Advanced glazing systems
and the economics of comfort

The Code for Sustainable Homes (CSH) was introduced in December 2006. The CSH is structured over six levels; level six being a net-zero carbon home. Given the comparative cost of renewable energy sources, the PassivHaus standard is arguably the most cost effective means of achieving CSH levels 4-6. Danny Harvey and Mark Siddall examine how our glazing system may cope ...

Residential buildings that are built to a high thermal standard, such as required by the PassivHaus Standard, the AECB's CarbonLite or the Code for Sustainable Homes, will require a more expensive thermal envelope as greater amounts of insulation and higher-performance windows will be required. These extra upfront costs will be offset, to some extent, by the reduced size and cost of the space heating plant. By considering building design in a holistic manner and rationalising the mechanical systems (ductwork for forced-air systems, plumbing for hydronic systems, and radiators) in such a manner as to minimise the length of service distribution routes, and in some cases even omit radiators, significant savings can be made in materials and labour[1].

Perimeter heating units, such as radiators, are used traditionally to counteract the cooling effect of glazing so by adding high performance glazing, therefore, we could conceivably eliminate the need for these completely and gain further savings. Further advantages of eliminating perimeter radiators are:

i) radiant heat losses through the external envelope are increased from perimeter radiators
ii) air temperatures above the heating unit next to the window would be greater than the average room temperature, thus leading to greater heat losses.

With these points in mind it is worth paying greater attention to window design and choice.

Windows are normally a large source of heat loss from a building, and as a consequence, windows with the greatest heat loss will have lower inner-glazing temperatures. In the absence of perimeter heating the temperature of the inner side of the innermost glazing surface will, on a cold winter's day, be sufficiently cold to cause thermal discomfort.

Cold inner window surfaces are undesirable for three reasons:

i) they create a sensation of coldness through radiant asymmetry
ii) they can cause downdrafts of cold air
iii) they can cool the air in contact with the window enough to cause condensation.

It is for these reasons that it is generally recommended that radiators or heating vents be placed at the base of the windows. Therefore, in order to permit the relocation, or even removal, of perimeter heating, the U-value of glazing needs to be reduced to a point whereby higher radiant temperatures can be achieved and downdrafts may be avoided, thus ensuring thermal comfort.

Establishing the boundaries for health and comfort

There are many aspects to the concept of comfort but thermal comfort may be considered to be of particular importance. Research by a Danish scientist, P O Fanger, helped to define the range of comfort criteria established within *ISO 7730: Ergonomics of the thermal environment*. Though some of Fanger's comfort criteria have now been challenged (mainly in relation to adaptive comfort conditions; particularly the temperature ranges that are considered an acceptable summer temperature range), most of the work is still considered to hold true; indeed, much of the work by the PassivHaus Institute is derived from these criteria.

The perception of temperature by the occupants of a building depends not only upon the air temperature and its velocity, but also on the emission of infrared radiation from the surrounding surfaces. The latter, in turn, depends on the temperatures and emissivities of the surfaces enclosing the occupied space, including window surfaces. If one surface, such as a window, is much colder than other surfaces (such as interior walls), this creates a radiant asymmetry. Human subjects also emit infrared radiation, and if the emission by humans is greater than the emission by the surrounding surfaces and its subsequent absorption, this will create a sensation of coldness even if the air is warm. Indeed, for calm conditions, the perceived temperature is close to the average of the air temperature and the average radiant temperature of the surroundings. In the following paragraphs, we discuss the implications of these phenomena for allowable window inner-surface temperatures.

Radiant temperature

Fanger's work permits a radiant asymmetry of up to 5°C. In this context it is worth noting that a small window, say less than 2.1m high, will have less of an impact upon radiant asymmetry when compared to a larger window with the same U-value. This is due to the simple fact that as the glazed area decreases the internal elevation will witness a proportional increase in the area of insulated wall. As a consequence, a greater permitted temperature difference between pane temperature and wall temperature may be possible whilst maintaining radiant comfort.

