THERMAL MASS, INSULATION AND VENTILATION IN SUSTAINABLE HOUSING – AN INVESTIGATION ACROSS CLIMATE AND OCCUPANCY

Paul Tuohy[1], Lori McElroy[2] and Cameron Johnstone[1]
[1]ESRU, University of Strathclyde, Scotland
[2] SUST, Lighthouse Building, Glasgow, Scotland

ABSTRACT

Sustainable housing standards are reviewed including the UK 2005 building regulations, the UK Advanced Standard and EU Passive-house Standard. Conflicts between the standards are highlighted. The significance of insulation, orientation, ventilation, thermal mass, occupancy, gains, shading and climate on predicted energy performance is illustrated. An ESP-r model is then used to investigate these factors across a range of climates and occupancy / gains scenarios. The investigation covers both heating and cooling energy requirements. The relative importance of key factors is quantified and a matrix of results presented with conclusions. The role of simulation in informing design decisions is demonstrated as well as the importance of considering climate and occupancy / gains patterns.

INTRODUCTION

The latest revision of the UK building regulations is planned to be released in 2005 [SEDD, 2003]. In Scotland the 2005 regulations do not require an improvement in insulation over those established in 2002. The UK Housing Energy Efficiency Best Practice Program specify the UK 'Advanced' standard [HEEBPp, 2002] based on the previously specified 'Zero Heating' standard where floor, wall and ceiling constructions are of high thermal mass [EEBPp, 1996]. Well documented examples of 'Advanced' housing in the UK are BedZED [HEEBPp,2002(2)], Hockerton [HEEBPp,2003] and the Vale's Autonomous house [Vale B, R, 2002].

The ‘Passive House’ standard has been the subject of EU THERMIE project BU/0127/97 ‘Cost Efficient Passive Houses as European Standards’ (CEPHEUS). More than 1000 houses have been built and the project has monitored 250 across Switzerland, Germany, Austria, France and Sweden [THERMIE, 1997]. The passive house target is total final energy demand for space heating, domestic hot water and household appliances below 42 kWh/m^2 pa and space heating below 15 kWh/m^2 pa. There is no specification relating to thermal mass, passive houses have been realised in thermally light and thermally heavy constructions. The passive-house standard specifies that mechanical heat recovery ventilation is used.

Table 1
Comparison of Standards

Building Standards	UK Advanced Standard	Passive-house Standard	UK 2005 Building Regs.
Wall U	0.15	0.1	0.3
Floor U	0.1	0.1	0.25
Roof U	0.08	0.1	0.16
Door U	1.5	0.8	2
Glazing U	1.5	0.75	2
Air-tightness	1ac/h @50Pa	0.6ac/h @50Pa	No spec
Vent’n	PSV or a-PSV or MVHR	MHRV	Extract or PSV or MVHR or MEV
Mass (th)	High	No spec	No spec

Many Passive Houses are included in the IEA Sustainable Solar Housing demonstration houses [IEA, 2004]. The demonstration houses in Tuusniemi in Finland (lat 62N) are entirely lightweight construction. The houses in Goteborg in Sweden, Thening in Austria and Dinkton in Switzerland have low mass wall and roof constructions with high mass concrete floors (the Thening house also has underground air pipe ventilation cooling). The Hanover, Germany terrace housing has low mass external walls but high mass internal and cross walls. The southern Switzerland demonstration house has a thermally massive construction similar to the UK 'Advanced' standard. In general the amount of thermal mass increases the more southerly the location apparently driven by summer cooling.

Professor Brenda Vale and Dr Robert Vale are the authors of the UK 'Zero Heating' standard on which the UK 'Advanced' standard is based. The Vales had previously designed, built and lived in the super–insulated, high thermal mass 'Autonomous House' and their experiences are documented in 'The New Autonomous House' [Vale, 2002]. The Vales quote New Zealand experience that heating demand was reduced by 40% by the addition of thermal mass to timber frame houses through concrete floors.

