THERMAL COMFORT

MASTERCLASS
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This month's article takes a few steps back to re-examine the fundamentals of 'operative temperature' to see how we can move forward with low-energy heating and cooling systems

As warm-blooded animals, humans produce their body heat internally. But this means that their internal organs need to be regulated within the fairly tight temperature range of 36.5C to 37.5C. If our core temperature drops below 35C, we suffer from hypothermia; and if it rises above 37.8C, we are said to be suffering from hyperthermia, sometimes called heat stroke.

Mild hypothermia is characterised by shivering and a loss of coordination. Severe hypothermia, where the core temperature falls below 28C, causes irrational behaviour and leads to death if unchecked. Nevertheless, people have recovered from profound hypothermia, with temperatures as low as 20C.

Hyperthermia is characterised by hot, dry skin, but the loss of mental faculty happens at a much smaller deviation from the norm than for hypothermia. By the time the core temperature rises to 40C, the condition is life threatening. Clearly humans are much more susceptible to overheating than to the cold. So we need mechanisms to lose heat to the environment in order to remain cool, but not lose too much heat or we become over-cooled.

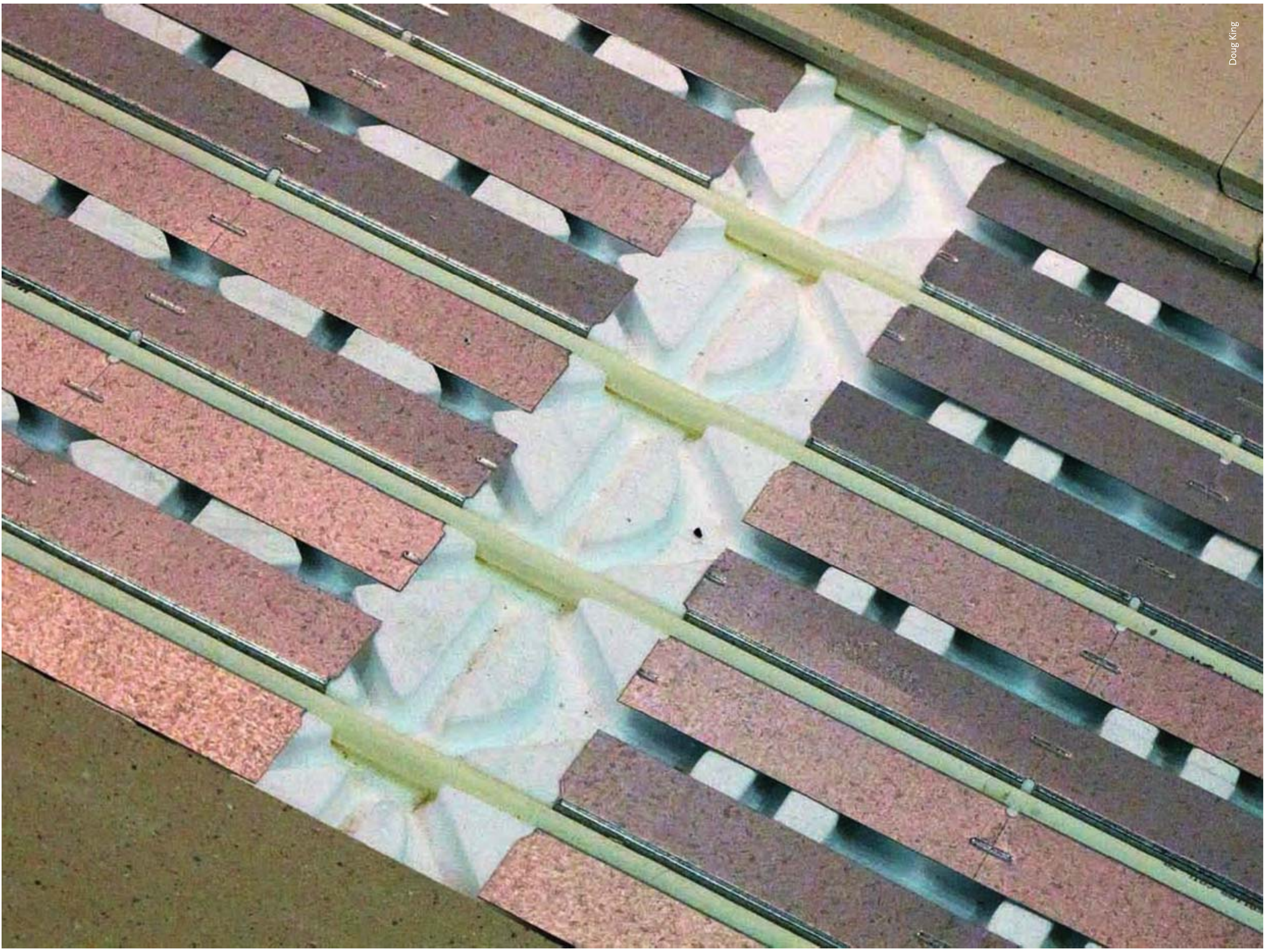
The human metabolism converts calories from food to energy in order for the body to function. Those calories that we do not use to do work, such as moving an object or moving ourselves, are converted into heat. We can lose heat to the environment through convection or conduction to the surrounding air, through radiant exchange with surrounding surfaces, and through evaporation of moisture from our skin and respiratory tract. The body has a number of mechanisms that automatically regulate our rate of heat-loss by these various means to maintain the correct core temperature.