Studies by the PassivHaus Institute have led to a set of criteria whereby the maximum temperature difference between the inner surface temperature and indoor air temperature is less than 3°C when the external conditions are –10°C [2]. As a consequence, at an internal air temperature of 20°C the radiant temperature would be no less than 17°C[3]. The PassivHaus Institute's adoption of the 17°C comfort criterion for windows is no doubt influenced by the need to ensure that downdrafts are appropriately considered.

Downdrafts

The development of downdrafts arises from the density difference between cold air in immediate contact with the window, and adjacent warmer air. The downdraft velocity of cold or cool air increases as the temperature difference, and/or the height of the window, increases. The downdraft is thus the cumulative effect of heavier air summed over the height of the window.

To assess the impact of downdrafts upon comfort criteria, the PassivHaus Institute has undertaken fluid dynamic analysis of glazing systems with a total height of 2.1m, a height that may be considered typical for a low energy house. Studies by Schnieders[4] and Pfluger[5] assessed external temperature conditions between –14°C and –16°C, rather than the -10°C design-day that is more usual for the central European climate, and determined that U-values <0.85W/m²K are acceptable where the internal temperature is 20°C[6].

The studies found that an inner pane surface temperature of 16°C (i.e. a 4°C temperature difference between the window and room air) results in a downdraft velocity of 0.11m/s at 0.1m from the window. *ISO 7730* states that when air has a velocity of 0.08m/s, less than 6% of people will feel a draft, and at less than 0.15m/s comfort criteria will be met. On this basis it can be concluded that a pane temperature above 16°C will achieve a very high degree of comfort; in fact this reportedly achieves ASHRAE Comfort Class 'A'[7].

Pending further information becoming available, the authors can only assume that when conditions allow a radiant temperature of 17°C the downdraft temperature will fall within the *ISO 7730* criteria. Using Computational Fluid Dynamic Analysis[8] Pfluger noted that, in a sufficiently airtight room, if the difference between the mean radiant temperature and the air temperature is less than 4.2°C then no air velocities will be above 0.09m/s thus ensuring that an excellent comfort range is achieved.

Recent PassivHaus studies pertain to windows that are 2.1m high, so as far as downdrafts are concerned, either a larger temperature difference, and thus higher U-value, would be permitted for less vertically-extensive windows, or greater levels of thermal comfort may be achieved by maintaining the same U-value and subsequent pane temperature. By the same merit, so as to avoid downdraft, a lower U-value and thus a reduced temperature difference (increased pane temperature) would be required when specifying vertically-extensive windows.

Stratified internal air

The issue of air stratification is important when considering a glazing specification, as the cold downdrafts can cause lakes of cold air within a room, that in there own right can cause discomfort. In this respect the PassivHaus Institute study of 2.1m high windows also examined the stratification of air[9]. The study found that at a distance of 0.5m from glazing (U-value 0.8 W/m²K) there is a temperature of 20°C at a height of 1.1m above the floor and 18.4°C at a height of 0.1m above the floor. This is a 1.6°C temperature differential and satisfies *ISO 7730*, as the room air temperature stratification is less than 2°C between head and feet of a sitting person. The internal pane temperature under this condition is 16°C. In this instance it is important to recognise that the radiant temperature of the walls and floors is also a factor in the study of internal air stratification.

Another study was conducted where the internal pane temperature was 13°C. At a distance of 0.5m from glazing (U-value 1.6W/m²K) there is a temperature of 20°C at 1.1m and 17°C at 0.1m. This is a 3°C temperature differential and fails to satisfy *ISO 7730*, as the room air temperature stratification is not less than 2°C between head and feet of a sitting person. The PassivHaus Institute also notes that in order to achieve suitable comfort conditions, *ISO 7730* requires that the floor temperature should be maintained between 19-29°C. Airtightness obviously can have an impact and lead to the development of drafts and cold air ponds. Beyond referencing the fact that the PassivHaus standard requires an airtightness of 0.6 air changes per hour at a pressure of 50pa, and recognising that the PassivHaus Institute's fluid dynamic analysis has been performed using this criteria, it is beyond the scope of this article to assess the impact airtightness upon comfort.

