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Predicting local thermal discomfort adjacent to glazing

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Predicting Local Thermal Discomfort Adjacent to Glazing

Simon J. Rees, PhD
Member ASHRAE

Kevin J. Lomas, PhD

Dusan Fiala, PhD

ABSTRACT

The sensations of thermal discomfort in the near-window regions of rooms may be significant. Close to windows occupants may be directly exposed to both transmitted solar irradiation and enhanced long wave radiation exchange due to window surfaces that are noticeably hotter or colder than other room surfaces. The superior insulating qualities of modern high performance glazing systems result in relatively higher surface temperatures in wintertime. This may reduce the local discomfort experienced by occupants and increase the utility of glazed perimeter spaces. In evaluating glazing systems one would like to quantify such benefits.

Prediction of comfort perception in this asymmetric radiant environment is challenging. Being able to account for local, and not just overall, sensations of discomfort is particularly important. In this work a multi-segment dynamic comfort model has been employed that incorporates recently developed models of local thermal comfort response. The work required the development of simulation methods able to predict the detailed long-wave and convective exchanges to the surrounding space and the absorbed solar irradiation. This has been done in an efficient and generic manner so that parametric studies of local comfort responses have been possible. Such studies have been used to examine the relationships between local discomfort and room and window temperatures as well as the role solar irradiation and clothing may play in determining satisfactory winter environmental conditions.

INTRODUCTION

In real buildings, there are a number of reasons why occupants find themselves seated, or standing, close to windows. Spatial planning may oblige some occupants must have desks

near windows, or it may be that occupants choose to be near a window to gain the benefits of daylight or external view. The thermal conditions to which such occupants are exposed are complex – asymmetrical and highly dynamic. They can be very different from central room positions because occupants may be directly exposed to both transmitted solar irradiation and enhanced long wave radiation exchange. As a result occupants in near-window regions may have quite different perceptions of the thermal comfort of the space than other occupants.

Long-wave radiation can be enhanced due to window surfaces that are noticeably hotter or colder than other room surfaces. At the same time, solar irradiation of the body surface can be a significantly larger than both convection and long-wave radiation. These radiant conditions are highly asymmetric and dependent on body position, posture and orientation; some parts of the body may be exposed to large heat fluxes while others may be completely shielded. The radiant fields are also highly dynamic as solar irradiation can vary rapidly and by up to two orders of magnitude. At certain times, the effects of solar irradiation may provide some compensation for cold glass temperatures. At other times solar irradiation may serve to raise glass surface temperatures higher than the room air temperature.

These effects – both the absolute magnitudes and the dynamics – are partly under the control of the building designer; glazings are available with a wide range of insulation and solar transmission properties and the window size and shape, and the room geometry and spatial planning, can be manipulated. However, the information available about the thermal comfort implications of these options is limited.

Thermal comfort research, over several decades, has enabled engineers to determine what room average tempera-

Simon J. Rees is a Research Fellow and **Kevin J. Lomas** is Director of the Institute of Energy and Sustainable Development, De Montfort University, Leicester, United Kingdom. **Dusan Fiala** is Deputy Director of the Institute for Construction Economics at the University of Stuttgart, Stuttgart, Germany.

tures should be maintained to provide general *overall thermal comfort*, and research into comfort under asymmetric radiant conditions has provided guidance on the limits of asymmetry that should be allowed. There is however, little guidance relating to the complex conditions near windows. This is largely because the prediction of human comfort responses near windows is complicated by the radiant asymmetry, which means that the comfort impacts are very localized: thermal conditions vary between one body part and another (adjacent one); and the perceived impact on comfort differs because (adjacent) body parts can have different sensitivities. Only with the recent development of detailed multi-segmental models has *local thermal comfort* prediction become possible.

A detailed understanding of, and model of, the complex conditions near windows would help to address a number of questions, such as:

- Can uncomfortable conditions be avoided by careful selection of the glazing system?
- Are there window geometries and shading details that can be adopted to minimize discomfort and maximize the utility of near window spaces?
- Can suitable system controls be devised to provide optimal local and overall comfort when solar fluxes vary rapidly?
- What forms of adaptation will best help occupants maintain comfort – shading, orientation, clothing etc.
- Can simple window performance metrics be devised that would help designers and building owners appreciate the comfort benefits of certain window designs?

The traditional mathematical models of human thermal comfort, such as those of Fanger (1973) and Gagge (1986) are founded on calorimetric principals but are only responsive to the body's overall thermal state. A modeling approach that can address questions of local discomfort near glazing must incorporate the following:

1. A thermo-physiological model that is able to predict the thermal conditions at individual body parts.
2. A model of local thermal comfort response.

The first requirement can be met by using a multi-segmental model such as the Berkeley Comfort Model (Huizenga et al., 2001) or the IESD-Fiala Model (Fiala et al., 1999). For this work, the IESD-Fiala model, which is familiar to the researchers, was used. The model uses a detailed representation of the human body and has the capability to reliably predict both the overall and local temperature responses and regulatory behaviors for a wide range of environmental conditions (Fiala et al., 1999, 2001 and 2003). The second requirement was met by extending the model so that the local discomfort response could be predicted from the thermal conditions of the individual body parts; and not just the overall thermal response (global PPD). This was done by incorporat-

ing into the IESD-Fiala model the local discomfort models developed by Fiala and Kubaha (2005).

