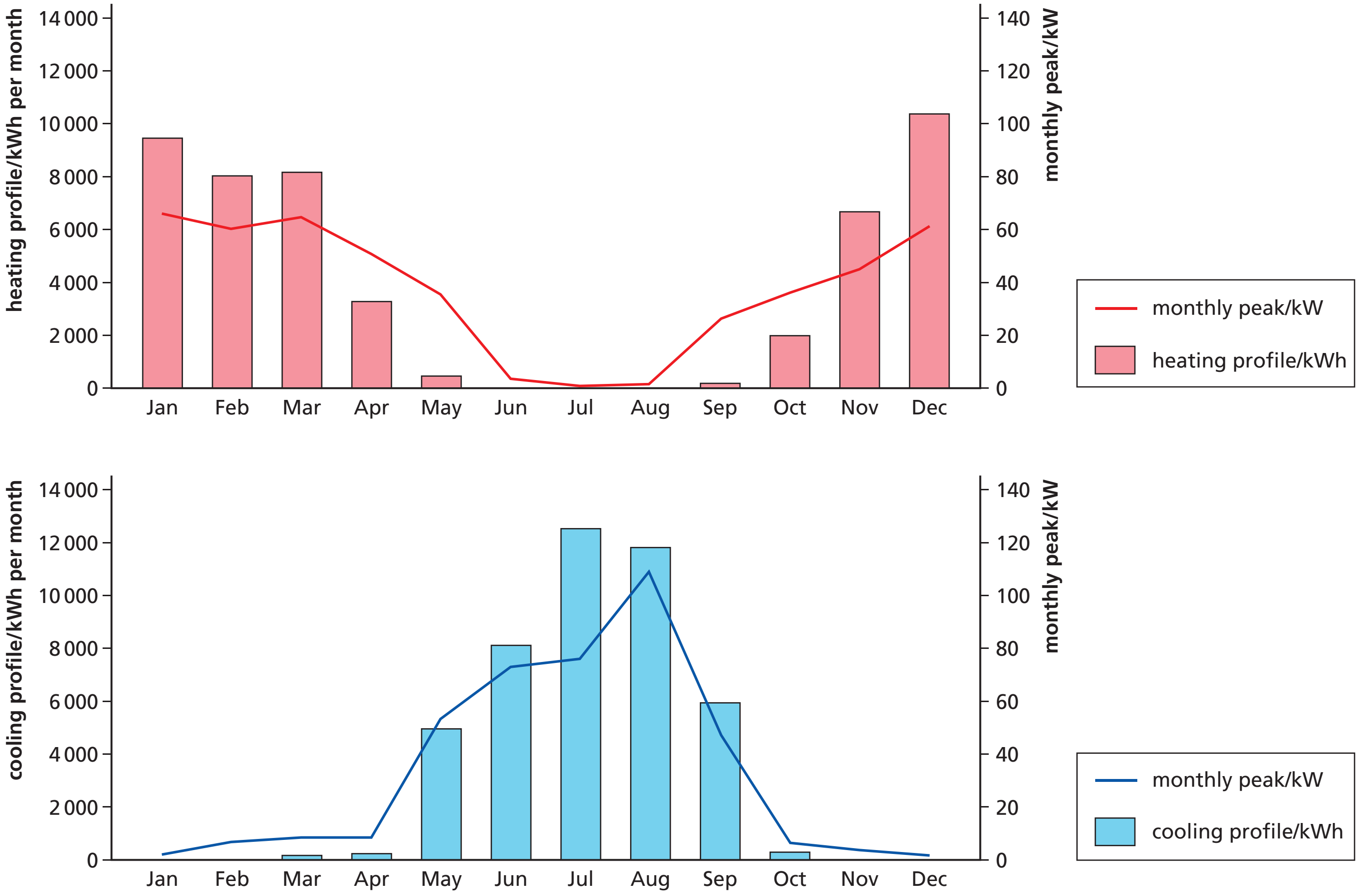

Figure 1 Heating and cooling demand

and cooling would be needed in the course of a year. This is a computer program that uses data about the building (areas and materials of walls, windows etc.) and about how the external temperature varies throughout the year. It calculates the rate at which energy will leave the building when the external temperature is below 20°C. (Energy leaves by conduction through walls, roof and floor, and is carried by warm air from the ventilation system.) The program shows it the amount of heating that will be required, hour by hour, through the year.