Condensation

Indoor air contains a certain amount of water vapour, but the ability of this air to hold water vapour decreases with decreasing temperature. As air temperature decreases with a fixed water vapour content, the relative humidity of the air increases, and when the relative humidity reaches 100%, condensation occurs. The temperature at which this occurs is called the dewpoint temperature. If the window temperature is below the dewpoint temperature, the air in immediate contact with the window will be cooled to the dewpoint temperature, and condensation will occur. This in turn can give rise to premature decay of the building components (such as the window frame, spacers and thus the overall glazing unit) and can foster the growth of mould and fungi that can also impair the indoor air quality. To avoid condensation problems the temperature of the glazing and window frame should be maintained above the dewpoint.

Figure 1 shows the relative humidity that results when saturated outdoor air is warmed to an indoor air temperature of 20°C. As colder air begins with a smaller absolute amount of water vapour, the resulting relative humidity (equal to the ratio of actual water vapour pressure to saturation pressure) is smaller under colder outside conditions. To the extent that the outside air is not saturated, the resulting relative humidity will be smaller, but it will be increased due to the addition of moisture from internal sources (primarily human exhalation, cooking, showering, washing and drying).

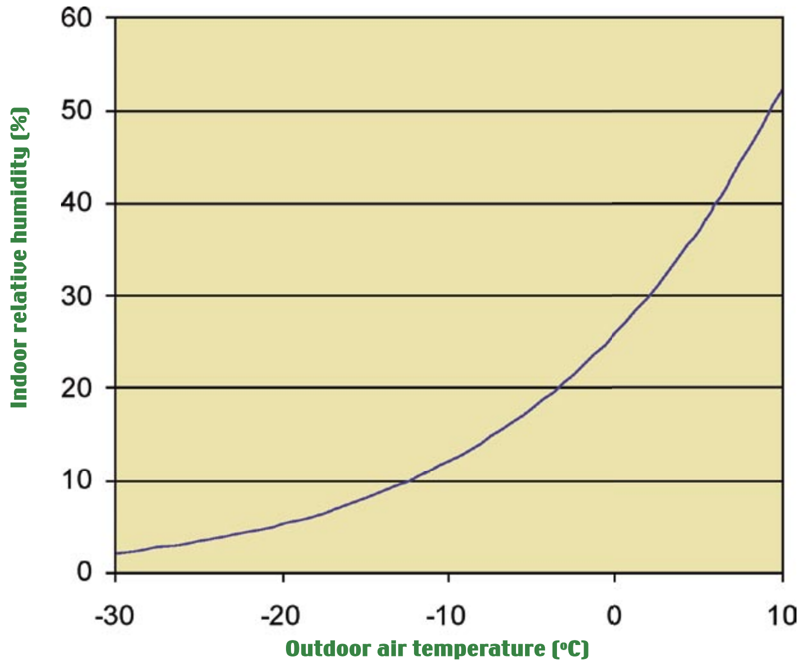


Figure 1. The indoor relative humidity that results when saturated outdoor air the temperature given on the x-axis is warmed to a temperature of 20°C.