Calculation of local variations in the thermal environment requires a modelling methodology that incorporates:

- a detailed representation of body geometry preferably in different postures;
- a means of accurately calculating longwave radiation between each surrounding surface and each body part;
- a means of accurately calculating the shortwave irradiation on each body part for a particular window geometry, orientation and solar position;

Accordingly, a detailed representation of an upright male (consisting of some 10,000 polygons) has been used to derive view factors for long-wave radiant exchange calculations. A radiosity and simplified ray tracing method was developed to calculate the incident diffuse and direct short-wave radiation.

The reported work was motivated by an interest in the comfort benefits of high performance glazing. It has however, led on to generic parametric studies and analysis of the relationship between local comfort and annual energy demands. The results of these studies could also be used to examine the relationship between window comfort performance and other parameters such as U-value.

MODELING LOCAL THERMAL DISCOMFORT

To be able to examine local discomfort in a range of environmental conditions any thermoregulatory model of the human body must be sufficiently discretized to allow the condition of particular body parts to be established – not just the overall thermal condition of the body. Multi-segmented thermophysiological models, of different levels of sophistication, have been developed over a number of years (e.g. Stolwijk 1971, Konz et al., 1977, and Wissler 1985). They allow the overall thermal condition of the body to be calculated and have been useful in providing insight into the physiological principals of thermal comfort. More recent models (e.g. Huizenga et al., 2001 and Fiala et al., 1999, 2001 and 2003) allow dynamic responses to complex heterogeneous environmental boundary conditions to be examined in considerable detail. The model used in this work was based on the IESD-Fiala model of human physiology developed at De Montfort University and the Egle-Institut at the University of Applied Sciences, Stuttgart. The model has been described in detail elsewhere and so only a brief description follows.

The Thermo-Physiological Model

The IESD-Fiala model uses a multi-segmental, multi-layered representation of the body with a detailed representation of its geometry. The overall geometry represent an average person of weight 73.5 kg, body fat content 14% and Dubois-area 1.83m². The body is divided into 19 elements consisting of multiple tissue layers. Each element of the body is subdivided into multiple sectors, e.g. the upper leg is divided

into interior, anterior, exterior and posterior sectors and the body as a whole has 59 such sectors (Figure 1).

The model of the human thermoregulation that is associated with the geometry, can be thought of as having two interacting systems: the controlling active system and the controlled passive system. The active system is simulated by means of cybernetic models that predict responses such as shivering, vasomotion and sweating (see, for example, Fiala et al. 2001). The passive system, which is of particular interest here, is constructed on the basis of the dynamic heat balances at each tissue element to account for: conduction of heat through the body sector; conduction to adjacent sectors; transport of heat by the blood stream; and metabolic heat production. Heat balances, and heat transfer processes, established for each body sector are coupled (from a thermal or mathematical point of view) by a model of the blood circulatory system. Heat rejection via respiration is also considered. Conduction heat transfer at each body sector is modeled using a one-dimensional finite-difference method and the whole system of equations is discretized in time using a Crank-Nicholson approach. Solution of the model equations provides predictions of body core and surface temperatures, heat fluxes, evaporation rates and wetted areas and other secondary quantities.

When considering asymmetric long-wave and short-wave radiant conditions – as we must when modeling near window conditions – the treatment of the body surface heat balance is of particular interest. In the IESD-Fiala model the surface heat balance at each body sector is formulated as,

$$q_{sk} = q_c + q_e + q_r - q_{sr} \quad (1)$$

Where

- q_{sk} = the net heat loss from the skin surface (W/m^2)
- q_c = the heat loss by convection to the air (W/m^2)
- q_r = the longwave radiation loss to the surrounding surfaces (W/m^2)
- q_{rs} = the absorption of direct and diffuse solar irradiation (W/m^2)
- q_e = the latent heat loss from the skin due to moisture evaporation (W/m^2)

Kubaha (2005) extended the original IESD-Fiala model so that, rather than using a linear radiant heat transfer coefficient, the following formulation was used,

$$q_{r,i} = \sigma \sum_{j=1}^n \varepsilon_i \varepsilon_j F_{i,j} (T_{b,i}^4 - T_{s,j}^4) \quad (2)$$

Where

- σ = the Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$)
- ε_i = the emissivity of the body sector, (-)
- ε_j = the emissivity of the surrounding surface (-)
- $F_{i,j}$ = the view factor of the body sector with respect to the surrounding surface (-)

- $T_{b,i}$ = the absolute temperature of body sector (K)
- $T_{s,j}$ = the absolute temperature of surrounding surface sector (K)
- i = the body sector index (1 to 59)
- j = the surrounding surface index (n in total)

In this study the representation of the body geometry, surrounding surfaces and associated view factors was treated in some detail and is discussed in a later section.

In many models of body heat transfer, shortwave radiant fluxes are approximated by multiplying the flux by a 'projected area factor'. In other words, shading and reflection from surrounding surfaces is not treated explicitly. In this work the model has been adapted in order to allow a complex representation of shortwave radiation at each body sector. This is described in detail in a later section.

A MODEL OF LOCAL COLD AND WARM DISCOMFORT

Understanding and modelling human perceptual responses to asymmetric radiation has been the subject of experimental investigation over a number of decades (e.g. Chrenko 1953, McNall and Biddison 1970, Olesen et al., 1972, Fanger et al., 1985, Zhang 2003). Most experimental work has been carried out in climate chambers under well-controlled conditions for vertical and horizontal surfaces.

