Assessing thermal comfort near glass facades with new tools

Sabine Hoffmann, Christoph Jedek, Edward Arens
Center for the Built Environment, University of California at Berkeley

1 ABSTRACT

Transparent facades impact the thermal comfort of occupants in multiple ways. This paper addresses such impacts both for generic glazing and for complex fenestration systems such as shades and blinds. The first step in the process of evaluating comfort for a specific façade is to calculate the solar radiation load on the occupant. The second step is to assess the person's physiological reaction to the radiation and how this reaction influences thermal sensation and perception of thermal comfort.

A newly developed tool (*SoLoCalc*) uses bi-directional scattering functions to characterize the radiant transmission of complex fenestration systems. The output is then linked to an advanced physiology and comfort model. Although this paper describes its use in evaluating glass facades, the tool applies equally to buildings with smaller window-to-wall ratios, or to skylights. A case study of a real construction project shows how the tool enables a new and comprehensive approach to assessing the impact of the building envelope on user comfort.

2 INTRODUCTION

Using glass as a dominant material for the building envelope offers great design opportunities for architects. In recent years the possibilities have been extended through the use of structural glazing, spandrel panels and a huge variety of coatings, films and frits. For the beholder from outside, successful glass architecture demonstrates transparency while for the occupant inside, the large transparent area may provide generous daylight and views. However, less successful designs can be seen to have shades and blinds closing off most of the window area, sacrificing view and daylight to avoid visual glare and occupant discomfort. In addition, large glazed areas often lead to excessive energy use compared to more traditional constructions with smaller window-to-wall ratios.

While a number of measures have been introduced to keep the energy consumption of glass architecture reasonable, the thermal comfort in the space behind the glass facade has typically not been thoroughly addressed. It is often considered to be the duty of the HVAC-system to provide comfortable indoor conditions – a task that may require great energy use to fulfill. With the attempt to build "greener" buildings, engineers aim more and more for low-energy technologies such as radiant cooling, natural ventilation, and personal environmental control [Zhang et al., 2009], and move away from uniformly air-conditioned spaces. It is within this trend that more attention is being paid to the influence of the facade on the comfort of occupants.

In order to assess the thermal conditions of a person sitting or standing in the perimeter zone of a large glazed area, one has to take into account the effects of the facade on air temperature, air movement, long wave radiation and solar load. The room geometry, transparent surface area, and the occupant's position in the room are as important as a number of physiological parameters. This is not addressable by traditional comfort models, all of which either do not take into account the physical presence of the occupant or treat the body as a cylinder or sphere. However, newer multi-segment-models such as the *Berkeley Comfort Model* [Huizenga et al., 2001] do describe the human body in detail and calculate its thermal state as it interacts with its surroundings. The human's perception of the thermal conditions is predicted by empirically determined models that relate skin temperatures and a person's thermal sensation and comfort.

For warm climates or in buildings where the need for cooling energy is predominant, it is essential to reduce the solar load through shading systems. The most favorable way to block the sun is through shading devices external to the glass that are integrated in the architectural design. Other, though less effective ways include blinds interior to the glass or within the glazing unit. For all these systems, the calculation of glass thermal performance values using the assumption of a normal solar incidence, as is commonly done for specular glazing, is no longer acceptable. That is why in recent years, substantial efforts have been made in the physical description of three-dimensional solar transmission through complex fenestration systems [Kohler, 2009].

Despite the progress that has been made in the fields of comfort assessment and solar transmission there has been no tool available that takes all influences on the occupants' heat balance into account: evaporative and convective heat transfer, long-wave radiation with the interior surroundings, and diffuse and direct solar radiation. Such all-embracing consideration will be possible in the future with an approach that combines current state-of-the-art models.

3 ASSESSING THERMAL COMFORT WITH A MULTI-SEGMENT MODEL

The significance of the building envelope for the overall energy balance of a building is well understood. The impact of the facade on thermal comfort is often less investigated because the still most frequently used metrics for thermal comfort, PMV and PPD[1], simplify boundary conditions and do not consider either solar load or the physical presence of the occupant. Therefore some of the main influences on how a person perceives conditions in the room are neglected within this simplified assessment.