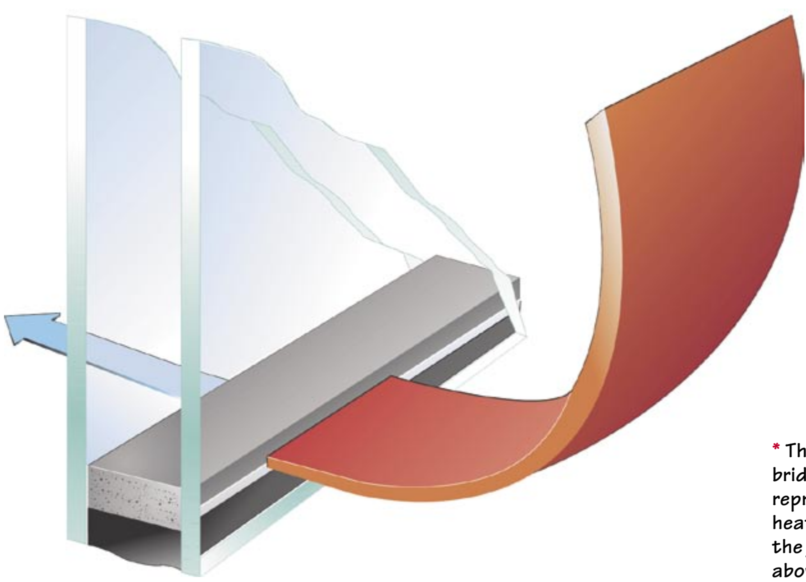
Figure 2 shows the dewpoint temperature for air at 20°C as a function of the relative humidity. For air that is already saturated, the dewpoint temperature is equal to the air temperature itself. At a relative humidity of 70% (quite a high value; 30-60% is a generally reasonable comfort range), the dewpoint temperature is 14°C.

In terms of thermal performance, a weak link in windows is often the spacer, which occurs between the internal and external panes. *The ASHRAE Handbook of Fundamentals* notes that the edge of the glazing unit is defined as being 60mm wide and is assigned a uniform thermal transmittance. The degree of thermal transmittance is dependant upon the type of edge seal and the spacer as well as the U-value of the glazing because only 15-20mm is directly covered by the spacer. The spacer may have a relatively high thermal conductivity and so can have a significant impact upon both the overall U-value and the surface temperatures adjacent to the spacer, for example, the heat loss through the thermal bridge caused by two aluminium strips of 0.5mm thickness and 1m length is the equivalent to the heat loss through a glass area of $15.5m^2$ [10]. Even a 2x2m pane with an aluminium spacer in the edge seal downgrades the U-value from 0.40W/m^2K to 0.58W/m^2K, a reduction of 45%. Therefore an isolating spacer of 1.20W/m^2K limits the reduction to just 22% (U-value 0.49W/m^2K)[11].

Not only are there increased energy losses but the low temperatures incurred by the spacer can lead to condensation at the perimeter of the window. Condensation risk can have a significant impact upon the longevity of a glazing unit and has been partly responsible for the failure of units in the past, as a consequence drainage should be provided to the edge seal. Traditionally, spacers were made of aluminium with thermal bridging values above 0.06W/mK (see note*). However, the latest generation of spacers uses reinforced polycarbonate, insulated stainless steel foil, foam or other similar materials, resulting in possible thermal bridging values of below 0.03W/mK. To avoid condensation risk it is important to ensure that windows are well designed and that high quality spacers are specified.

Synthesising the design criteria

Based on the above, we can summarize the conditions required for thermal comfort with windows as a temperature on the innermost glazing surface:



New technology spacer bars for double glazing can reduce heat loss and condensation significantly especially when combined with 'low e' glazing and gas filled units.

Picture courtesy of Edgetech.

*** The linear thermal bridging coefficient represents the additional heat flow associated with the junction, over and above that obtained from the U-values and areas of the plane elements. Source: BRE IP 01/06**

- no less than 15°C according to Fanger or no less than 17°C according to the PassivHaus Institute, based on considerations of radiant asymmetry
- no less than 16°C based on considerations of downdraft velocities
- more than 14°C based on the need to avoid condensation.

These conditions are applicable to a 2.1m high window with an indoor temperature of 20°C and an indoor relative humidity of 70%. If the window is less high, lower temperatures would be permitted, based on considerations of radiant asymmetry and downdrafts, while if the indoor relative humidity is less than 70%, a lower temperature would be permitted based on a consideration of condensation. If the indoor temperature is warmer, a warmer inner-glazing temperature would be required, based on all three considerations, it is worth noting that the warmer air temperature would increase the window inner-glazing temperature by almost the same amount, thus no change in U-value would be required.