Cold and warm cutaneous thermal receptors are distributed in a heterogeneous manner over all parts of the body surface. Consequently, skin surface temperature response has been found to correlate well with perceived *global* or whole-body thermal comfort (Gagge et al., 1967, Gonzales et al., 1973). Furthermore it has been found that perceived *local* discomfort can be similarly correlated with, and predicted using, local skin temperatures (Issing and Hensel 1982). This is the conceptual basis of the model of local cold and warm discomfort developed by Kubaha (2005) and is the platform for the extension of the IESD-Fiala model used in this work.

The basic approach, for each body part, is to use the difference between the local skin temperature and a reference value, as a measure of the thermal stimulus and then to correlate this difference with the responses of subjects tested under carefully controlled experimental conditions.

The basic temperature difference is given by,

$$\Delta T_{sk,i} = T_{sk,i} - T_{sk,ref} \quad (3)$$

where

- $T_{sk,i}$ = the local skin temperature (K)
- $T_{sk,ref}$ = a reference skin temperature (K)
- $\Delta T_{sk,i}$ = negative values of indicate local cold stimulus and positive values of indicate local warm stimulus (K)

However, not all body parts are equally sensitive to skin temperature stimuli, so a sensitivity parameter must be introduced. Furthermore, the choice of reference temperature, and the values of the sensitivity coefficients, varies depending on

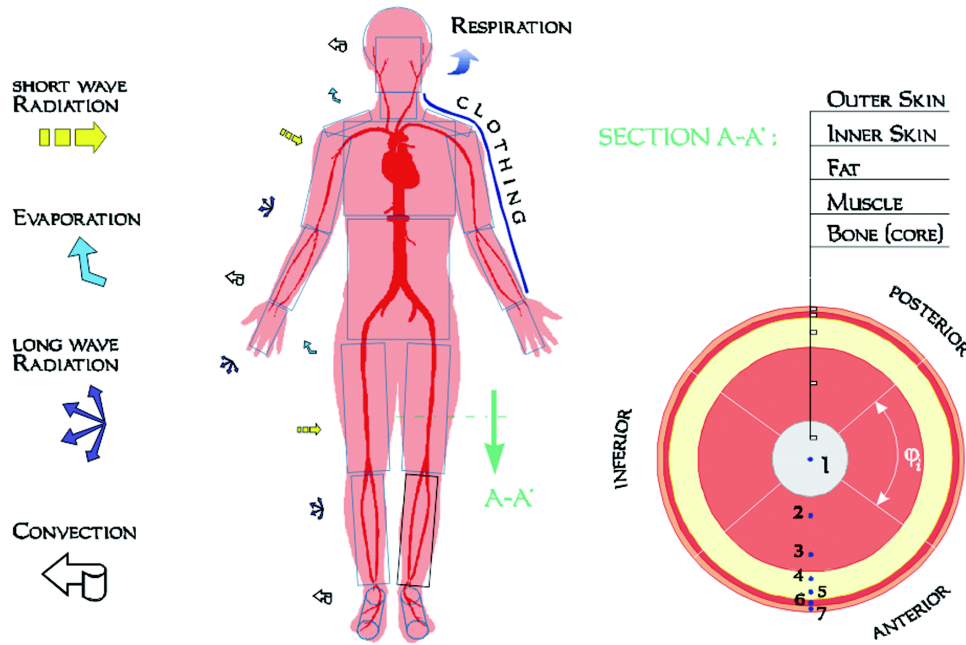


Figure 1 A conceptual representation of the passive elements of the IESD-Fiala multi-sector thermo-physiological model.

whether local cold stimulus (LCS) or local warm stimulus (LWS) is being considered.

In modelling LWS, the most appropriate reference temperature was found to be the local skin temperature under thermally neutral conditions ($T_a < T_R < 30^\circ\text{C}$, still air, 40% RH, 0.8 met and no clothing). Thus the local warm stimulus (LWS) for body sector i is given by,

$$LWS = C_{sk, w, i} (T_{sk, i} - T_{sk, i, 0}) \quad (4)$$

Where

$T_{sk, i}$ = the local skin temperature (K)

$T_{sk, i, 0}$ = the local skin reference temperature (K)

$C_{sk, w, i}$ = the skin sensitivity coefficient with respect to warm stimuli (K^{-1})

Local sensitivity coefficients measured by Crawshaw et al. (1975) were used to derive warm stimulus sensitivity coefficients for the model (Table 1).

In modelling LCS, Kubaha (2005) found the most appropriate reference temperature to be the mean body skin temperature. Thus, the LCS for body sector i is given by,

$$LCS = C_{sk, c, i} (T_{sk, i} - T_{sk, m}) \quad (5)$$

Where

$T_{sk, m}$ = the mean body skin temperature

$C_{sk, c, i}$ = the skin sensitivity coefficient with respect to cold stimuli

The derived skin sensitivity coefficients (Table 1) are based on the local sensitivity coefficients measured by Nadel et al. (1973), Steven et al. (1973) and Crawshaw et al. (1975). Simulation of the experiments of Fanger et al. (1980 and 1985) and

McNall and Biddison (1970) by Kubaha showed that the sensitivity weighted temperature stimuli correctly indicated which body sectors w

To establish the correlations between LCS and Local Cold Discomfort (LCD), data from the asymmetric radiation experiments of Fanger et al. (1980 and 1985) and McNall and Biddison (1970) were used. These data include cases of cool-cold ceiling, cool-cold vertical panel and cold wall boundary conditions. Regression analysis was carried out using an exponential function that asymptotically approached the 0% and 100% discomfort conditions. The final form of the correlation for the percentage of people predicted to be dissatisfied due to local cold discomfort (LCD) is given by,

$$LCD = \frac{100}{1 + 99810e^{3.39LCS}} \quad (6)$$

The regression line ($R^2=0.791$) and the experimental data for a number of arm, leg and foot sectors is shown in Figure 2