The program also calculates the amount of cooling required when the external temperature is above 20°C. Figure 1 shows the results of these calculations, month by month, and it is surprising to find that almost as much cooling is required as heating.

Thermal mass

In designing the building, the architects incorporated several large concrete columns, positioned so that they are exposed to the Sun's rays during the day. Concrete has a high specific heat capacity so, on a sunny day, these columns absorb energy but heat up only slowly. At night they cool down slowly, releasing energy into the building so that it stays warm for longer. Designing buildings to take advantage of the (freely available) energy of sunlight like this is known as *solar gain* (Box 1).

Architects and engineers refer to the *thermal mass* of these structures. Just as an object with a high mass is hard to accelerate

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Box 1 Solar gain

How much energy can a concrete block store? Consider a concrete pillar that absorbs sunlight, so that its temperature rises by $\Delta\theta = 10°\mathrm{C}$ (= 10 K) in the course of a day. The column is 10 m high and its cross-sectional area is $0.5\,\mathrm{m}^2$. For high-density concrete:

specific heat capacity, $c = 1000\,\mathrm{J\,kg^{-1}\,K^{-1}}$

density, $\rho = 2300\,\mathrm{kg\,m^{-3}}$

$$\begin{aligned} \text{mass of column, } m &= \text{density} \times \text{volume} \\ &= 2300\,\mathrm{kg\,m^{-3}} \times 10\,\mathrm{m} \times 0.5\,\mathrm{m^2} \\ &= 11\,500\,\mathrm{kg} \end{aligned}$$

$$\begin{aligned} \text{energy stored, } Q &= mc\Delta\theta \\ &= 11\,500\,\mathrm{kg} \times 1000\,\mathrm{J\,kg^{-1}\,K^{-1}} \times 10\,\mathrm{K} \\ &= 1.15 \times 10^8\,\mathrm{J} \end{aligned}$$

It is helpful to convert this to kWh, where $1\,\mathrm{kWh} = 3.6 \times 10^6\,\mathrm{J}$. So:

$$Q = \frac{1.15 \times 10^8\,\mathrm{J}}{3.6 \times 10^6\,\mathrm{J\,kWh^{-1}}} = 31.9\,\mathrm{kWh}$$

This figure is comparable to the average daily heating requirements for a typical small house in the UK.

Concrete structure of the IOP HQ

or slow down, so a building with a high thermal mass responds only slowly to external temperature changes. Consequently, as the external temperature changes during the day, the temperature inside the building changes relatively slowly.

As shown in Figure 2, the external temperature T_o reaches its maximum value shortly after noon. Adding thermal mass to a building causes its internal temperature T_i to reach a lower maximum temperature later in the day, reducing the need for cooling.

Energy from underground

The heating and cooling system of the IOP HQ had to meet the following demands:

- peak heating load of 75 kW, peak cooling load of 121 kW
- total annual heating load of 56 757 kWh, total annual cooling load of 52 444 kWh

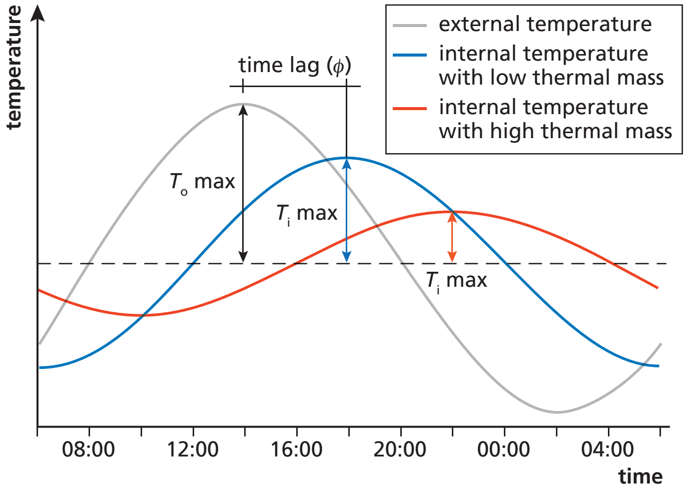

Figure 2 Thermal mass

Most buildings in the UK are heated using fossil fuels, such as natural gas, an unsustainable energy source. Similarly, most cooling systems use electricity generated using fossil fuels. The IOP HQ uses *ground source heat pumps* (GSHPs) for both heating and cooling. These take advantage of the fact that, in London, if you penetrate more than 2 m below ground level, the temperature is close to 12 °C. Sunlight is absorbed at the surface, warming the ground, and this energy gradually conducts downwards to maintain this more or less constant temperature.