Permitted U-values

High-performance windows (i.e. windows using low-E coatings and inert gases) dramatically reduce heat loss compared to conventional double-glazed windows. The by-product of decreasing heat loss is that the temperature on the inner surface of the window will be closer to the interior air temperature. For a window with a sufficiently low U-value, the temperature on the inner side of the inner glazing surface will be sufficiently warm that radiant asymmetry and downdrafts are negligible and there is no risk of condensation even in the absence of perimeter heating units.

The results are plotted in Figure 3, which gives the inner glazing inner-surface temperature as a function of the window U-value for various outdoor temperatures at 5°C intervals. The temperature results apply only to the component with the indicated U-value; thus, to deduce the temperatures in the centre of glass, use the centre-of-glass U-value, while to deduce the temperature of the frame inner surface, use the frame U-value. For the radiant asymmetry and downdraft comfort criteria, it would be appropriate to use the whole-window U-value, since the effects of radiant asymmetry on thermal comfort and the generation of downdrafts depend on the temperatures averaged over the entire window area, so use of a real-average U-value will

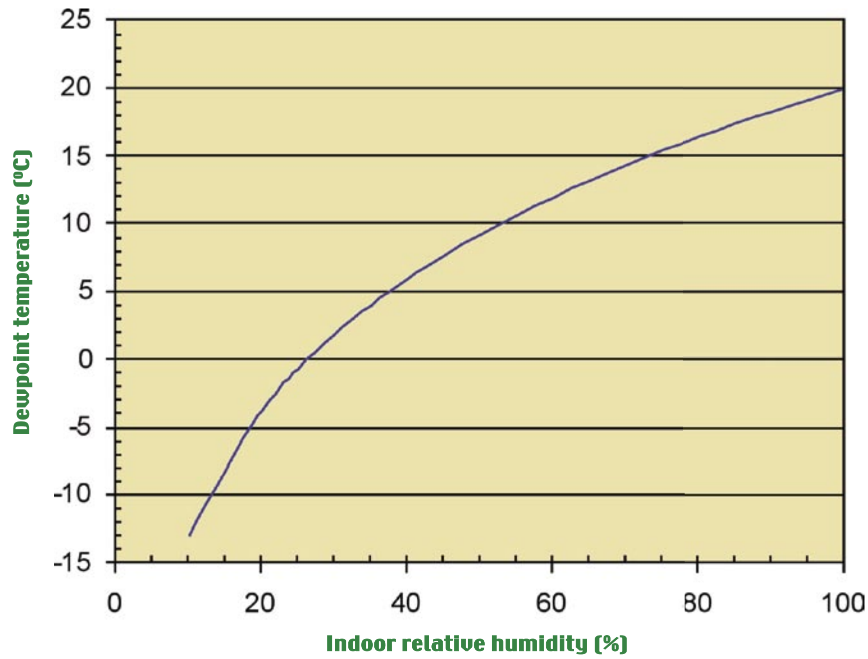
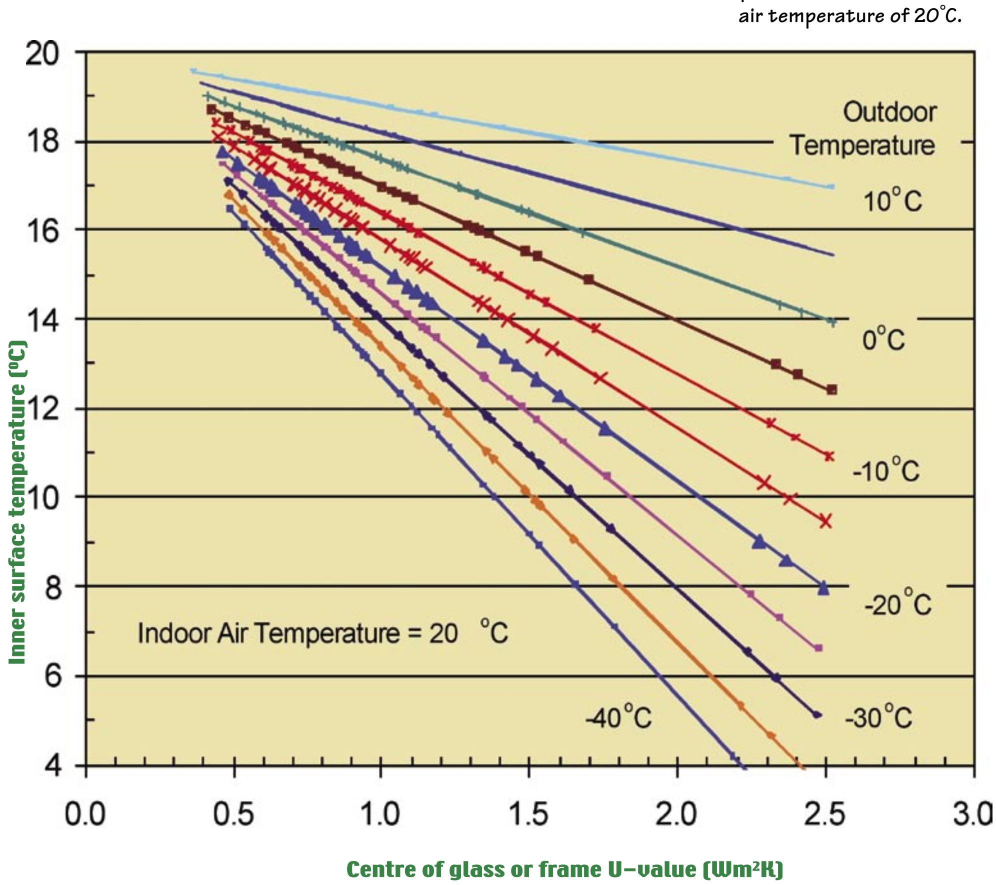


