Hot topic

Masterclass
Professor Doug King

In his second masterclass, Professor Doug King looks at how the natural thermal response of buildings can influence the design and control of HVAC systems

Doug King

An experiment to classify the thermal response of a TermoDeck slab being conducted at the University of Bath

We think we know what thermal mass is all about. After all, we use it to night-cool low-energy buildings. But how many of us stop to consider how a building's thermal response will impact on the building services systems that we subsequently design?

If we don't consider the thermal response as part of our system design, then we may get into trouble. The natural response of the building fabric can have a fundamental effect on the operation of HVAC systems, especially when these are close coupled to the mass, such as in underfloor heating or TermoDeck ventilation.

An easy way to understand the periodic thermal response of a building is to consider an electronic analogy: a simple circuit with a resistor and capacitor (RC) in series (see Figure 1) behaves in the same way as the thermal mass of materials in a building. In the analogy, the resistance to thermal conduction in a material is represented by the resistor and its heat capacity by the capacitor.

A step change to the input voltage (switch) causes current to flow through the resistor, building up charge on the capacitor. Thus, the voltage across the capacitor rises over time until it reaches the input voltage, whilst the current reduces as the inverse. Exactly the same can be observed if we change the temperature at the surface of a material. Initially, heat flows into the material and its temperature rises until it reaches equilibrium with the source.

Now, by adjusting the values of resistance and capacitance, we can tune the response, or time constant, of the RC circuit relative to the periodicity of the change in input (Figure 2). As we increase the time constant, the output waveform tends towards a saw-tooth, smoothing out the transients and delaying the occurrence of peak amplitude. The circuit is now acting as an integrator: its output is approximately proportional to the time since the last change in input, whilst its peak value is the amplitude of the input change.

Eventually, when the time constant is long enough, the capacitor does not become fully charged before starting to discharge again and the output becomes attenuated in amplitude. At this point the circuit is acting as a low pass filter, attenuating transients whose frequency is less than the response frequency of the >

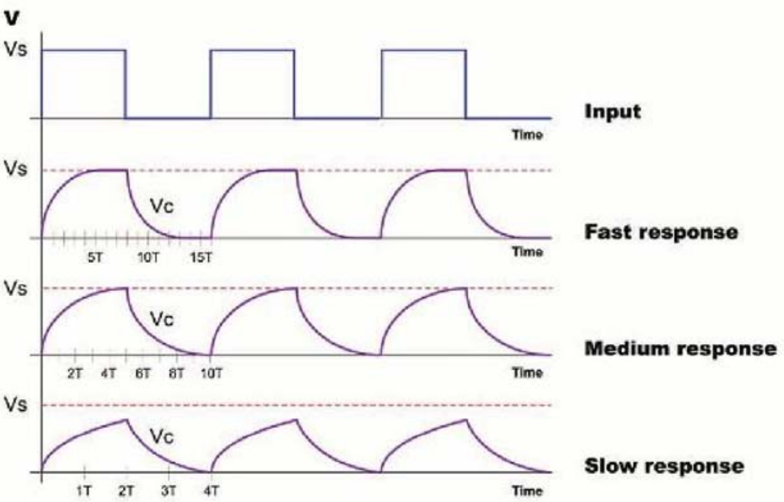

Figure 1: The simple RC circuit can be used as an analogy to thermal response in a building. When the switch is closed, current flows through the resistor to charge the capacitor. The Time Constant T = RC is the time for Vc to rise to (1-e-1)Vs