Further cases from the data sets of Fanger et al. (1980 and 1985) and McNall and Biddison (1970) were used in the development of correlations between Local Warm Stimulus and Local Warm Discomfort (LWD). A correlation function of the same exponential form was employed in the regression analysis and a correlation coefficient $R^2=0.806$ calculated. The final form of the correlation for the percentage of people predicted to be dissatisfied due to local warm discomfort (LWD) is given by,

$$LWD = \frac{100}{1 + 14.33e^{-1.73LWS}} \quad (7)$$

Table 1. Coefficients of Sensitivity to Local Warm and Cold Stimuli (After Kubaha, 2005)

Body Part	Body Sector	Cold Sensitivity Coefficient ($C_{sk,c,i}$)	Warm Sensitivity Coefficient ($C_{sk,w,i}$)
Head	forehead	0.0310	0.0545
	head	0.0389	0.0682
Face	anterior	0.0389	0.0682
	L&R exterior	0.0389	0.0682
Neck	anterior	0.0214	0.0292
	posterior	0.0274	0.0373
	L&R exterior	0.0274	0.0373
Shoulders	left and right	0.0228	0.0222
Thorax	anterior	0.0202	0.0202
	posterior	0.0228	0.0222
	L&R inferior	0.0228	0.0222
Abdomen	anterior	0.0228	0.0222
	posterior	0.0152	0.0172
	L&R inferior	0.0152	0.0172
Upper Arms	anterior	0.0152	0.0172
	posterior	0.0152	0.0172
	inferior	0.0151	0.0112
	exterior	0.0151	0.0112
Lower Arms	anterior	0.0151	0.0112
	posterior	0.0151	0.0112
	inferior	0.0108	0.0043
	exterior	0.0108	0.0043
Hands	hand back	0.0108	0.0043
	palm	0.0108	0.0043
Upper Legs	anterior	0.0171	0.0170
	posterior	0.0171	0.0170
	inferior	0.0171	0.0170
	exterior	0.0171	0.0170
Lower Legs	anterior	0.0107	0.0045
	posterior	0.0107	0.0045
	inferior	0.0107	0.0045
	exterior	0.0107	0.0045
Feet	instep	0.0107	0.0045
	sole	0.0107	0.0045

The regression line and experimental data for a number of arm, leg and foot sectors is shown in Figure 3.

The IESD-Fiala model, extended with the local comfort model of Kubaha (2005), was implemented in a computer program that allows many of the environmental boundary

conditions (e.g. air velocity, humidity, temperature, surface temperature, solar irradiation) to be varied at each step in dynamic simulations. Other parameters affecting the thermal state of the body such as metabolic rate, drink intake and clothing can also be varied.

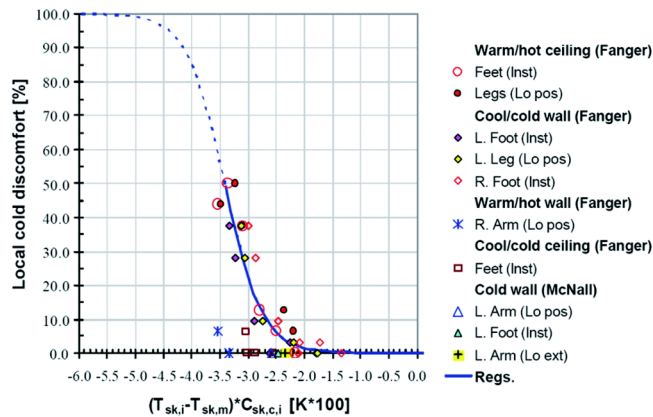


Figure 2 Local Cold Discomfort (LCD) as a function of Local Cold Stimulus (LCS) (Kubaha 2005).

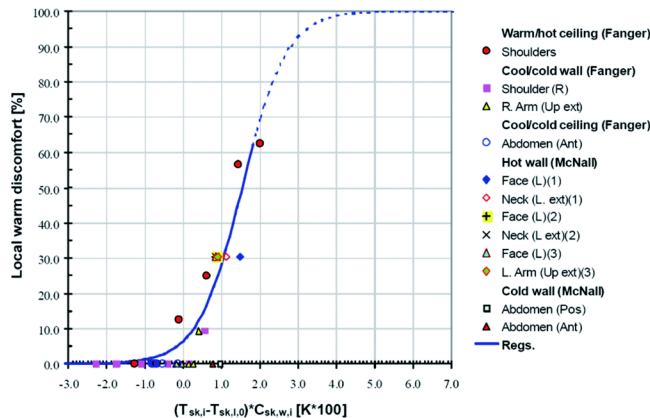


Figure 3 Local Warm Discomfort (LWD) as a function of Local Warm Stimulus (LWS) (Kubaha 2005).

NEAR-WINDOW HEAT TRANSFER

When an individual is located in close proximity to a window, it is clear that one side of the body will experience the radiant fluxes associated with the glazing system and the other will not. There are however, other, more subtle, effects at play. For example, if a person stands one meter away from a one square meter window with one meter sill height (a geometry studied in this work), the shading effect of the sill, could mean that lower anterior abdomen will experience very different long-wave radiant fluxes to the adjacent anterior sectors of the upper leg - even though they are oriented the same way. Similarly, adjacent body sectors may experience very different short-wave radiant fluxes, even if both face the window, because angled solar radiation will illuminate some sectors while others are in the shadow of other body parts. A combination of numerical methods has been developed to enable these subtle effects to be modeled.