Figure 2. The dewpoint temperature as a function of relative humidity for an indoor air temperature of 20°C.

Figure 3. Variation in the temperature of the innermost glazing surface as a function of window U-value for different outside air temperatures and an indoor air temperature of 20°C.



be adequate. Condensation, however, depends on the temperature of the coldest surface, which is likely to be the frame.

From Figure 3, we determined, for each outdoor air temperature, the centre of glass at which the inner temperature is equal to 15°C, 16°C, and 17°C. The results are shown in Figure 4, which gives the U-value below which perimeter heating units can be eliminated as a function of the coldest anticipated outdoor temperature, given acceptable inner temperatures of 15°C, 16°C, or 17°C. The more stringent temperature threshold (17°C) would be applicable to floor-to-ceiling windows, where downdrafts are more easily initiated, while the less stringent criterion (15°C) should, due to concerns about downdraft and radiant asymmetry, only be considered to be applicable to windows of, say, 1m height (the authors consider that optimal comfort criteria should be sought i.e. 17°C inner pane temp). If adopting an inner pane temperature of less than 16°C attention should be given to calculating the Mean Radiant Temperature and the downdraft potential before determining the appropriate window size. Note that, if the indoor air temperature were maintained at 22°C rather than 20°C – as many people may prefer – the inner glazing temperatures would be just under 2K warmer than shown in Figure 4. By establishing a design-day internal pane temperature of 17°C a certain level of safety is introduced that can help to ensure that comfort conditions are not compromised in those hours, or indeed on those days, when the design-day temperature is exceeded.

Window frame considerations

Due to the small area involved, radiant asymmetry and the creation of downdraft are not of great concern with regard to window frames, but condensation must still be avoided. However, as noted above, the temperature requirement to avoid condensation is less strict than the requirements related to radiant asymmetry and downdraft. In particular, for indoor air at 20°C, the dewpoint temperature ranges from 4°C at 35% RH to 14°C at 70% RH, so temperatures warmer than these limits would avoid condensation. Figure 4 can be used to determine the maximum permitted U-value that will be needed to maintain a frame temperature of 15°C as a function of the external temperature. The U-value of a typical timber window frame ranges between 2.1-3.1W/m^{2}K [11]. Adopting 10°C as the minimum permitted frame inner-surface temperature (roughly equal to the dewpoint at a relative humidity of 50% for 20°C air temperature), the maximum permitted frame U-value is 2.7W/m^{2}K for an outdoor design temperature of -10°C (a typical minimum winter temperature in much of the UK). For an outdoor design temperature of -40°C, the maximum permitted frame U-value is 1.4W/m^{2}K.