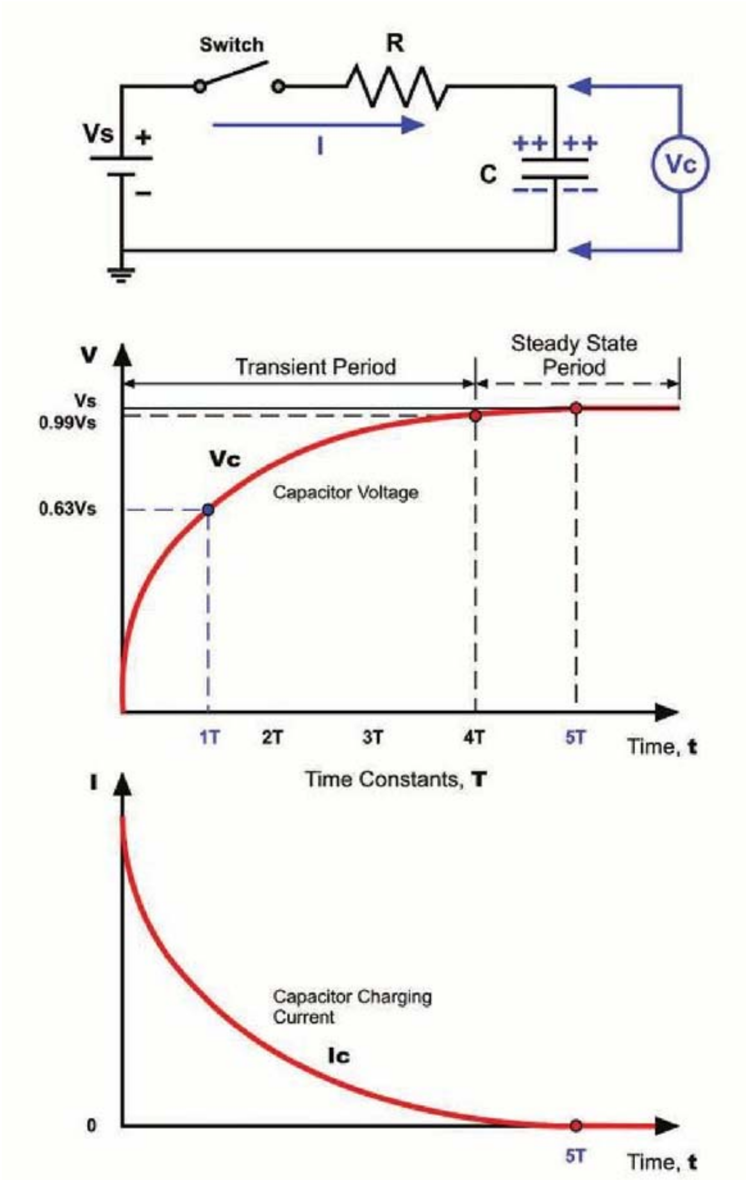

Figure 2: As the time constant (T) of the system increases the response to the input signal becomes slower. The system acts initially as an integrator and then as a low pass filter, attenuating signals of less than 5T duration

> circuit. At extreme the output voltage will become the time average of the input, a property that is used to smooth out ripples on DC power supplies.

We see exactly the same behaviour in buildings when we increase the thermal mass as we do by increasing the capacitance in the RC circuit. The natural response of the building begins to act as an integrator, delaying the rise in temperature. Should we be able to incorporate sufficient thermal mass, then we can not only reduce the peak temperature, but also delay the occurrence of the peak until the end of daily occupancy, thus further reducing the temperature rise experienced by occupants.

Ultimately, as we continue to increase thermal mass, the temperature of the building structure would tend towards the diurnal average of the space temperature as it filters out short-term changes.

Now, few things in nature produce square waves; furthermore, we may need to consider complex composite waveforms when multiple periods are involved, such as diurnal and seasonal variations in temperature. The effect of thermal mass on these analogue waveforms is essentially the same, but the analysis is more complicated and we'll come back to this subject in the future. For now I want to stick with simple step change inputs, such as the start and end of daily occupancy gains or switching cycles of HVAC plant.

The crux of the matter when it comes to designing HVAC systems is: if the natural response of the system is of the same order as the period of the change in the heating or cooling input, then the inertia of the thermal mass will act as an integrator. An integrator is a fundamental part of most HVAC controls but, if

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we don't allow for the natural integral effect of thermal mass, the combination can lead to the accumulation of very large errors and the loss of control.

This can manifest itself in many ways, from large temperature overshoots in underfloor heating systems, to the increase in overheating over a period of days with TermoDeck-like systems.

Some of the most difficult issues to identify often occur when refrigeration plant is coupled to high thermal mass systems, such as in ground-source heat pumps (GSHP) or embedded slab cooling systems. I am often asked to diagnose apparently intractable problems with the operation of chillers and heat pumps. GSHPs in particular are now sold almost routinely as plug-and-play devices.

However, the step control nature of most refrigeration machines can cause great problems if the hydraulic systems are not designed to account for the transients caused by the delay in heat transfer into the ground or into the slab.

In an underfloor heating system the primary heating circuit is highly tolerant to varying return water temperatures that result from the slow response of the thermal mass to a change in flow temperature. Refrigeration machines, on the other hand, are not at all tolerant to the spikes in return temperature that occur before the thermal mass has time to soak up the change.

If the natural response of the building significantly exceeds the periodicity of the control changes, then it will act as a low pass filter and we may not be able to control the temperature at all. This is not common, but can occur in extremely heavy buildings like churches, or where the heating or cooling system is actively coupled to the thermal mass as in TermoDeck or embedded slab heating or cooling.


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In an underfloor heating system the primary heating circuit is highly tolerant to varying return water temperatures

Such systems may have response times in excess of the daily occupancy period and so cannot be operated on a conventional daily on-off cycle. The thermal mass needs to be charged up to stabilise at close to the operating temperature before it will start to respond to control changes. To operate the heating or cooling on a simple occupancy cycle would result in the thermal mass filtering out such short term changes and instead tending to follow longer term swings in the ambient temperature. This may lead to a building becoming uncomfortable a few days into a hot spell, with no means of respite.

So, thermal mass is not just significant for night cooling in naturally ventilated buildings. We must ensure that we understand the natural response of the building fabric when designing any heating or cooling system. But we must also ensure that the controls design and the subsequent operation of the building also take account of the thermal response.

These issues will become ever-more important as we seek increasingly low energy solutions for buildings. We must ensure that we communicate our design intentions throughout the supply chain and inform the end users of our buildings how the natural response will impact on their experience of the buildings, and how to operate them to maintain low energy consumption.

If we do not do so, we risk installing systems which, while nominally of the correct capacity, may not actually be able to control the building to a comfortable temperature, or may result in excessive energy consumption to do so. ●

Doug King is principal of King Shaw Associates and visiting professor of building physics at Bath University. He was author of the Royal Academy of Engineering report, *Engineering a Low Carbon Built Environment*.