If we get too cool we can increase our rate of heat generation or increase our level of insulation. Shivering is involuntary muscular activity designed to increase heat production. Vasoconstriction restricts blood flow near the skin to reduce heat-loss, and goose bumps appear when hair follicles contract in order to make the hairs stand up, trapping an insulating layer of air against the skin. We can also increase our clothing insulation, which is a cultural, rather than a biological, adaptation to the cold.

If we become too warm, vasodilatation increases the flow of warm blood to the body surface for cooling. Panting and sweating are both means of increasing heat-loss through evaporation of moisture, either from our respiratory tract or from sweat glands beneath the skin. The presence of liquid sweat on the surface of the skin is actually an indicator that this cooling mechanism is already overloaded.

Thus, in order to do full justice to our thermal adaptability, it is necessary to have an index for comfort that takes into account the rate of metabolic heat generation, clothing insulation, air movement over the body and the processes of heat transfer by radiation, conduction, convection and evaporation. The standard method for assessing thermal comfort with all of these parameters is the predicted mean vote (PMV).

One purpose of this Masterclass series is to look for simpler methods of analysis that can lead to insights about the design of building services. Thus, as most heating or cooling systems affect the sensible temperature rather than the humidity or air



velocity, it is useful to have a temperature-only index for thermal comfort. CIBSE now uses 'operative temperature' as the index for comfort to align with the ASHRAE and ISO standards, which is directly equivalent to dry resultant temperature, as follows:

$$t_c = \frac{t_r + \sqrt{1\ v}\, t_{ai}}{1 + \sqrt{1\ v}}$$

where t_c is the operative temperature, t_{ai} is the internal air temperature, t_r is the mean radiant temperature, and v is the air velocity. In this expression, $\sqrt{1\ v}$ represents the ratio of the convective to radiative heat transfer coefficients at the surface of the body. Thus, at higher air velocities heat transfer by convection dominates, but at very low velocities the primary means of heat transfer would be radiation.

In a room with no forced air movement – either mechanical or natural – it is assumed that the air velocity due to natural convection is 0.1m/s and so the expression for operative temperature simplifies to the following:

$$t_c = \frac{t_{ai} + t_r}{2}$$

This tells us that, for normal indoor design conditions, the air and mean radiant temperatures are equally important.

For buildings with lightweight finishes, which are heated or cooled with conventional systems that act on the room air, the air temperature, mean radiant temperature and therefore operative temperature are all likely to be similar due to the heating of surfaces by the air. This is probably why so many of us only consider air temperature for the majority of heating and cooling installations.