GSHP performance

A GSHP works like a refrigerator or freezer. A fridge takes energy out of warm objects inside it and transfers that energy into its surroundings via the array of black tubing on the back. To heat a building, a heat pump takes energy out of the ground and transfers it into the air inside the building.

At the heart of a ground source heat pump (or a refrigeration unit) is a circuit around which a refrigerant passes (Figure 3). The refrigerant is first compressed and passed through a condenser. In changing from gas to liquid it releases energy to its surroundings — this is the energy available for heating a building.

The refrigerant then expands through an expansion valve. As the liquid becomes a gas its temperature drops. This is because

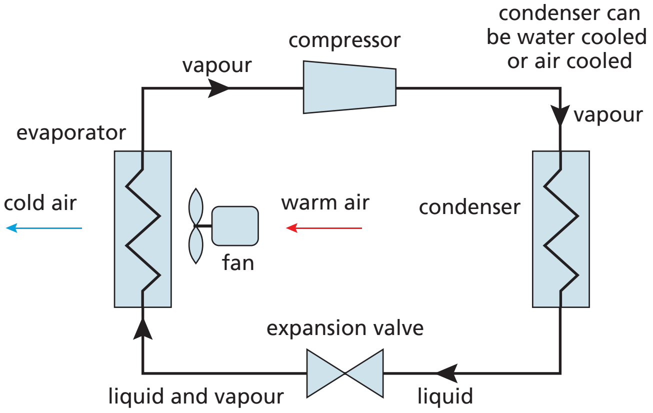

Figure 3 A simple vapour-compression circuit

energy, known as latent heat of vaporisation, is needed to separate its molecules. This cold liquid/vapour mixture passes through tubing in an evaporator, where it can be used to cool air (as in a fridge) or liquid coolant (as in a GSHP).

It takes electrical power to make a GSHP function. An electric compressor is needed to compress the coolant and force it round the circuit, and the power needed to operate the compressor and circulation pumps must be less than the rate at which energy is extracted from underground.

An effective heat pump will transfer several joules of energy for each joule of energy required to operate it. This is expressed by the *coefficient of performance* (COP):

$$\text{COP} = \frac{\text{energy transferred to building}}{\text{energy transferred to the pump}} = \frac{Q_H}{W}$$

The IOP's GSHPs have a COP of 4.6 when they are operating at their most effective — that is, they transfer 4.6 J of energy to the building for every 1 J supplied to them. Most domestic refrigerators and air conditioning systems have a COP less than this.

Installing the GSHPs

During the construction of the IOP building, ten deep holes were drilled into the ground, each of diameter 200 mm and penetrating to a depth of 72 m. Each hole is fitted with a probe, with a central tube down which liquid coolant is pumped. The coolant then returns to the surface via the outer part of the probe (Figure 4). As it rises, the coolant is in close contact with the ground and absorbs energy from it. Thus, the coolant emerges at the top warmer than when it went down. Baffles produce turbulent flow, ensuring that the coolant makes good contact with the walls.

The coolant is water with added propylene glycol as antifreeze. This is needed because, on occasion, heat pumps have extracted so much energy from the ground that the temperature has dropped below 0 °C, causing the whole system to freeze solid.

On a cold day, the energy of the warmed coolant is used to heat air; warm air is then distributed around the building.