The geometric model of a standing person in a neutral pose was extracted from one generated using animation/illus-

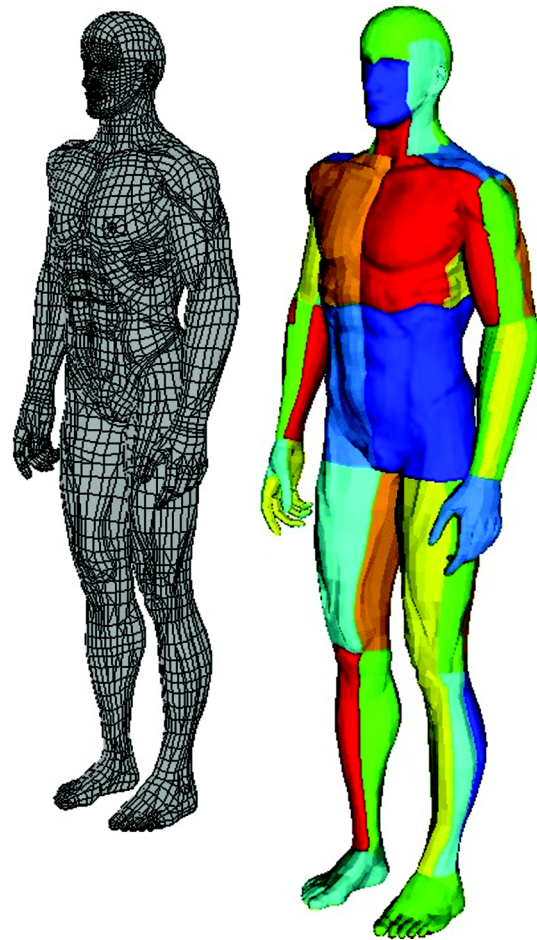


Figure 4 Outline of the polygonal representation of the body (left) and colored according to body sector (right). There are 59 body sectors in total.

tration software (Curious Labs 2000) and consists of over 10,000 polygons (Figure 4). The raw geometry required significant processing to ensure consistent polygon representation and to associate each polygon with a sector of the thermal model. The body geometry was combined with a simple polygon representation of a prototypical room to form a complete enclosure. In this study the room was 5m deep, by 4m wide and 2.7m high with a 1m by 1m window above a 1m sill in the center of the shorter side. The data reported here was calculated with the body facing the window and standing with its vertical axis at a number of positions between 0.75m and 2.0m from the inside surface of the window.

Both long-wave and diffuse shortwave radiation were calculated using radiosity methods, which enabled the same view factors to be used in both calculations. Accurate view factor calculation, where there are a very large number of partially obscuring polygons, is complicated but was accomplished using the VIEW3D program (Walton 2002). Reduction of the view factors for the whole set of approximately 10,000 polygons to a set of view factors for every body sector

and room surface (69 surfaces in total) allowed long wave fluxes for the non-convex body surfaces to be calculated in a simple manner within the comfort model code. Parametric thermal comfort studies are not burdened by these calculations, as they only have to be done once for each geometric configuration.

The approach taken to the treatment of shortwave fluxes was to normalize the solar irradiation for each body sector surface. This was done by defining an irradiation coefficient according to the incident short wave flux at each body sector that arises from a unit flux at the window inner surface. This can be calculated for diffuse irradiation by applying a unit diffuse short wave flux at the window surface and using a radiosity formulation with the previously calculated view factors. Response factors for direct short wave fluxes are – unlike diffuse fluxes – dependent on solar azimuth and elevation. The method adopted to calculate direct irradiation coefficients was to calculate the direct irradiation falling on each polygon by applying a ray tracing method at regular azimuth and elevation intervals. Further radiosity calculations, to find the proportion of direct solar flux that arrived at a particular body sector surface by diffuse reflection, were made by treating the illuminated polygons as diffuse short wave sources. Thus a set of direct solar irradiation coefficients were produced for each chosen azimuth and elevation angle (see Figure 5 for an example).

Normalizing the shortwave radiation, and pre-calculating the view factors, means that the boundary conditions become the surface temperature and the transmitted direct and diffuse solar irradiation at the window *inside*, rather than *outside*, surface. Window surface temperature can be calculated by a number of means but this does not need to be done within the comfort model. In other words, a generic study of how comfort is affected by inside surface temperature can be undertaken – not just one that applies to a particular type of glazing. Similarly, solar position and transmitted irradiation are inputs to the model rather than outputs. This can allow, for example, solar irradiation and sun position to be pre-calculated by a building energy simulation tool and the dynamic comfort response subsequently calculated. Measured solar flux and window surface temperatures could also be applied.

PARAMETRIC STUDIES

It was possible, by applying the tools and methodologies described, to carry out a number of parametric studies. The studies presented here illustrate the potential of the predictive system and focus on the effect on local comfort of different window and room temperatures, the effect of clothing levels and diffuse solar gains. The emphasis of the discussion is on winter conditions i.e. cold discomfort and moderate solar fluxes.