David Finney (architect) reported in 'Building for a Future' on his experiences of design, building and living in his own high mass and low mass low energy homes [Finney, 2004]. The houses are built to approximately 2002 building regulations (England) with walls having a U-value of 0.35 W/m^{2}K. He quotes the Architects Journal: "computer simulation has suggested that, overall, a high inertia house will use at least 10% more energy, dependent on the level of insulation". He reports his experience that in the high mass house "more fuel was clearly required to 'charge up' and keep the high thermal capacity walls 'filled' if they were not to act as cold sinks".

CIBSE in their Guide F [CIBSE, 2004] state "a less thermally massive building would have shorter preheat periods and use less heating energy"

There have been several investigations published [Pollard et al, 1998, Thomas, 1999] on the influence of thermal mass and insulation on space heating (and cooling) across New Zealand temperature zones (latitudes 32 to 47) which show a beneficial impact of thermal mass that decreases with distance from the equator. The UK climate zone extends beyond the latitudes covered by these studies (lat 49 to 62).

The embodied energy and heat required to dry-out high thermal mass houses are concerns although it has been shown that in the whole life energy analysis the operational energy demand is the most important factor [Lazarus, 2002, Mithraratne, 2001].

The objective of this study is to resolve the conflicting views on the impact of thermal mass, ventilation and insulation standards on energy use for heating and cooling. This will be achieved through an investigation into the key factors driving operational energy demands across a range of climates and occupancy / gains patterns.

THE MODEL

Brenda and Robert Vale put forward a simple calculation model illustrating the role of thermal mass, insulation and ventilation, They illustrate this model by applying it to a representative section of their house which will be referred to as the 'Vales Room'. The theoretical Vales Room is very similar to the test buildings being used by UCLA to investigate thermal mass and ventilation for cooling in the Californian climate [LaRoche, 2004].

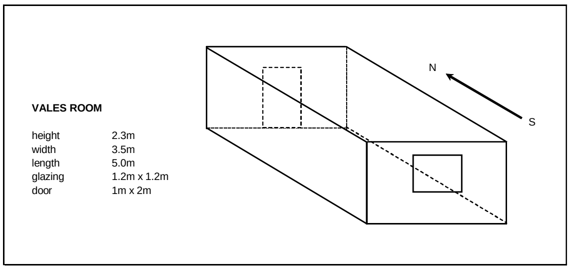

Figure 1 The Vales Room

The basic argument behind the construction of the Vales 'Autonomous' house on which the UK 'Advanced' standard is based is that the, good insulation and heat recovery ventilation minimise heat demand while the thermal mass allows any heat gains to be captured and become useful heat when required. The Vales model suggests that a low loss building (0.1 W/m^{2}K) of heavy thermal construction (16.56 MJ/K thermal mass) with heat recovery ventilation (0.21 effective ac/h) at an initial temp of 21 degrees can survive 0 degree external temperatures for 1 week without requiring heating. It is postulated that this storage capacity can allow a building to survive cold spells without requiring heating. This assumes that throughout the cold season the gains and ambient temperatures allow the mass to stay sufficiently charged so that heating is not required, this is obviously dependent on insulation, ventilation, occupancy / gains and climate. Similarly the simple model indicates that the high mass building has an increased capacity to maintain comfortable temperatures in times of high external temperatures when compared to a low mass equivalent.

Some negative aspects of thermal mass can also be postulated from this simple model. Gains may be highest when the occupants are in residence, in the high mass house the gains do not transfer as directly into increased temperatures but will be partially absorbed in the fabric. During periods without occupation the high mass house will maintain a higher temperature than the low mass house and hence loose more heat than a low mass house (driven by the higher temperature difference to the outside temperature) and therefore require more heat to re-charge.

This simple model illustrates some principals of thermal mass but does not allow detailed analysis of realistic heating and cooling requirements for comfortable temperatures in real climates. For this a more sophisticated model is required, for this study ESP-r was the simulation tool of choice.

An ESP-r ‘Vales room’ was created with both low and high thermal mass constructions representative of standard construction techniques. For the low mass construction only low mass elements are within the insulation envelope (plasterboard, softwood, carpet etc.). For high mass the concrete elements are inside the insulation envelope and connected to the room air. For each construction type the insulation thickness was varied to represent the different insulation standard to be investigated (Insulation standards labelled: ‘0.45’ = ‘1999 regulations’, ‘0.3’ = ‘2005 regulations’, ‘0.1’ = ‘Advanced’).