3.1 Physiology model

Due to the complex geometrical relationship between facades and occupant, a more detailed model to represent the human body and the thermal impact on the occupant is

1 PMV: Predicted Mean Vote, PPD: Predicted Percentage of Dissatisfied [Fanger, 1970]

necessary. In this paper a mathematical multi-node thermo-regulatory model is used that is based on experimental and numerical work over the last 50 years from [Stolwijk, 1971], [Tanabe et al, 1998], [Huizenga et al., 2001] and others. It describes the physiological processes through a complex set of equations in which the human body is represented through 16 body parts, each of them consisting of a core layer, a muscle layer, a fat layer and a skin layer. Layers are connected to each other through conduction and body segments are linked via a blood flow model.

Within the body there are heat sources and heat sinks: the core layers of chest and back are cooled by the breathing of ambient air, and muscle layers generate metabolic heat under work activity and when shivering. The outer layer connects the body to the ambient conditions. The main heat transfer processes at the outer layer are the convective, longwave radiative, evaporative heat transfer, and the absorption of impinging solar.

A heat balance is established during every time step of the transient simulation and solved numerically; the model then outputs body temperatures for each time step as a result. If the heat balance of the body is not neutral, the resulting skin and core temperature emit signals to the hypothalamus. The modeled human body reacts then with shivering or sweating and with dilation or constriction of blood vessels where the effects on the heat balance are taken into account within the next time step.

3.2 Sensation and comfort model

Several human subject tests have shown that there is a strong relation between skin and core temperatures and thermal sensation and comfort. These relationships have been put into equations [Zhang, 2003] and implemented into the *Berkeley Comfort Model* software to derive sensation and comfort from the physiological predictions of the model [Zhang et al., 2009].

The outputs of the sensation and comfort algorithms are thermal sensation (in terms of being warm or cold) and thermal comfort (in terms of feeling comfortable or uncomfortable). Both metrics range from -4 (very cold or very uncomfortable) to +4 (very hot or very comfortable). They are given for each of the 16 body segments (local sensation / local comfort) as well as for the whole body (overall sensation / overall comfort).

The local sensation output for one body segment depends on the calculated skin temperature with high skin temperatures leading to warm or hot local sensations and low temperatures leading to a cool or cold sensation. The definition of high or low skin temperatures refer to setpoint values implemented in the program. Some body parts are more susceptible to heat than others, e.g. the head. The relationship between the local sensation for the 16 body parts and the overall sensation is complex.

In contrast the correlation between local sensation and local comfort for one body part is straightforward. The further the local sensation metric is from neutral (neutral conditions equal 0 for the sensation metric), the less comfortable one perceives the thermal conditions for that specific body part. The most uncomfortable body parts determine the overall perception of thermal conditions: if e.g. only the head and two other upper body parts show a significant increase in skin temperature, thus high values for sensation, the conditions for these body parts are perceived as uncomfortable and the person will overall feel uncomfortable.

4 IMPACT OF GLASS FACADES ON THERMAL COMFORT

The impact of glazed surfaces on the thermal comfort of occupants can be significant for two reasons: their transparent property allows solar radiation to enter the room, and the glazing’s inner surface temperature, which may be very different from the surface temperatures of other interior surfaces, causes longwave radiant heat exchange and convective heat flows in the adjacent space. Thus the glazed area influences the body’s heat balance through convection, long-wave and short-wave radiation.

(Note: The following does not look at potential condensation on cold surfaces or other issues (daylight, acoustics) which are not directly related to thermal comfort.)

4.1 Effects of convection

In heating climates or during winter in mixed cooling / heating conditions the inner surface temperature of a glass facade or window is usually several degrees below the room air temperature. Warm air moving along the cold surface will be cooled through convective heat transfer. As its density increases, the cooled air follows the gravitational force and moves towards the floor. This eventually causes a continuously rolling air flow with a draft of cold air in the foot region that can lead to an uncomfortable feeling of cold feet.

