Energy efficiency and comfort

Chairman: Andrew Wilkes, Principal, Andrew Wilkes Management
Speakers: Doug King, Principal, King Shaw Associates
Colin Hamilton, Senior Partner, Max Fordham LLP
Dr. Darren Woolf, Arup Research and Development

Introduction: Andrew Wilkes

I'm an engineer and it appears that most of us in this session are engineers, so it's good to be in a room that's fairly cool compared with the others, which were extremely hot. An appropriate reminder when considering 'energy efficiency and comfort'. We also drank a lot of free water which was good for us!

We're here to talk about various aspects of how important building services are. If you've been at any of the other sessions, you'll have noticed that everyone's talking about how important services are to project management, to cost, to integration, to inter-relationships with the other professionals involved, and, of course, to the end users. So it's interesting that we've got the graveyard session here to go through this important subject.

We have three interesting speakers. Doug King is going to start us off with the basics. I'm very excited to announce that Doug King has just changed is career: he is now in his own practice, King Shaw. Previously he was with Buro Happold, and before that he was with Max Fordham, so he knows our second speaker, Colin Hamilton, very well. Then Darren Woolf of Arup Research is going to explain the possible development and extension of mechanical services using Computational Fluid Dynamics (CFD).

First speaker: Doug King

Let's consider the basics. Unfortunately, because the guys who are following me have got lots of pretty pictures of buildings to show you, it falls to me to try and entertain you with some very dry and uninteresting physics and psychological comfort factors in design.

I've loosely entitled this paper *Response as a Factor* because we've got to recognise that the heating, ventilation and air conditioning (HVAC) systems you put into a theatre are actually only about one-third of the operating system as far as the audience is concerned. The response factor of the audience is a very important part of the overall system, as is the response factor of the building. You ignore the first at your peril, and if you know how to use the second you can come up with some very energy efficient and cunning designs, some of which Glenn Howells was talking about earlier in one of the Architecture and Planning sessions, for instance.

So how do we typically go about the design of services installations in theatres? Mechanical and electrical (M&E) services engineers tend to be fairly hidebound by numbers. Numbers are easy to work with; they're easy to set down on paper and they're easy to put ticks or crosses against. So, unfortunately, the kind of criteria that are used for developing comfort in theatres have been generally based on comfort criteria derived from office-based work conditions. And when you think about it, you couldn't get much further away from a typical office-based working situation where you've got no choice over your working environment or really what you're doing, than, for instance, the Globe Theatre, where people seem to enjoy the experience of theatre regardless of the fact that the climate is not tightly controlled to comfort parameters.

Typical Design Criteria

Temperature	21±1°C
Humidity	50±10%RH
Air Movement	≤0.2m/s
Air Quality	<2.5% CO_2

Doug King is a building physicist and environmental engineer with broad experience in the design of low energy building services. Having developed new models for servicing a number of building types, he specialises in finding novel engineering solutions to complex design problems. He worked on the Savoy and Royal Court Theatres in London and has been contributing to the redevelopment of the Royal Shakespeare Company's theatres in Stratford upon Avon using low-energy design throughout.

Comfort – The Human Response

- Temperature
- Humidity
- Air Movement
- Air Quality
- Light Quality
- Activity
- Noise

- Quality of Show
- Proximity to Action
- Comfort of Seat
- Legroom
- Distractions
- Clothing
- Companion

So let's take our average audience member. Thermal comfort is not simply an issue of temperature; there are a whole range of issues that will affect somebody's perception of comfort, and therefore their enjoyment, above and beyond simple temperature and humidity. Obviously air movement contributes to thermal comfort. Air quality and light quality are much more imperceptible in their effect on people, but they still have a psychological impact. The activity that people are carrying out is probably one of the most important factors affecting comfort. If we consider people who are working in office-based environments, those working in a typing pool are far more likely to complain about poor environmental control or poor temperature control than those working in, for instance, their own private office. So your environment and your activity are very important psychological factors in your perception of comfort. And so is noise; the effect of noise on your comfort level is very, very subtle, but equally important.