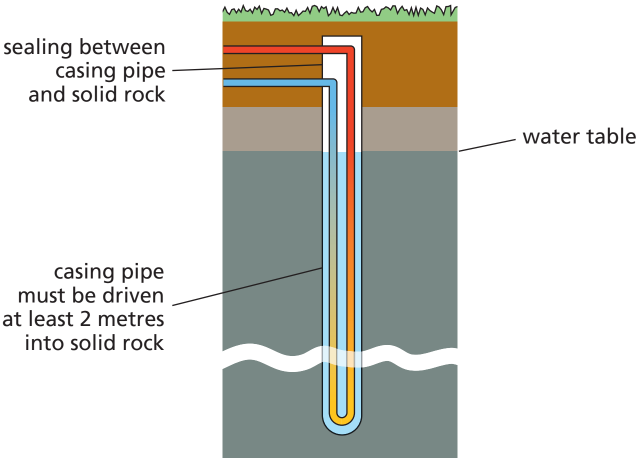

Figure 4 The type of GSHP probe used for the IOP building

A ground source heat pump probe installed as part of a new build

One great advantage of using a GSHP system is that, when the building is warm and cooling is needed, the system can operate in reverse. Warm coolant is pumped underground; energy is transferred into the surrounding rock and the coolant returns to the surface at a lower temperature. In effect, energy captured by the building in the summer is pumped underground and is then extracted in the winter when heating is needed.

In the case of the IOP building, the compressors can use electricity generated by *photovoltaic panels* on the roof — another way of avoiding the use of fossil fuels. (See 'Photocells: generating electricity using solar radiation', Physics Review Vol. 26, No. 1, pp. 2–6.)

More sustainability

The IOP HQ has several other features that contribute to reducing its demand on the environment.

As already mentioned, there are photovoltaic panels on the roof. These supply electricity to the building during the day, and

Chimneys on the IOP HQ

any excess is transferred to the grid. At night electricity is drawn from the grid.

Internal lighting makes use of light-emitting diodes (LEDs). These are many more times efficient than traditional filament lamps, and more efficient than compact fluorescent lamps. Since they are made of a solid material, they are robust and last much longer.

For those working in the building, ventilation can be as important as heating and cooling. The building uses a system of *passive stack ventilation*. This means that warm air naturally convects through the building, rising upwards and leaving through chimney stacks on the roof. The term ‘passive’ implies that no active pumping is required to remove warm, stale air from the building.

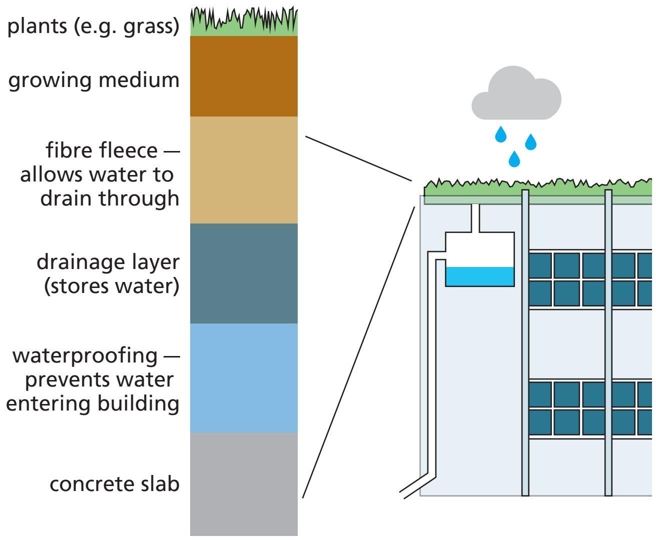

Figure 5 Blue-green roof

Finally, the building has a blue-green roof (Figure 5). This is a composite structure designed to hold rainwater in the event of a downpour and to release it gradually. Traditional buildings have hard roofs so that stormwater flows almost instantly into the drainage system, possibly leading to flooding. The blue-green roof is designed to retain rainwater. Water evaporating from the roof contributes to cooling; some of the water retained by the roof is transferred into tanks and used for flushing toilets. And the vegetation on top is good for wildlife.

See for yourself

The IOP headquarters building is at 37 Caledonian Road, London N1 9BU. Parts of it are open to the public, with exhibitions and interactive exhibits — call in when you are nearby.

You can find out more about sustainable building design and many different aspects of modern physics on the IOP website:

www.explorephysics.iop.org

and sign up for regular updates from the IOP at:

www.iop.org/qubit

David Sang taught physics for 13 years. He has contributed to over 100 science textbooks.