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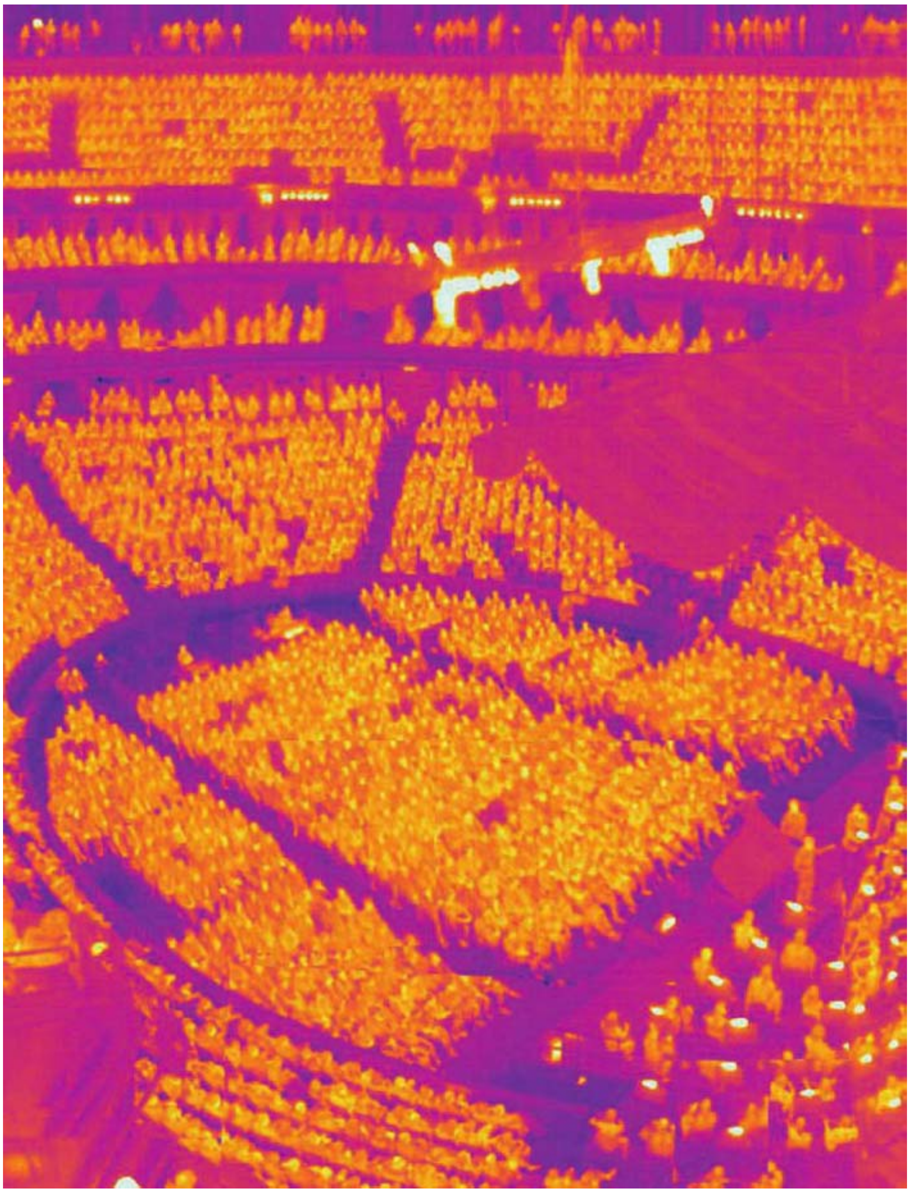
Embedded heating and cooling systems work by changing the surface temperature of building elements. The energy is transferred to the room environment by convection, conduction and radiation. Since occupants sense the radiant temperature of the surfaces, as well as the air temperature, this component of heat transfer can play a significant role in comfort, reducing the need to control tightly the air temperature



The importance of mean radiant temperature is well illustrated by the case of the Royal Albert Hall. This thermograph shows that, due to the unusual arrangement of the space, the internal surfaces are almost entirely lined with audience, with the same radiant temperature as each other. Thus, despite the hall having a chilled air supply, a feeling of thermal discomfort can arise due to the high radiant temperatures. The hall differs significantly from a conventional proscenium theatre, where the audience sits facing the cooler walls of the stage house and can therefore lose heat by radiant exchange

such as underfloor heating, it becomes essential that we consider the operative temperature. A large part of the heating or cooling output of surface systems, whether active or merely passive using thermal mass, is radiant, and therefore we cannot make any judgements about the comfort of the space by considering the air temperature alone.

In thermally massive buildings with passive night cooling it is not unusual to find the surface temperatures at the start of the day reduced to just above the diurnal average, around 20oC in summer. If sufficient fresh air is introduced at the outdoor condition during the day, the internal air temperature rise due to the sensible heat gains could be limited to a few degrees above ambient. However, the operative temperature under such a scenario would be the average of the air temperature and mean radiant temperature, significantly lower than the air temperature alone.

If the building's cooling system were operated under air temperature control, then the refrigeration plant would be started early in the day. However, recognising the contribution of radiant temperature in thermal comfort would delay the point at which refrigeration was necessary for several hours, or even allow passive cooling to meet the demand entirely.

Similarly, using large surface areas of floor or ceiling for radiant heating and cooling can influence the operative temperature in the room, even with air temperatures that are outside the traditionally accepted range. Since large surface area systems can be effective at much lower temperature differentials, these systems can be used to great effect with low temperature heating and high temperature cooling sources, such as heat pumps or even when using ambient sources, such as groundwater.

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Humans sense operative temperature, and most thermal modelling software outputs operative temperature results, but we don't yet control buildings on operative temperature. This is partly due to the difficulty in measuring mean radiant temperature, which varies with position in a room, but plenty of research work has been done on instruments that can measure operative temperature. It is about time that our controls industry started producing combined air and mean radiant temperature sensors. Even an approximation of operative temperature at a single point would be a substantial improvement over convective air temperature sensors, when it comes to controlling buildings with mixed heating and cooling sources. This small step would unlock a giant leap forward in the promised energy efficiency of surface heating and cooling systems and of passive thermal mass. **CJ**