The effects of inner surface temperatures on local air movement and air temperatures can be determined by direct measurement or by computational fluid dynamics software. The results can be incorporated into the calculation of the person’s thermal state by inputting the corresponding heat transfer coefficients and air temperatures for different body parts into the multi-segment model [Voelker, 2011].

The same approach of first determining convective heat transfer coefficients and temperatures and then using them as input parameters can be used for other possible convective effects in the room, such as natural ventilation, mechanical ventilation (w or w/o air conditioning) and drafts due to cracks in the window / frame seal or to other parts of the facade that are not airtight.

4.2 Longwave radiation heat exchange between occupant and facade

All surfaces in a room emit longwave radiation and so does the occupant via her outer surface. Important for the body's heat balance is the difference of the radiation emitted to the ambient and the energy received from the surroundings (including reflective radiation). The parameters that influence this heat balance are the surface temperatures to the fourth power, the emission coefficients, and the geometry.

Compared to the inner surface temperatures of partitions, ceiling, and floor, glass facades tend to have significantly lower temperatures under heating conditions (cold outdoor temperatures with little solar radiation). In the presence of solar radiation they can show significantly higher temperatures than the inner walls especially when using solar coatings, frits or tinted glass due to the heat absorption in the glass.

To assess the influence of longwave radiation to and from glass facades on comfort it is convenient to use an advanced calculation tool such as *Window6*[2] in order to determine the surface temperatures at the inside of a glazing systems (w or w/o shading).

How much heat is exchanged between two surfaces not only depends on the emissivity of the surfaces and their temperatures but also on the geometry determining how much one surface can see of another. In the case of the occupant of a room it is critical how far the person is sitting (or standing) from the considered surface. If the surface temperatures exceed a certain comfort range, the only way to maintain a comfortable heat balance is to move further away so that the facade is seen less. The mathematical description of this influence is expressed by view factors [Howell, Siegel, 1972].

4.3 Solar radiation on occupant

Solar radiation that is transmitted through the transparent (or translucent) part of the facade and that hits the occupant in the room produces a heat load on the human body. The main part of the radiation energy is absorbed on the surface of either the skin (in the case of nude body parts such as face or hands) or the fabric (in the case of clothed body parts) and leads to a temperature increase of those outer layers. The values for solar absorption on the skin range from 0.6 to 0.9 and from 0.3 to 0.9 for common clothing. Following the general rules of heat transfer, the increased temperature of the outer layer reduces the heat flux from the inner core to the outside, meaning that the body cannot dispose of additional heat as readily as before.

4.3.1 Diffuse and direct radiation through the facade

The glazing industry provides a huge variety of coatings and films in glazing systems to address the issues of heat transfer and solar load through windows and glass facades. The optical properties of coatings and films in combination with specific substrates are

2 http://windows.lbl.gov/software/window/window.html

available from the International Glazing Database (IGDB) that provides more than 3800 entries in its current version (IGDB 21.0 as of February 2012). The transmission and reflection values in the IGDB are given over the entire solar spectrum, allowing the transmission of a particular glazing system to be calculated at one wave length and then integrating the spectral data to the integral values: visible transmittance (Tvis), transmittance over the whole solar spectrum (Tsol) and solar heat gain coefficient (Tsol + secondary heat gain through conduction, convection and radiation). These performance indices are calculated for a normal incidence angle of the sun.

Although some of the available coatings provide very low SHGC values, other options of reducing solar load are often more favorable for a specific project. These options include exterior shades (horizontal or vertical, operable or fixed etc.), blinds in the gap of an insulating glazing unit or double skin facade, frits on the glass and others. These measures are dominated by diffuse components where the direct ray is no longer transmitted in the same direction as when it impinged on the facade but is redirected in other directions and/or scattered.

Unlike in specular glazing systems[3], the assumption of normal incidence nearly always leads to wrong results when applied to shading systems. For example, horizontal slats will not improve a calculated SHGC coefficient for the system when assuming an incidence angle of 0°, but in practice horizontal slats are very efficient at blocking sun rays at high solar altitudes.