Table 2
Construction details

Element (thick in m)	Low Mass	High Mass
Roof	* insulation .013 plasterboard .003 plaster	* insulation .150 re-concrete .008 plaster
Walls	* insulation .013 plasterboard .003 plaster	* insulation .100 conc block .012 plaster
Floor	.100 concrete * insulation .0075 softwood .0050 carpet	* EPS insulation .150 concrete .010 clay tile

THE HEATING INVESTIGATION

To investigate the impact of thermal mass, insulation and ventilation on heating demand across climates and occupancy/gain scenarios the matrix of simulations shown below was carried out for the ‘Vales Room’. This matrix was replicated for three different ventilation strategies and for a north facing room to investigate the influence of solar gain.

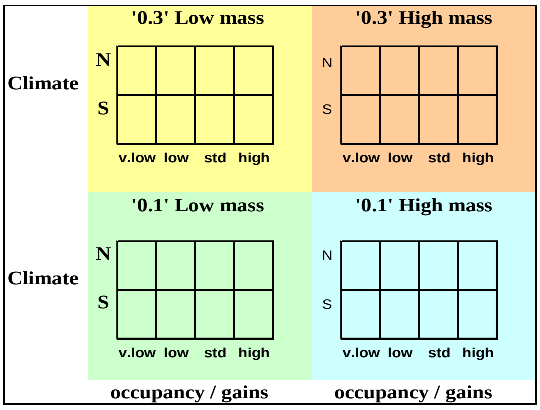

Figure 2 Heating investigation matrix

The climates available in the ESP-r database were reviewed and the Jersey (lat 49.2) climate file selected to represent a southerly warm winter climate, the Copenhagen (lat 55.6) climate file was chosen to represent a northerly cold winter climate. Full simulation was carried out with 30min time-step from July through to the end of December and this data used to project annual heating energy usage.

Four occupancy / gain scenarios were defined as follows: very low (weekend occupancy only, low gains, free float when unoccupied), low (low occupancy, low gains, float when unoccupied), standard (standard occupancy, standard gains, float when unoccupied), high (constant occupancy, high gains, night setpoint at 17deg). The heating was ideally controlled during active occupied periods to maintain air temperature at 21 deg. Heat delivered was assumed to be 100% convective. The gains from occupants, lights, appliances, cooking and hot water used were from the Vales book. These values were cross referenced against SAP2001 typical data [BRE, 2001] and found to be in good agreement.

The baseline ventilation rate was set at 0.45 ac / h. The 0.45 ac/h ventilation rate was chosen as the normal level for advanced houses [Vale, 2002] and is also close to the 0.5 ac/h given by SAP2001 for very airtight dwellings naturally ventilated. The 1 ac/h rate was selected to represent an increased ventilation scenario where occupants desire more airflow, 1 ac/h was in the past a recommended ventilation rate for dwellings. The 0.21 ac/h ventilation rate was chosen as it was used in the Vales calculations to represent the thermal air change rate for a house with MVHR. In all cases the ventilation air source was assumed to be at the ambient outdoor temperature.

To simulate the effect of occupant use of shading and cross ventilation for avoidance of overheat during warm periods the room was ideally cooled if above 23deg during occupancy and if above 25deg when unoccupied.

Some additional investigations were carried out e.g. 1999 regulations (‘0.45’) in northerly climates.

HEATING INVESTIGATION RESULTS

Detailed operation:

The figure below shows the full timeframe plot for low thermal mass Advanced (0.1) construction for the standard ventilation and occupancy / gain scenario in the Copenhagen climate. The heating season starts on 1st November and peak heating load is 0.5kW. The results for the 2005 regulations (0.3) construction are 23rd Sept and 1.6kW respectively.