A variety of windows have U-values this low; PassivHaus window frames typically have U-values of 0.7-0.8W/m^{2}K. On colder days, the indoor relative humidity will tend to be lower than on less extreme days, due to the smaller initial water vapour content of the air, thereby providing a safety margin that increases just when it is needed most. Thus, we conclude that, with adequate ventilation (with heat recovery, of course!), condensation will not be a problem even under extreme weather conditions. By using the 15°C temperature curve of Figure 4 in choosing frame U-values, it is possible to establish a very conservative minimum U-value for a frame, thus ensuring that a tolerable inner-surface temperature can be satisfied.

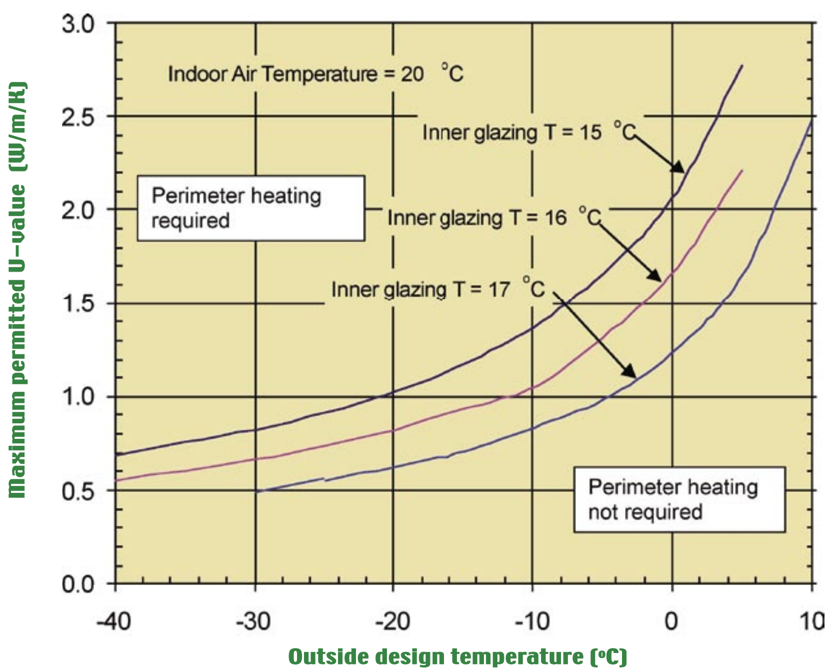


Figure 4. Whole window (Ug) or frame U-values that result in a temperature of the innermost glazing surface or the inner surface of the frame of 15°C, 16°C, or 17°C for a range of outdoor air temperatures and an indoor temperature of 20°C.

A short note on specifying double and triple glazing

The specification of triple glazing is reasonably unfamiliar to many within the UK. As the low-e coating can be placed on a number of surfaces there are a couple of watch points that should be observed. The first is that if specifying the low-e on planes three and five (counting from the outside) the central pane can be subject to high levels of thermal stress, as a consequence it should be made of toughened glass[12]. Specifying the low-E coatings on planes two and five results in a solar gains of about 50%, whereas specifying the low E coatings on planes three and five results in a slightly higher solar gain of 52%. Due to the relatively small difference in g-value a design decision regarding the additional cost of toughened glass vs. solar energy payback is warranted. In terms of thermal performance advanced triple glazed units are now available with Ug ranging between 0.4-0.7W/m^{2}K thus permitting whole window U-values (Uw) of <0.85W/m^{2}K. In terms of U and g-value, other glazing systems such as HeatMirror, available from SouthWall Technologies, can achieve similar levels of performance and recently they have even achieved U-values as low as 0.3W/m^{2}K, though at this level of performance the solar gains from such glazing is currently dramatically compromised (g-value 0.2).