The significance of the solar incidence angle for the transmission of shading systems is obvious. LBL introduced the method of bi-directional data for these so called complex fenestration systems in the algorithms of “Window6” [Kohler, 2009]. The output of these algorithms, the “Bi-Directional Scattering Distribution Function (BSDF)”, is used in the newly developed calculation tool *SoLoCalc* described in Section 5. The BSDF contains information about the hemispherical distribution of transmitted solar radiation into the room for any given incidence angle. The transmitted radiation contains direct components (if any) as well as the diffuse components. (For more information see also: Christian Kohler: Simulation of Complex Glazing products, BEST3, April 2012)

4.3.2 Perception of diffuse and direct radiation

Although they both represent a heat load on the body, there are differences in the perception of diffuse and direct radiation. A uniformly distributed (diffuse) radiation on the body increases the local sensation of all body parts to a similar extent. The result is an overall warm sensation while the overall comfort can still be acceptable (depending on intensity and duration of the conditions).

---

3 Specular glazing: transmitted solar radiation follows the incident direction, without diffusing or scattering effects

Local direct radiation (with usually higher intensity than diffuse radiation) on only a few body parts raises skin temperature locally. That leads to high values of local sensation for the irradiated body parts while the local sensation of the non-irradiated segments is not influenced. The overall comfort rating is likely to be more uncomfortable because the most uncomfortable local segment dictates the overall comfort.

Figure 1 shows the prediction of overall sensation and overall comfort as well as for local comfort (see color scale in the middle referring to the color of the body parts) for the same heat load impinged on the body under steady-state conditions. In the picture on the right side, a heat load of 80W hit head, hands, the left upper arm and parts of the upper body.

In the picture on the left side, the same heat flux was distributed uniformly over the person. The results, calculated with the *Berkeley Comfort Model* software, show very uncomfortable values for head and hands in the case of direct radiation which leads to an overall comfort score of -2.8 that is equivalent to very uncomfortable. The person who receives the same heat flux (80W) in form of diffuse radiation feels less warm (overall sensation 1.5 compared to 3.0 for direct radiation) and more comfortable (overall comfort -1.1 compared to -2.8).

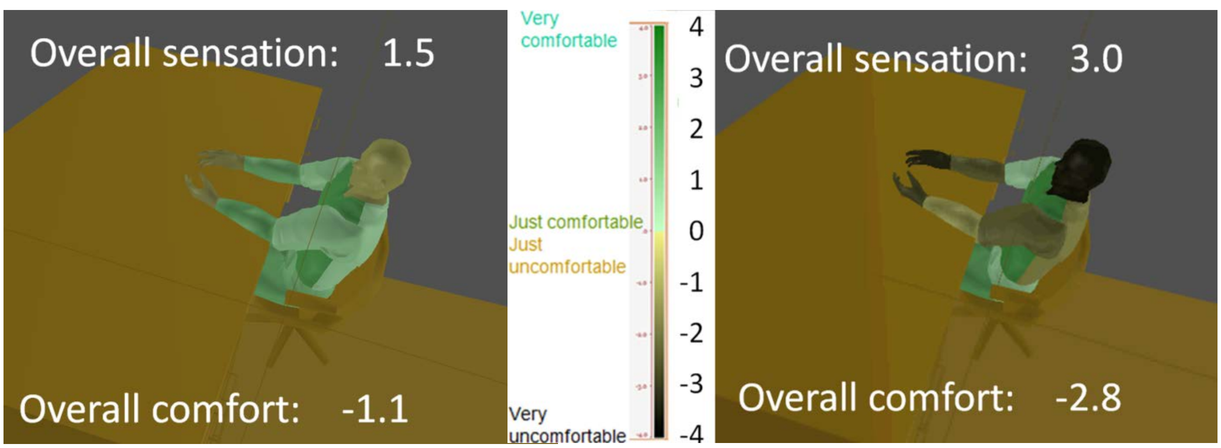

Figure 1: *Sensation and comfort for a solar heat load of 80 W calculated with the "Berkeley Comfort Model"*

Left: *diffuse radiation uniformly distributed over the whole body*
Right: *direct radiation on head, hands and upper body*

5 THE SOLAR LOAD CALCULATOR "SOLO CALC"

To account for diffusing or light redirecting elements in the facade, a new tool was developed as part of a research project within the Center for the Built Environment [Hoffmann et al., 2011].This tool, called *SoLoCalc*, calculates the solar load onto occupants by making use of data for three-dimensional transmission through complex fenestration systems as available in the *Window6* software.