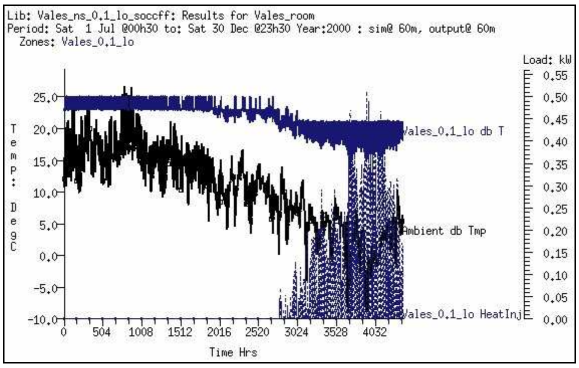

Figure 3 Full timeframe plot

The graph below illustrates a northerly October day with high direct solar gain followed by one with only diffuse gain for a low thermal mass house with low occupancy / gains built to the 2005 building regulations. For the second heating period (16-22 hours) the low thermal mass room air and wall surfaces have been heated to almost the demand temperature by the solar gains and so the low mass house requires less heating than a high mass house where the solar gain resulted in a smaller change in temperature. Overall the heating required for the low and the high thermal mass buildings for the two day period are 3.35 kWh and 3.82 kWh respectively.

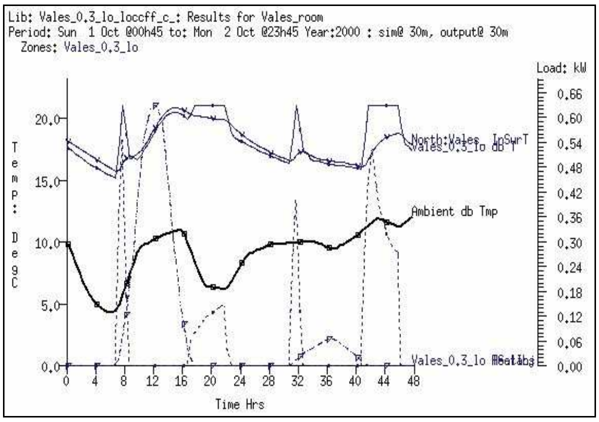

Figure 4 Two October days, low mass

Throughout the heating evaluation the results were reviewed for thermal comfort of occupants using the embedded Percent Mean Vote (PMV) and Percent of Persons Dissatisfied (PPD) metrics which are documented in the ASHRAE Fundamentals Chapter 8 'Thermal Comfort' [ASHRAE, 2001] and are used as a standard. The clothing level was set at 0.7 Clo to represent normal winter indoor clothing (no jumper) and the occupant activity level was set at 1.5 MET (or 87W) to represent a mix of sedentary and light activities. The values that are deemed acceptable when the house is occupied and the occupants awake is within +/- 5 PMV (or <= 10% PPD) for perfect comfort and within +/- 1 PMV (or <= 26% PPD) for a slight discomfort but acceptable comfort level. The graph below shows the PPD, db temp, surface temp and ambient temperature for the '0.3' insulation standard house with low occupancy and gains in the northern climate for two cold days in December.

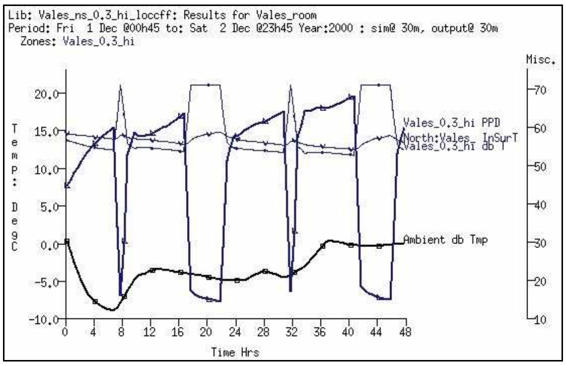

Figure 5 Thermal comfort

These examples illustrate the various mechanisms which contribute to the heating demands of the buildings and the show the importance of analysing using a complex model and detailed climate data. The next section looks at the summary statistics for the full matrix of simulations over the heating season.

Summary statistics:

In this section the cumulative heating demand in kWh/m^2 pa is compared for the different cells of the experimental matrix where the room is south facing and the ventilation is 0.45ac/h.