Effect of Window Temperature

The model in the initial study was configured with clothing to represent business wear, briefs, long-sleeve shirt and

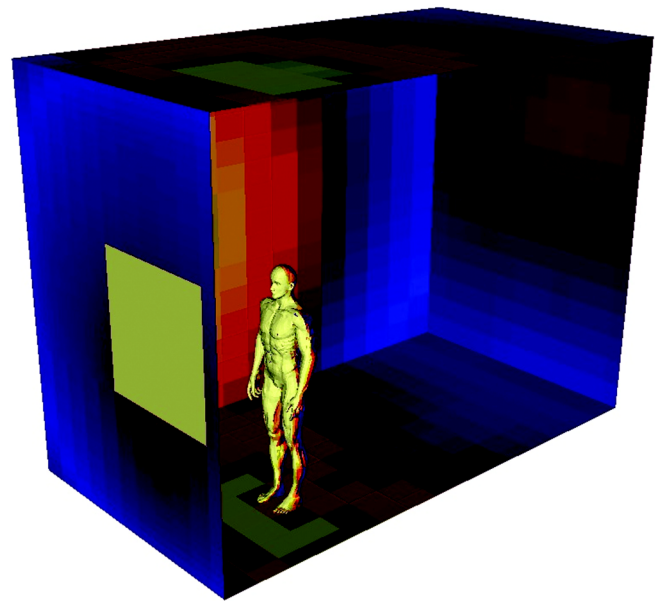


Figure 5 A section through the room to illustrate the direct and diffuse short-wave radiation distribution for a solar azimuth angle of zero and an elevation 30 degrees (a moderate room and body surface reflectivity of 0.5 was used).

long pants, along with angle-length socks and shoes (0.7 clo). Metabolic rate, air speed and humidity were set at values appropriate to light office work (met=1.3, v=0.1m/s, RH=50%). The occupant was standing at a distance of 1m behind, and facing, a 1m by 1m window. In the initial study of the effects of window temperature no solar gain was applied.

The predicted steady-state LWD and LCD for each window and room temperature combination were plotted as separate surfaces (Figure 6). The plotted LCD and LWD values are those of the most severely affected body part. It is apparent that for many conditions both LWD and LCD are experienced simultaneously, each at different body parts. At the intersection of the planes the local discomfort of the body part perceived to be the coldest is equal to the local discomfort at the body part that is perceived to be the warmest. By plotting the results in this way some other interesting features also emerge.

It is evident that the highest levels of local discomfort occur when both the room and window temperatures are low – as might be expected. For the situation simulated¹, the LCD surface is much steeper than the LWD surface, which indicates a generally lower tolerance to reductions in (either the window or the room) temperature below that which is deemed thermally neutral than to increases above the neutral condition. Furthermore, the most severely affected body part changes as the boundary conditions alter (see below) and this accounts for

¹. Draft free conditions are also assumed.

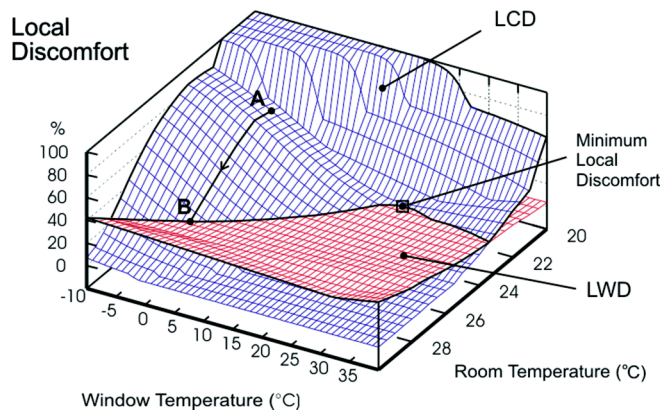


Figure 6 Local discomfort according to room operative and window surface temperatures.

the discontinuous nature of the LCD surface, and less obviously so, the LWD surface.

The conditions of lowest local discomfort (equal LCD and LWD) are represented by the shallow valley at the intersection of the two planes that runs across the parameter space. The level of local discomfort experienced at the valley bottom (the y-axis value in Figure 6) does, of course, increase away from the neutral state point and so, although at a minimum, the local discomfort may still be unacceptably high. Consider a situation in which the window temperature is particularly low, say 0°C; the room temperature can be increased (above 22.5°C – point A on Figure 6) to markedly reduce the degree of local discomfort (from 55.9% at point A to 20.7% at point B where the room temperature is 27.5°C). However, while ‘turning up the heating’, can offset the effect of the cold window, the level of local discomfort (at 20.7%) is still, probably, unacceptably high.

Bands of minimal or ‘acceptable’ comfort have been examined further by considering conditions where both local and global discomfort are predicted to be insignificant (a result of less than 10%). These conditions are illustrated in Figure 7 (which is, in effect, a birds-eye view of Figure 6). The curved lines chart the course of the intersection of the two planes in Figure 6, and these separate the two shaded regions: one in which LWD is more severe than LCD and the LWD exceeds 10% (top right region); and the other in which LCD is more severe than LWD and LCD exceeds 10% (bottom left region). In the unshaded region both LCD and LWD are less than 10%. This is a region is surprisingly small in this case.