Solar gain

When adopting a holistic passive solar approach, one should also consider that whilst high performance glazing benefits from improved comfort and reduced heat loss it suffers from a reduced solar heat gain coefficient. As a consequence care should be take to specify glazing that optimises the g-value and thus allows the greatest passive solar contribution, thus reducing the over all space heating demand. It is recommended that the g-value be maintained above 50%. In order to ensure a net-contribution to the space heating, detailed computer modelling is required.

Conclusion

This article has shown the means by which comfort can be economically achieved and perimeter radiators can be omitted from conventional designs. Furthermore it has considered that through the provision of fewer larger panes (rather than many small panes), and the provision of opening lights, in such a way as to provide adequate but not excessive ventilation, will mean that proportion of perimeter frame will be managed. As a consequence the resultant heat losses, and the degree of self shading and the potential for the exploitation of solar gains will be optimised.

By taking a holistic approach to design, new opportunities are afforded that can avoid increased costs or loss of comfort. By facilitating reduced service runs, or the removal of a conventional heating system (as in the PassivHaus standard), high-performance glazing can allow a value-engineered solution whereby various trade-offs can begin to minimise, if not completely offset, any additional capital or whole life cost incurred by seeking to increase energy efficiency and reduce energy consumption.

L.D. Danny Harvey and Mark Siddall

NOTE: The selection of the external design day temperature is at the sole discretion of the designer and the client. To this end it is recommended that all calculations and design criteria should be checked on a project specific basis.

Thanks to: Chris Herring of Green Building Store, Nick Grant of Elemental Solutions and David Olivier of Energy Advisory Associates.

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3. The handbook of the PassivHaus Planning Package 2004 cites that early studies (Feist 1993) relate to glazing that is 3m high, this condition, presumably at –10C, necessitated a U-value of <0.8 W/m^{2}K.

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An even greener theme this year at Homes for Good

Ecos Trust will host the fifth Homes for Good exhibition at the Royal Bath & West Showground near Shepton Mallet on Friday 28th and Saturday 29th March - the original, not for profit exhibition which focuses on building and living sustainably. In 2008 the exhibition will evolve and become even greener, by incorporating a sustainable landscapes theme, providing visitors with inspiration on designing and managing greener gardens. By hosting the Homes for Good exhibition each year since 2004, Ecos Trust has ignited and strengthened a mainstream market for sustainable materials, designs and services, which continues to grow, making it easier for the building industry and home owners to adopt greener building and lifestyle practices both in the home and at work.

Corina Reay, Homes for Good exhibition coordinator comments: "It is crucial that we are not just told why we urgently need to become more sustainable, but that we are advised how to go about it, and how we can fit it around our lifestyles and businesses. "Homes for Good is about bringing sustainable experts together under one roof in a relaxed environment to exhibit, lead conferences and hold presentations. This allows visitors to talk with professionals in person, whether they are interested in a very specific topic or have a general enquiry about sustainable buildings, gardens and greener day to day lifestyles. It could be that guests want to learn about how they can save energy in their homes or at work, or that they want to find out about building, or living in an eco-home. We look forward to welcoming people to Homes for Good, answering their questions and advising them on a range of sustainable issues."

A number of exhibitors at Homes for Good will focus on gardening sustainably by demonstrating to builders and developers how garden design and appropriate planting is beneficial during the early stages of development. Professionals will give advice on a variety of practices, such as how to ensure that outside spaces are productive for owners, beneficial to wildlife and in some cases how they can be a source of external insulation to the building, improving its energy efficiency.

For more exhibitor or visitor information about Homes for Good 2008 please contact Corina Reay on tel: 01458 259400, email: corina@ecostrust.org.uk or visit the new Homes for Good website: www.homesforgood.info

HOMES FOR GOOD '08
sustainable home & garden exhibition