The graphs below show the annual heating energy requirement in kWh/m^2 p.a. for each of the occupancy / gain scenario's. (X-axis key: insulation standard, thermal mass, climate i.e. Copenhagen or Jersey). It can be seen that climate and insulation standard have consistent effects where the effect of thermal mass varies with insulation standard, climate and occupancy / gains.

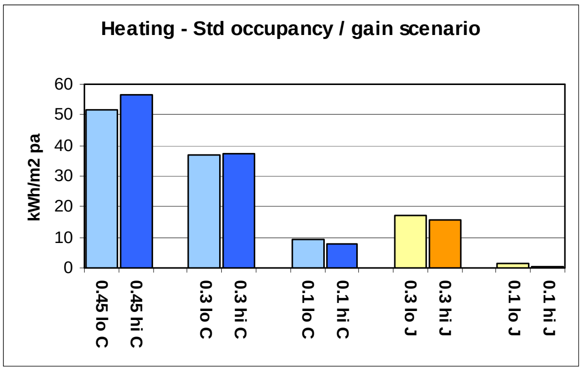

Figure 6 Heating, Std occ/gains scenario

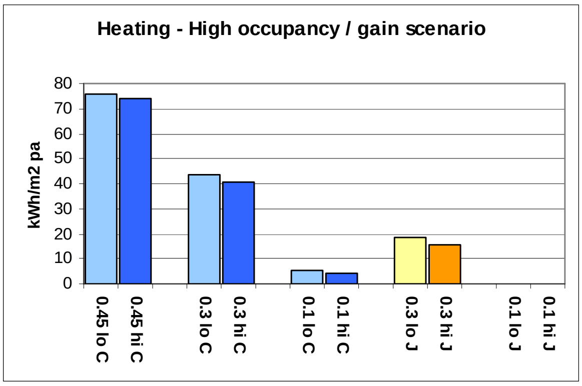

Figure 7 Heating, High occ/gains scenario

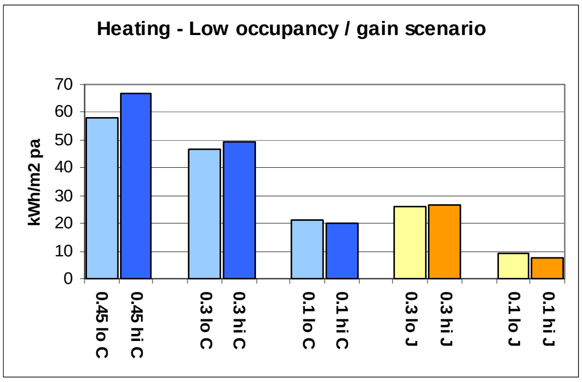

Figure 8 Heating, Low occ/gains scenario

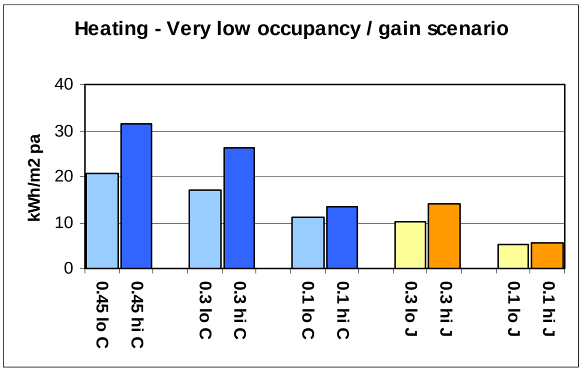

Figure 9 Heating, Very Low occ/gains scenario

The table below summarises the impact of thermal mass on heating demands. The percentages represent the difference in heating requirement between thermally low and high mass constructions as a percentage of the heating required by the low mass house i.e. [{Heat(hi) – Heat(lo)}/Heat(lo)]*100%. In this table differences only differences > 6% are shown.