We can extend that outwards, and have a look at comfort in relation to theatre. It's well recognised from research that's been done at the Royal Shakespeare Theatre and others that the number of complaints over comfort conditions in the auditorium relate directly to the critical acclaim for the show itself. The type of show is also likely to give rise to the variety and range of complaints that are received; comedies tend to be complained about less than dramas and tragedies.

So thermal comfort is only a very small part of the comfort equation, which in fact involves a whole lot of physical and psychological factors to do with the overall experience of theatre, most of which are actually dominant, and far, far more important than the control of temperature to within ±1°C.

We see this from the simple statistics that show that human beings are comfortable at different temperature ranges wearing

Winter Clothing: Suit, Dress and Jacket 20–21°C	Summer Clothing: Tee Shirt, Light Dress 24–26°C

different levels of clothing – which is really obvious! In the summer we dress lightly because it's warmer; it allows us to perspire, we can regulate our temperature more easily. In the winter people are dressed more heavily because it's colder outside, and simply that adaptive response of human beings to the external environment affects the temperature ranges at which they are comfortable inside a building at those times of the year. So again, it kind of explodes the myth that we should be controlling space temperature to within tight bounds.

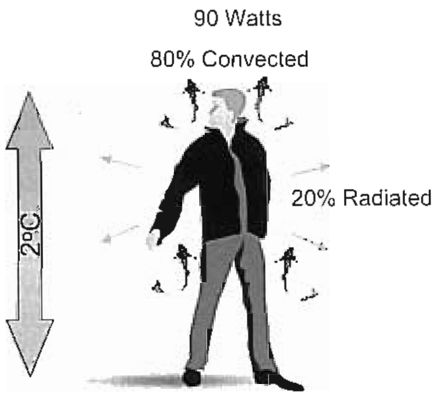
Other research which has come out of studies of workplace comfort is that allowing human beings a degree of choice and a degree of freedom also psychologically impacts on their perception of comfort. Allowing people to vary their environment, or take control of their environment, gives rise to a greater tolerance in temperature fluctuations. For instance, in an office-based environment, people who are engaged in a variety of activities rather than one single desk-based task are generally more tolerant of temperature fluctuations in a range up to about 4°C. That's 4° beyond what would be the comfortable temperature band for their clothing for the season. So these are factors that are all building on top of each other, and each time we incorporate these factors we move further and further away from the 22° or 20°±1°C temperature band within which services in theatres tend to be designed.

Going to the theatre is a special occasion, so you're already psychologically prepared, you're psyched up for the experience of the performance, which means that your expectation of the surroundings is going to be affected. Taking off a jacket in a

• **Special occasion**	**4.0° C**
• **Desk fan**	**3.0° C**
• **Dress for the occasion**	**2.5° C**
• **Open the window**	**1.5° C**
• **Interval drinks**	**1.0° C**
• **Choice of chair**	**0.5° C**

Possible temperature tolerances as a result of external factors.

workplace environment is normal, but going to the theatre is an occasion that people tend to dress up for. Therefore you can see that there's often a clothing response specifically related to going to the theatre. And many people will have a cold drink before the performance and in the interval. So there are lots of factors that we can relate to theatre visits from this kind of research to show again that people's response is not necessarily as we'd expect it. Also, I don't think we can do an awful lot about opening windows in theatres, or providing an individual choice of chairs, but there we go!

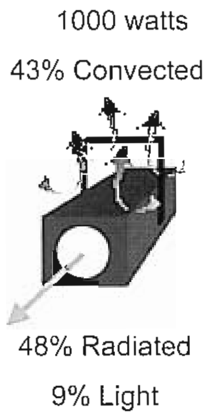


Let's go back to the audience members. A human being is a thermal system. We generate, typically, about 90 watts (W) of 'sensible' heat gain while we're at rest. 'Sensible' heat is the heat that raises temperature and is therefore perceptible, as opposed to heat that's lost by perspiration, which is evaporation. Seated at rest, as in a theatre or in our sitting around here at the moment, we're generally emitting about 90 W of sensible heat. Typically this is – and it varies enormously – about 80% convected off the body as a warm plume of rising air, and 20% which is radiated to the surroundings, depending on the relative temperature of the body and the surroundings, and the amount of clothing you are wearing.