5.1 Bi-directional scattering distribution function

SoLoCalc is based on bi-directional scattering distribution functions (BSDF). This information is provided from *Window6* in form of a matrix where the columns represent the hemispherical incidence angle of the sun ("outer hemisphere") and the rows represent the hemispherical transmission of solar radiation into the room ("inner hemisphere"). This concept allows for an easy access to the necessary data during the simulation.

SoLoCalc calculates the incidence angle on the facade for the location of the building, hour and day of the year and for the orientation of the facade. This incidence angle (expressed in spherical coordinates) gives the information which column of the BSDF matrix has to be chosen. The three-dimensionally transmitted energy has then to be attributed to the body parts of the person sitting (or standing) behind the facade. These values can be derived from the rows of the BSDF matrix.

While the coupling of the outer hemisphere to a given solar incidence angle is straightforward, the linking of the transmitted energy to the occupant needed a new approach in *SoLoCalc*.

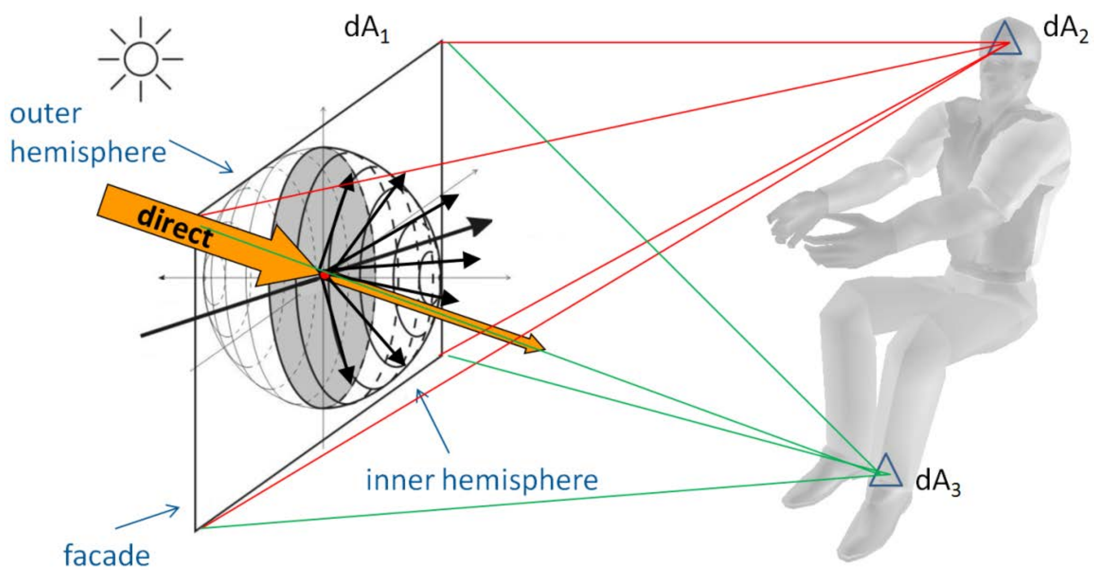

Figure 2: Linking the 3-D transmission to the solar load on certain body parts

5.2 Application of the viewfactor method to shortwave radiation

The approach that was chosen in *SoLoCalc* is to use viewfactors (as described above for longwave radiation exchange) for solar radiation. In general, the use of viewfactors in the calculation of radiative heat transfer is justified where the emitter can be considered as uniformly diffuse, which is only true for ideally diffusing systems. Nevertheless, in our case the viewfactor method is applicable for not-ideal scattering systems due to the incremental nature of the data. In the BSDF files the inner hemisphere is subdivided into a substantial number of "bins" (e.g. 145 bins for a "full size matrix" in *Window6* [Klems, 1994]). Each bin corresponds hereby to a defined solid angle on the unit sphere. The viewfactor method treats the emitting surface as a uniform diffuse emitter for this solid angle. The emitted heat flux is the amount of solar load transmitted in this particular direction.