Table 3
Impact of thermal mass on heating energy

Building Standard	Climate	Demand / Gain Scenario			
		V low	Low	Std	High
1999 Regs (0.45)	North	52%	15%	10%	
2005 Regs (0.3)	North	53%			-7%
UK Adv (0.1)	North	20%		-12%	-19%
2005 Regs (0.3)	South	41%		-8%	-14%
UK Adv (0.1)	South		-14%	-60%	-100%

The heating investigation matrix was repeated for the 0.21ac/h (MVHR) and 1ac/h ventilation rates, as expected the ventilation rate had a large effect with the effect being greater in the more highly insulated houses. Only the 0.21 ac/h case consistently meets the 15 kWh/m^2 pa passive house standard.

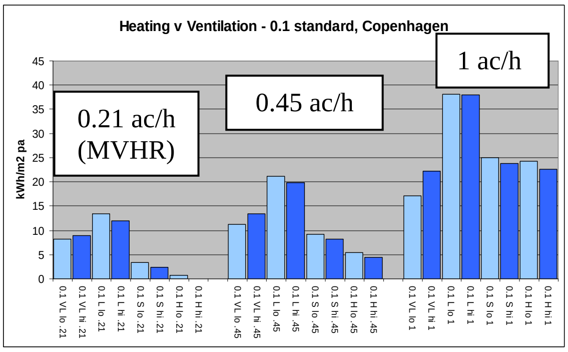

Figure 10 Impact of ventilation

The matrix was also repeated for the north facing Vales Room. Solar gains supplied less than 10% of the heating load in the northern climate and around 20% in the southern climate.

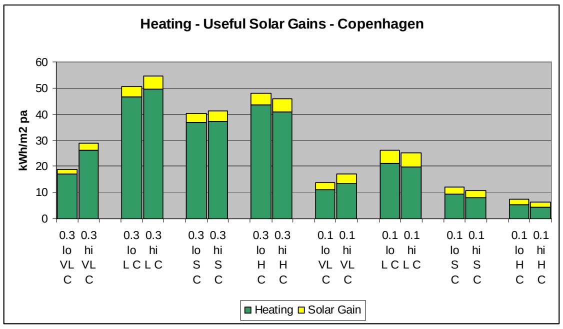

Figure 11 Impact of solar gains

When the results are averaged across the occupancy scenarios and compared to a 2005 regulation (wall U-value of 0.3W/m^2K), 0.45ac/h, south facing baseline the impact of the different factors on heating demands are shown below. For the northern climate the base case requires 36 kWh/m2 pa space heating energy while the same case in the southern climate requires only 18 kWh/m2 pa. Improving insulation to 'Advanced' standard has the largest positive effect while control of ventilation is also a primary factor. The orientation also has a significant effect. On this averaged analysis the effect of thermal mass is small.

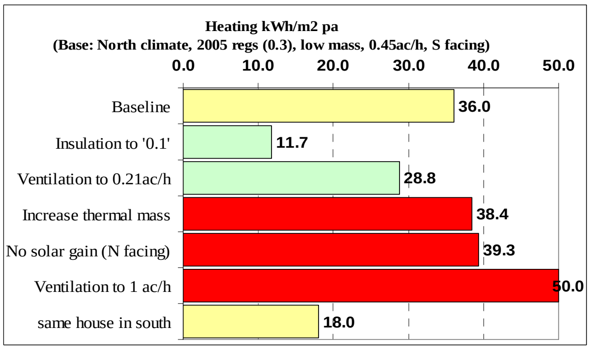

Figure 12 Impact to Heating (N ‘0.3’ base)

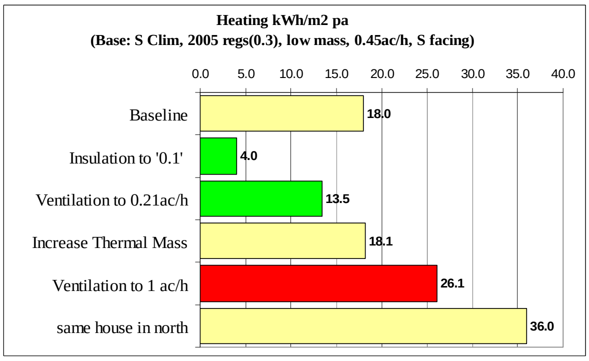

Figure 13 Impact to heating (S ‘0.3’ base)

Similar analysis was carried out against an ‘Advanced’, 0.45ac/h, south facing baseline yielding similar trends although relative effects against the lower ‘Advanced’ baseline were larger.