There's another issue that relates very specifically to comfort of people, and that's that the air *in contact with the body* should be maintained at a relatively even temperature. Typically we find that 2°C difference between head and feet is tolerable, which is important when we're talking about ventilation systems.

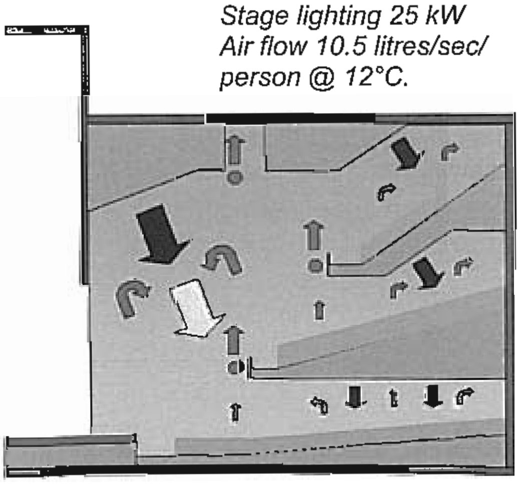
The other principal thermal system in a theatre auditorium is the technical installations. And the aspect that the M&E engineers get most excited about in theatre design is the stage lighting. The effect of a typical 1,000 W luminaire hung on a balcony front is considerable; nearly half of the heat energy of that luminaire is radiated along the beam line, and as the lights are pointed at the stage – which is after all the principle of stage lighting – then the thermal effects of that luminaire are actually radiated on the stage, not dissipated within the volume of the auditorium itself. What the engineers should be more interested in is the remaining half, which is convective energy from the casing of the luminaire, which is dissipated into the auditorium. If you do some quick comparisons; an auditorium of, say, 1,200 people which is two-thirds full, each person radiating 90 W each, is about equivalent to a 60 kW lighting rig running at full. So when you look at it in those terms, given that front of house lighting rigs of 60 kW very rarely burn continuously at full power, the thermal characteristic of the audience is far more dominant in the auditorium than is the stage lighting. And that's something which is not well understood by a lot of HVAC designers who are designing systems for theatres.

Let us consider the principles of ventilation by looking at a simple model auditorium and stagehouse shown below. We will concentrate on the auditorium volume because we're interested in the comfort of the audience here, not the comfort of the actors; that will have to be considered at a later Conference! We put the audience in as a heat source, and obviously we've got convection as the dominant thermal force that's rising from the audience. We put in other heat sources – the typical lighting locations – and within the auditorium what we're really interested is the convective heat load in that space. Remember that the remaining heat from the lanterns is generally radiated onto the stage area which, unless you're working in the round or with a big thrust stage, is generally within the volume of the fly tower. And if nothing else happens then, obviously, with all this convected heat you end up with a build-up of heat in the space and with stratification: we all know the simple principle, warm air rises.



Above: the heat dissipation from a typical luminaire and left: the heat dissipation from a typical person.

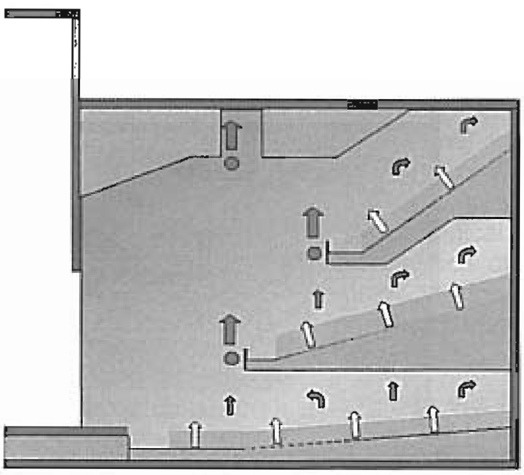
Ventilation principles – mixing system: Audience heat 100 kW Stage lighting 25 kW Air flow 10.5 litres/sec/ person @ 12°C.