This local comfort zone can be compared with the range of room and window temperatures for which the overall (global body) discomfort was predicted to be less than 10% – the hatched region in Figure 7. This data was produced using the IESD-Fiala model (Fiala et al., 2003). This is effectively the range of conditions predicted to be acceptable when only mean body surface temperatures are considered and local vari-

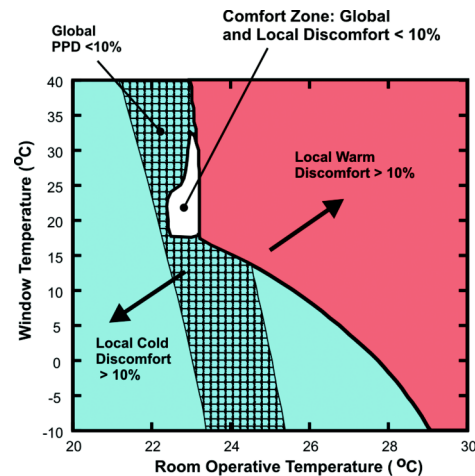


Figure 7 Variations in Local Discomfort exceeding 10% according to room operative and window surface temperatures. Typical office clothing including a long sleeve shirt is simulated. The body is 2.0m from the window and there is 100W/m² transmitted diffuse solar radiation.

ations are ignored. This would be the prediction made by most other thermal comfort models. Such global comfort predictions would suggest that: (a) comfort perception is insensitive to window temperature and; (b) that the effects of low or high window temperatures can be mitigated by relatively small adjustments to the room temperature. However, while such adjustments might yield overall thermal comfort, as the example above illustrated, they will generally not simultaneously result in overcoming local discomfort. This is because the range of conditions where local discomfort (and global discomfort) are simultaneously acceptable is rather narrow; the local comfort zone (unshaded) is small and lies wholly within the global comfort region. More generally put, there are a wide range of conditions, for this situation, where global comfort may be acceptable but few where local discomfort will be fully achieved.

It was noted earlier that the LCD and LWD planes are defined by the body part with the greatest predicted discomfort and that the body part in question differs with the environmental conditions. To illustrate this, Figure 7 has been colored according to the body part predicted to have the severest local discomfort (Figure 8). In the room arrangement simulated, the body parts experiencing the most noticeable local cold discomfort were those facing the window – the face, back of hands, and lower arms. These sectors were unprotected by clothing and the face has a high sensitivity to cold (Table 1) and was fully exposed to long-wave radiation loss by virtue of its position and orientation (it had a high view factor with respect to the window).

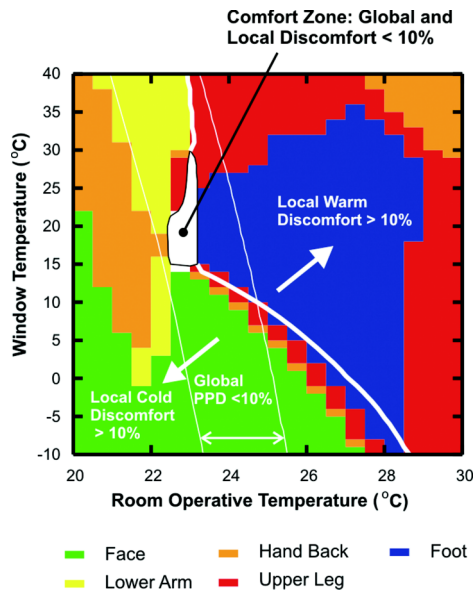


Figure 8 Body part sensitivity to room and window temperature. Typical office clothing including a long sleeve shirt is simulated. The body is 1.0m from the window and there is 100W/m² transmitted diffuse solar radiation.

Effect of Clothing

One of the practical things an individual can do to adapt to cold conditions near windows is to increase their level of clothing. The mitigating effect of, or sensitivity to, clothing levels has been investigated by repeating the parametric calculations with different clothing ensembles. By adding a sweater over the long-sleeved shirt the zones of local comfort are significantly larger than with the shirt alone (Figure 9). In other words, a much larger range of conditions, including very low window temperatures, can be tolerated. However, the range of conditions over which local comfort can be maintained is still smaller than the range over which global comfort can be achieved. We can say that it is more difficult to maintain local cold comfort than global body comfort.

The addition of the sweater meant that the arms were no longer subject to cold discomfort. The chief indicators of local cold discomfort remained the hands and face. However, these were found to be generally more comfortable at lower window temperatures than when the arm was only covered by the shirt. This is perhaps surprising as the hands and face are equally exposed whether the sweater was worn or not. The differences in the predicted response occurred because, when the sweater was worn, the surface temperatures of the hands and face were higher for a given set of environmental conditions. One explanation is that, the insulating properties of the sweater reduces the loss of heat from the blood as it passes through the arm and so the temperature of the blood reaching the hand is higher

Discomfort Zones: Mitigation due to clothing adaptation

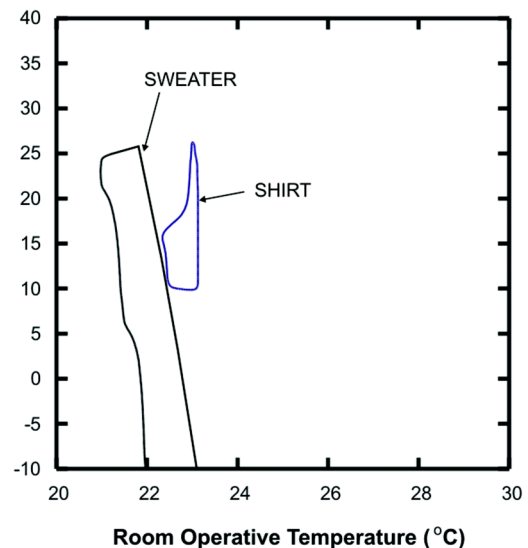


Figure 9 Variation of 10% contours of discomfort (both global and local) according to clothing type. Clothing types are: business dress with long sleeved shirt and with added sweater. The body is 1.0m from the window and there is 100W/m² transmitted diffuse solar radiation.

than it would otherwise be. Similar results were found in simulations with a jacket rather than sweater.