COOLING INVESTIGATION

A second room was created with a 1.25m shade overhanging the south façade. In practice this shading element could be realised as a roof overhang, balcony or purpose built shade.

A third room was created to simulate the window covered by an opaque shutter. This case was realised by replacing the window with an opaque wall element with the same U-value.

Initial investigations confirmed that the ‘Standard’ occupancy / gain scenario (daily occupancy, average gains) and ‘High’ occupancy / gains scenario (constant use, high gains) used for the heating evaluation were worst case for summer overheating and these were used in the cooling investigation.

Two ventilation patterns were investigated, the first labelled ‘summer ventilation’ is a constant 4.5ac/h which is to represent windows constantly open, the second labelled ‘night cooling’ is 4.5ac/h from 6pm until 8am and 0.45ac/h during the day between 8am and 6pm which represents windows mainly opened during the cooler parts of the day. Both of the evaluated ventilation schemes are simple and designed to represent normal practice by occupants.

The available climate files in ESP-r were analysed and the Birmingham (lat 52.5) and Paris (lat 48.7) climate files used for the study of summer cooling simulations These climates were then used to infer performance in other cooler climates.

COOLING INVESTIGATION RESULTS

The maximum temperatures should be viewed in the context of the comfort of the occupants. The ASHRAE Fundamentals chapter 8 [ASHRAE, 2001] on thermal comfort gives the maximum summer comfort level as around 27 degrees (dependent on humidity). However it is also reported that when external temperatures are elevated then internal temperatures up to 28 - 28.5 degrees can be tolerated without discomfort [Evans, 2003].

The tables below show the maximum dry bulb temperature experienced for the 3 different ‘Vales-rooms’ (south window exposed, shaded and shuttered) for the case of the 2005 regulations insulation levels (0.3), Birmingham climate and the standard occupancy / gain scenario.

Table 4
Peak temperature, high thermal mass

south window solar exposure	high thermal mass	
	sum vent	night cool
Exposed	27.5	27
Shaded	26.5	25.5
Shuttered	25	24.5

Table 5
Peak temperature, low thermal mass

south window solar exposure	low thermal mass	
	sum vent	night cool
Exposed	31	33
Shaded	29	29.5
Shuttered	28.5	28

It can be seen that the high thermal mass construction maintains dry bulb temperatures within the comfortable range but the low mass construction suffers from overheating. Both shades and shutters have a significant positive effect. This analysis was repeated for the different insulation levels, occupancy / gains scenarios and Paris climate. Results showed similar trends. The '0.1' results were similar to the '0.3' case above. The Paris climate or high occupancy gains add around 1 degree to peak temperatures. Full results of the cooling study are in the thesis of this author [Tuohy, 2004].

The responses of the thermally light and heavy constructions are shown below for the Advanced construction, summer ventilation case.

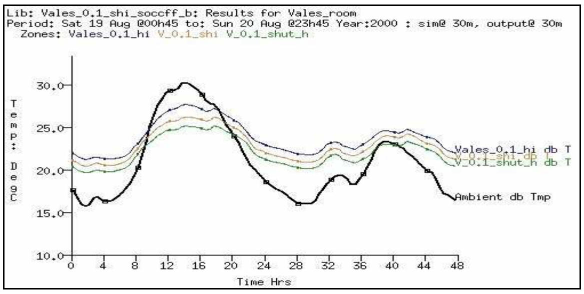

Figure 14 Peak temp, high thermal mass

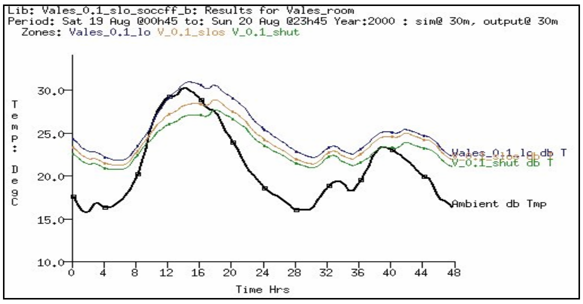

Figure 15 Peak temp, low thermal mass

Analysis of the ESP-r climate database and also the CIBSE documentation [CIBSE, 1997] indicates that temperatures >25 degrees are rare in northern UK but have historically occurred up to 2.5% of the time in southern UK. Predicted climate changes could lead to increased occurrence in future.