Now we come to the problem. The typical design for HVAC in theatres, as developed from the 1920s through to the 1950s, was to provide overhead supply air from a roof-mounted ventilation plant, which process created mixing of the air in the auditorium space. You try and push cold air in at the top of this stratified space, and what you end up doing is entraining all of the hot air into your cold supply air and mixing up the whole auditorium to a more or less uniform temperature. Looking at the mathematics, you take your 100 kW of audience load, that's your 1,200 people at 90 W a person, you take your lighting rig, say 60 kW, 43% of that expressed as convected load in the space, and you end up with the kind of ventilation rates that we see over and over again in these types of buildings, of about 10½ litres per second (l/s) (22.25 cu.ft/minute, cfm) per person. Well, it's actually variable, between about 10 and 15, but it's the right ballpark with a supply-air temperature of about 12°C; absolutely typical.

If we stop trying to *fight* the thermal effects that are happening in the auditorium and *utilise* them instead, we can work on the displacement principle. In this case we introduce air at more spread locations, possibly at a higher temperature, underneath the audience, so that the direction of flow is now in the same direction as the convective flows, and we don't create the turbulent mixing that you'd expect at high level. This has the effect of basically displacing the convected warm air away from the audience and creating, if you like, bubbles of supply air throughout the audience-occupied zones.

Ventilation principles – displacement system: Audience heat 20 kW Stage lighting 0 kW Air flow 8 litres/sec/ person @ 20°C.



If you do the maths on that, we find that we're really dealing with the inter-radiated thermal effects on the people, which we recognised was about 20% of the heat output of a person. The rest of the heat will be convected away from the head and shoulders and carried away by the displacement air, so you're not dealing with that as a cooling load within the volume occupied by the audience.

Similarly, the lighting is all convective in this simple model, and therefore we are reducing the effective cooling load that we have to provide to about 20 kW, and if you look at the required air volume in plain, bald terms, you're talking about 8 l/s per person (17 cfm) at about 20°C. It's not a significant reduction in the air volume, because we've got to recognise the comfort requirement of the audience and this temperature gradient across the body.

Remember that this is all still working for a room design temperature in the occupied space of 22°C. But the big difference here is the supply air temperature, and the change in supply temperature from 12°C up to 20°C represents an enormous saving in cooling energy. In fact you're now down to levels of cooling where you can start to consider thermal mass cooling, as Glenn Howells was describing for various theatres he has done, using passive cooling effects in the mass of the building to provide a significant proportion of that cooling load.

If we accept the principle that human beings are actually comfortable in a wide range of temperatures, you can allow that range of temperature to fluctuate by season, and by show, and even by audience demographic, if you know your audience well enough. This is because you know that younger people are much more tolerant to temperature fluctuations than elderly people. When all these factors are taken into account, we are in a position to start talking seriously about cooling auditoria without the use of mechanical cooling, and potentially at much lower ventilation rates than 8 l/s (17 cfm), but you've got to know what you're doing in order to achieve this.

Thermal mass cooling is the popular buzz-word today in many fields of building engineering, not just in theatres. To remind us what thermal mass cooling is about, I think everybody understands that if you walk into a cave it's generally at about the same temperature winter, summer, night and day, and it's around about 15°C. The reason for that is that there is sufficient thermal mass. When we say 'thermal mass' we're actually talking about sufficient heat capacity in the rock and the ground surrounding the cave system so that any energy introduced into it, through lighting or through a flow of outside air into that space, is absorbed into the mass of the surrounding rock with an imperceptible change in its temperature.

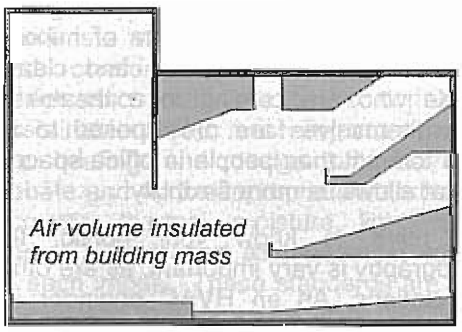
If we apply that to buildings and look at our model theatre again, it is probably cold after being left empty overnight and before the start of activities during the day. But in typical theatres architects are very keen on lightweight finishes – lots of drapes, lots of applied finishes to decorate the auditorium – and this tends to isolate the thermal mass of the building from the air inside the space. Therefore when you apply your heat sources, the air in the space heats up and, in the absence of any other effects, it just keeps heating up. And it heats up very quickly, because the capacity of air to hold energy without the temperature rising is very small. So with a very small amount of energy put into an air space the temperature rises very rapidly.