Effect of Solar Irradiation

The relationship between local discomfort adjacent to glazing and solar irradiation is a complex and dynamic one. It is conceivable, for example, that heat lost from particular body parts by excessive long-wave radiation to a cold window surface may be mitigated to some degree by coincident solar irradiation. This is intuitively correct but is also reflected in the formulation of the model's skin heat balance as set out in Eq.1.

When considering winter conditions it is useful to examine what happens to the local comfort zones as the solar radiation is increased. Model predictions showing local comfort zones for a number of solar fluxes are shown in Figure 10. These data include the local comfort zone with 100W/m² flux presented in Figures 7 to 9. It is apparent that the range of window temperatures where there is negligible local cold discomfort is lower. For example when there is 300W/m² solar flux, window surface temperatures in the range 5-10°C can be tolerated without local discomfort² but temperatures higher than 10°C will induce local warm discomfort.

2. Note that solar fluxes have been modelled as diffuse fluxes. Although 500W/m² may be a high value of diffuse flux, combinations of different values of direct and diffuse irradiation show similar trends.

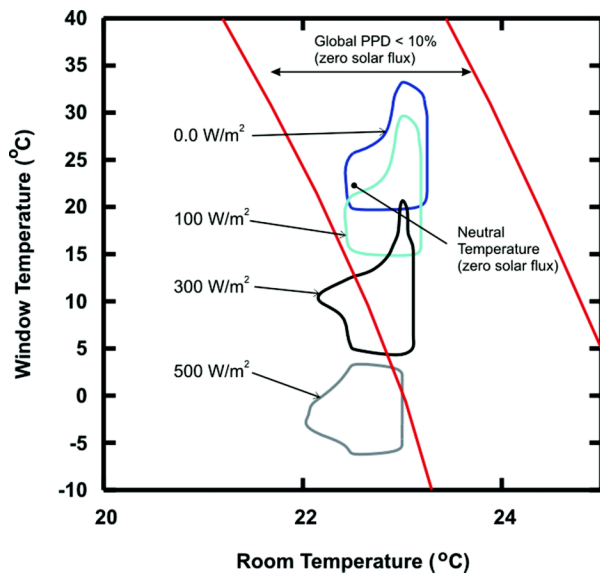


Figure 10 Variation of 10% contours of local cold discomfort according to diffuse solar irradiation (flux at the inside window surface). The upper body outer clothing is a long sleeve shirt. Note the 100 W/m^2 data is as presented in Figures 7 to 9 but with a different horizontal scale.

The results suggest that the temperature range that induces negligible local discomfort is very sensitive to solar irradiation levels. When conditions are dynamic there may be times with both low window temperatures and low solar flux and then, quite soon afterwards, times with high solar fluxes and higher window temperatures. Local comfort conditions may therefore swing from periods of noticeable local cold discomfort to periods of local warm discomfort. Such dynamic conditions will be studied in subsequent work.

CONCLUSIONS

The reported work concerns the prediction of local thermal comfort in buildings close to perimeter windows. This paper focused on steady state predictions, for a single person, wearing office clothing, standing in a prototypical room, within one meter of a window. The impact of the window and room temperatures, solar radiation gains, and the way the person was clothed, on local warm discomfort (LWD) and local cold discomfort (LCD) is predicted and discussed.

The basis for this work was a detailed, multi-node dynamic model that allows simulation of the thermo-physiological behavior of 59 sectors of the human body, and the calculation of local skin temperatures and heat transfer rates; the IESD-Fiala model. This model was combined with recently developed models of local thermal comfort, in which the local skin temperature differences, and the sensitivity coefficients of each body sector, are used to calculate local thermal

stimuli. By using new correlations between these warm and cold stimuli and experimental measurements in asymmetric radiant environments, as reported in the literature, the LCD and LWD could be calculated for each body sector.

This thermal model was combined with a detailed polygonal representation of the person and a radiosity and simplified ray tracing method were used to calculate long wave, and diffuse and direct short-wave radiation factors. This allowed radiation effects to be normalized and so numerous conditions could be easily simulated. The temperature and short-wave radiation at the inside surface of the window provide the boundary conditions.

Parametric studies allowed the extent of LWD and LCD, and the body parts associated with the most severe discomfort, to be mapped for the different boundary conditions. In most of the cases studied, anterior hands, arms and face sectors showed the greatest levels of LCD. Local comfort (both LWD and LCD less than 10%) was achieved for only a small range of boundary conditions that lay within the global thermal comfort envelope. The range of conditions providing local comfort was wider when a sweater was worn, rather than just a long-sleeved shirt. The additional clothing reduced the extent of LCD at the hands and face, probably because the blood supplied to these exposed areas was warmer.

The studies showed that the predicted global comfort was insensitive to the window surface temperature. This suggests that models that only predict global comfort, and that do not include explicit representations of local discomfort, will not reveal problematic environmental conditions in near window regions.

The modeling methods developed in this work allow the effects of time-varying window temperature and solar irradiation to be explored. These boundary conditions can be predicted by dynamic thermal building energy simulation models. Such work would enable the true dynamic relationships between local discomfort, solar irradiation, glazing type and area, and energy use to be explored. Studies of this type have been initiated.

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