For the chosen approach it is necessary to subdivide the geometrical description of the occupant (called "manikin") into small plane polygons where a group of polygons represents a body segment. The currently used manikin consists of 1356 polygons to form the 16 body segments. It is also necessary to subdivide the facade into partial areas with an adequately chosen discretization.

For the viewfactor calculation we currently use the open source software *View3D*[4] to handle the number of surfaces and the amount of blocking [Walton, 2002] but other software tools that provide viewfactor calculation would be possible as well. The viewfactors between the manikin polygons and the façade are necessary input values for the algorithms implemented in *SoLoCalc*.

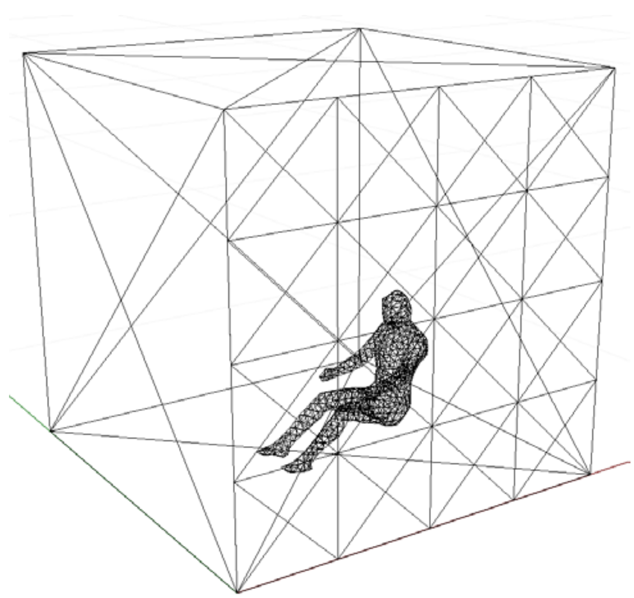

Figure 3: Meshing of manikin (1356 polygons) and facade (64 polygons)

4 http://view3d.sourceforge.net/

6 CASE STUDY

The case study presented here was initiated as a collaborate project between ZGF Architects, Portland and CBE. More details about the project, a hospital building in Denver, can be found in an associated BEST3 paper by Mark Perepelitza: Building Enclosure Performance Research - Applications in Professional Practice.

With the help of the following example the importance of the described approach will become obvious: the necessity for the detailed calculation of solar load onto the occupant because of the variation of sensitivity for different body parts, the concluding overall perception of the conditions and finally the comparison of how comfortable the occupant would feel for different options such as solar coatings, frits and/or shades.

The case study looks at a specific room geometry and specific occupant location within a building in Denver, Colorado. The results shown here were calculated for a patient room at the South façade of the building, with a person (visitor or patient) sitting in a chair at a distance of 9 feet from the glazing parallel to the façade, looking towards the West.