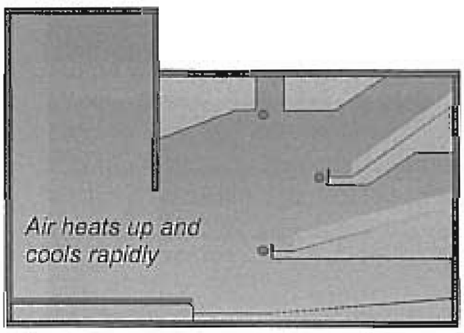
If we now consider the response to an applied heat load – and in a theatre we look specifically at intermittent loads because the duration of a performance is relatively short compared to a 24-hour period – the space-temperature responds very rapidly to these loads in a typical lightweight theatre auditorium. It responds equally rapidly at the end of the performance when the audience leaves, the lights are all turned off, and the temperature drops away again. This is shown in the top set of diagrams below.

If we take our cold auditorium but we eliminate all of these lightweight finishes and connect the air volume, that is the mass of the air space, to the mass of the building structure itself, we've got a very different proposition when it comes to putting heat sources into the space. Now when we put energy into the space it heats up the air. But we also have to heat up the structure of the building itself and, since the capacity of the structure of the building to hold energy is enormous compared to the airspace, a lot more energy can be put into the space for the same unit temperature rise. Conversely, for the same energy input the unit temperature rise is much smaller. That's the principle of thermal mass cooling.

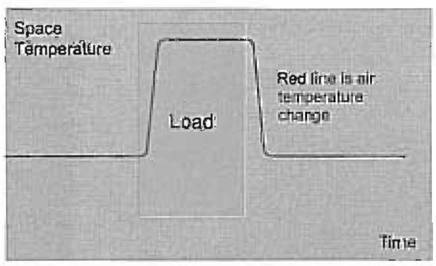
We are able to use thermal mass cooling based on this slow response. The building as a heating–cooling system, as indicated by the green line in the lower set of diagrams, responds much, much less quickly than does the air inside the volume. We find very often in an intermittent occupancy like a theatre that the building doesn't heat up to a great extent before the audience leaves again, the lights are turned off and it starts to cool down. So we can use that effect to, again, displace the cooling load.

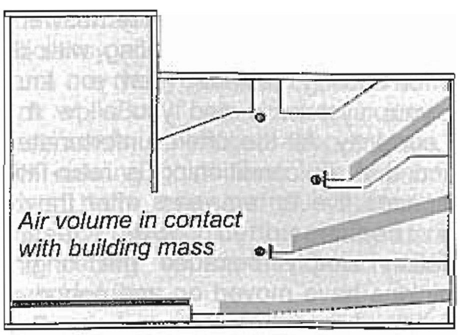
Now this is something that theatre managers actually understand empirically, but they don't recognise exactly what's going on. If you plot the typical profile of the load in a theatre space over 24 hours, you might start with some casual occupancy around about

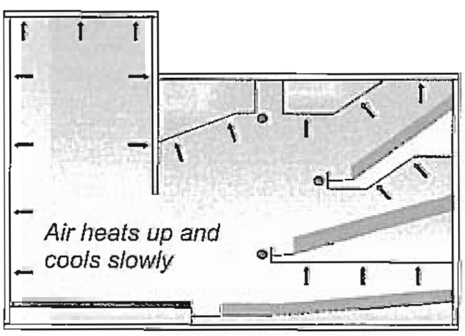




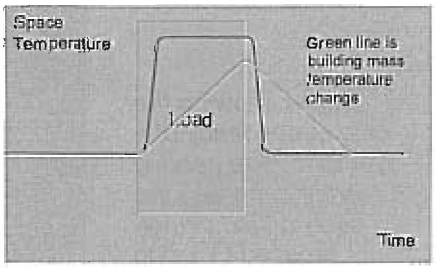
Top: auditorium with lightweight finishes.