DISCUSSION

The successful UK high thermal mass low energy houses (Vales Autonomous, Hockerton, BedZED) are all super-insulated to advanced standards, have heat recovery ventilation and are situated in the southern half of the UK and so fit within the parameters where high thermal mass gives reduced heating demand.

The passive heat recovery ventilation of BedZED would appear to have some potential benefits over the mechanical systems at Hockerton and the Autonomous house in terms of electricity requirement .

The Passive House standard of < 15 kWh/m2 space heating through super-insulation and MVHR appears achievable across all occupancy / gain scenarios and UK climates for both high and low mass constructions in this study.

The results are consistent with the New Zealand heating studies which showed that in lower latitudes (Auckland, 37 deg) there is a significant benefit of high mass but at higher latitudes (Invercargill, 47 deg) the benefit becomes relatively smaller. In this study it has been shown that at higher latitudes than New Zealand there are cases where high thermal mass gives a space heating penalty.

The high mass house in the 2004 Finney article was built in 1976 to standards looser than the 2005 regulations, this property was also stated to have significant cold bridging, in contrast the 1998 low mass house was closer to the proposed 2005 regulations, the experience of the high mass house requiring more heating is consistent with the finding that high mass houses with poorer insulation require more heating. The Architects Journal article [Burberry, 1974] indicating high thermal mass buildings consume >10% more heating energy was based on construction standards of that time and ventilation rate of 2 ac/h. These results are not applicable to modern buildings.

The CIBSE Guide F advice that intermittently heated higher mass buildings use more heating energy also appears not to be appropriate to the majority of cases.

The IEA demonstration houses range from thermally light timber frame, through light frame with concrete flooring to the heaviest which have multiple high mass elements. The trend is towards higher mass in more southerly climates for purposes of cooling.

For the southern UK climate high thermal mass combined with shading or shuttering can maintain comfortable internal temperatures and avoid summer overheating even on days when the external temperatures are above those for conventional ventilation cooling. Low thermal mass construction can be somewhat marginal for comfort in these conditions even when shuttered. The low mass building could lead to increased probability of adoption of air conditioning .

Table 6
Indicated constructions

UK climate region	Building Reg's	Type of construction indicated by 'Vales room' with 100% convective heat delivery and ideal control (Heating (H) or Cooling (C) benefit in brackets)			
North	0.3	Low mass (H)	Either	High mass (C)	High mass (H,C)
	0.1	Low mass (H)	Either	High mass (H,C)	High mass (H,C)
South	0.3	Either	High mass (C)	High mass (H,C)	High mass (H,C)
	0.1	Either	High mass (H,C)	High mass (H,C)	High mass (H,C)
Occupancy / Gains Scenario		Very Low	Low	Standard	High

Overall for the 'Vales Room' modelled in this study the optimum construction type indicated is shown in table 6 above for 2005 and Advanced insulation standards.

The 'Vales room' used in this study has demonstrated the effects of the chosen factors on heating and cooling requirement of this representative structure.

It is strongly recommended that energy simulation of proposed housing designs for intended occupancy, gains and climate should become a requirement.

CONCLUSION

Key factors influencing space heating energy use in sustainable housing have been analysed and their relative impact assessed across a range of climates and occupancy / gain scenarios.

Insulation standard, ventilation strategy and orientation have consistent effects on heating energy requirements while the effect of thermal mass varies with insulation standard, climate and occupancy / gains scenario.

Thermal mass, ventilation, shading and shuttering are shown to have a large influence on summer peak temperatures with high thermal mass construction having a consistent beneficial effect.

1-size fits all guidelines have limitations in their applicability and can become obsolete and outdated.

This study has demonstrated the role of simulation in informing design decisions and the importance of considering climate and occupancy / gains patterns in sustainable housing design.

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