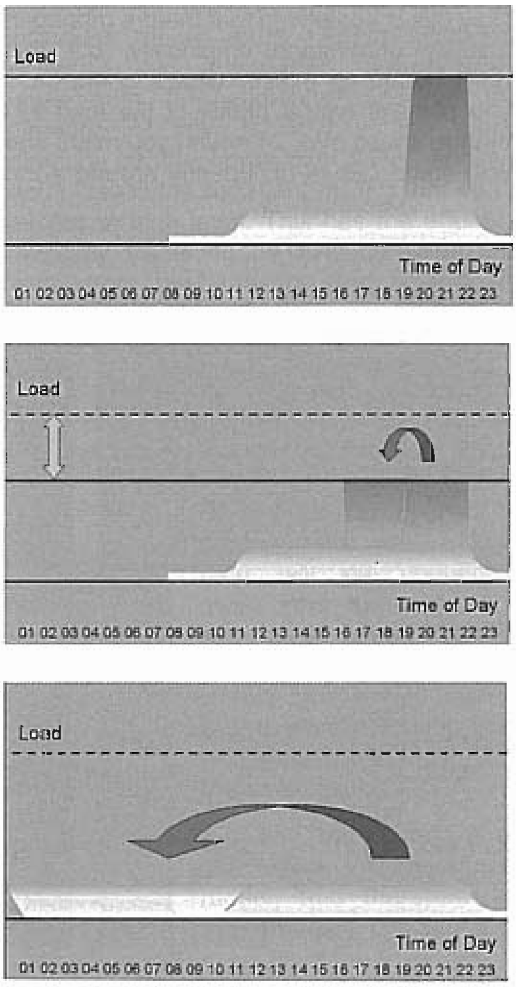




Bottom: auditorium with air in contact with building mass.



8 am with the cleaners coming in, and maybe activity in terms of rehearsals and onstage working begins around midday. This continues through to the early evening and then you get the big peak loads corresponding to a performance with audience in the space. Typically, that means that the HVAC designers size cooling systems for this peak load. They size them for the peak load of the maximum audience and the maximum lighting rig when everything's blasting on at once in the middle of the summer. Very few theatres are equipped with that level of cooling – certainly older theatres won't be – and a lot of theatre operators are familiar with having to deal with a shortfall in the cooling capacity of their installed plant. And the way they deal with this is by pre-cooling the building for a couple of hours before the audience arrives so that the auditorium is already cooled; it's got more ability to absorb energy and this keeps the temperature down during the performance. What they're effectively doing is displacing part of that cooling load in time and storing it in the thermal mass of the building.



Graphs showing the time dependency of a typical theatre heating load and the way the cooling load can be reduced by using thermal mass cooling.

Now if we understand that empirically – and a lot of theatre managers actually have to use this on a daily basis in order to maintain reasonably comfortable conditions in their auditorium – we can extend that idea. We can start to design the thermal mass of the building as part of the heating–cooling system, and we can take the entire performance cooling load and displace it by 12 hours. By displacing it and spreading it over a period of time we are making much lower demands on the quality of the energy that we're putting into the system. To provide air conditioning during a peak load performance requires really quite high-grade energy, for instance electrically operated chillers. If we spread that cooling load over time and store it in the building overnight, we can use much, much lower-grade energy, and in most instances we can actually use the cooling energy of cold night air and store that in the thermal mass of the building. And that's exactly the way that the Playbox, and the other theatres that Glenn Howells was talking about, operate in order to regulate the daytime temperature by thermal mass effect. Obviously the significant gain is in the grade of the energy and the amount of energy used in cooling the space.

There are a number of key points to recall from this, first of which is to recognise that comfort is a state of mind, and it's not strictly down to temperature. It's affected by a whole range of factors which can be influenced for better or worse. We can recognise that fact and use it to engineer more flexible buildings. State of mind is dependent on the situation, and clearly people who are coming to a theatre to enjoy themselves are predisposed to be more tolerant than people in office spaces, so that allows us more flexibility.

You have to know your public; the demography is very important, as are other expectations. As an HVAC engineer it's essential to obtain a proper briefing from the client or the theatre management. And air conditioning is not the only answer – there are other ways of dealing with the need for cooling, provided that you know what your system is and you allow it to work correctly. All too often, unfortunately, we find that air conditioning is retro-fitted into spaces five to ten years after they've been commissioned with passive ventilation simply because the original technicians have moved on and nobody in the building knows how to operate it. Ω