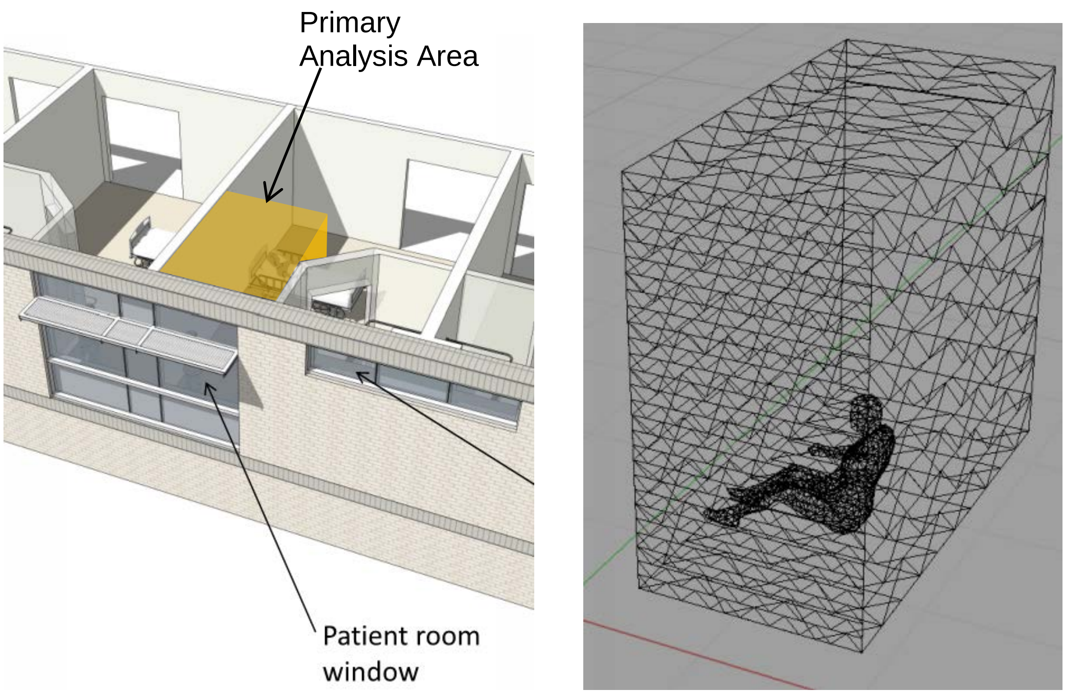

Figure 4: Denver hospital patient room (see also Mark Perepelitza: Applications in Professional Practice)

An extremely clear summer day was chosen as boundary condition with a peak radiation of 985 W/m^2. In order to make the decision of which would be the necessary measures to minimize thermal discomfort, the situation was modeled with and without exterior shading.

6.1 Solar load on the body

Due to the relative narrow room width, the number of hours when direct sunlight hits the person through the façade is limited. In the case of a solar coating without exterior shade, the person receives direct radiation for the first time around 11 am with the left lower extremities being irradiated (Fig. 5). The upper body is irradiated during the peak hours of solar load between 1 and 2 pm. In the late afternoon hours after 3 pm when the sun moves towards the West, the direct radiation that hits the body decreases.

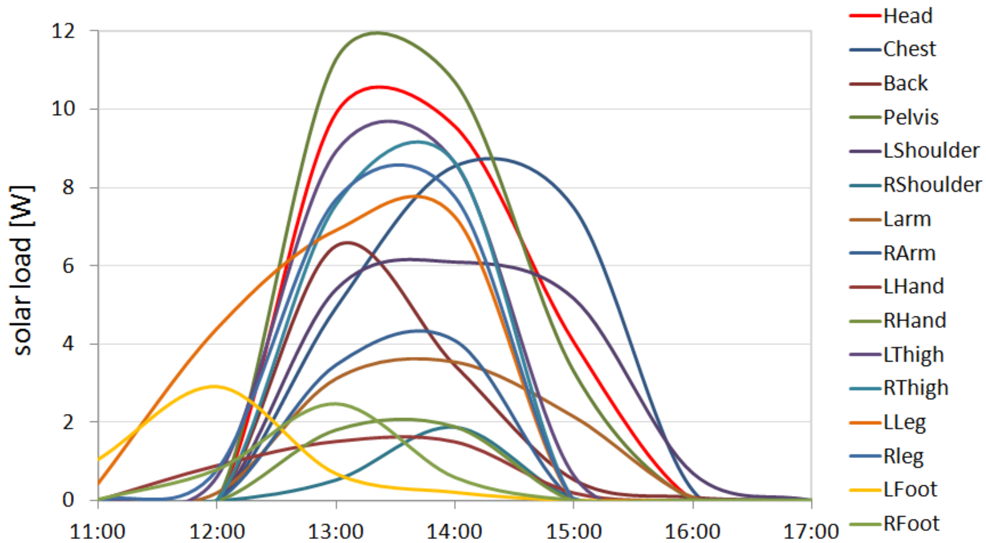

Figure 5: Solar load on body parts for a solar coating with SHGC = 0.33

If an exterior shade is mounted in addition to the solar coating of the glazing (Fig. 6), not only the overall solar load is significantly reduced, the received radiation is also distributed more evenly over the different body parts due to the diffusing effect of the exterior shade, and the period of time of irradiation is reduced.

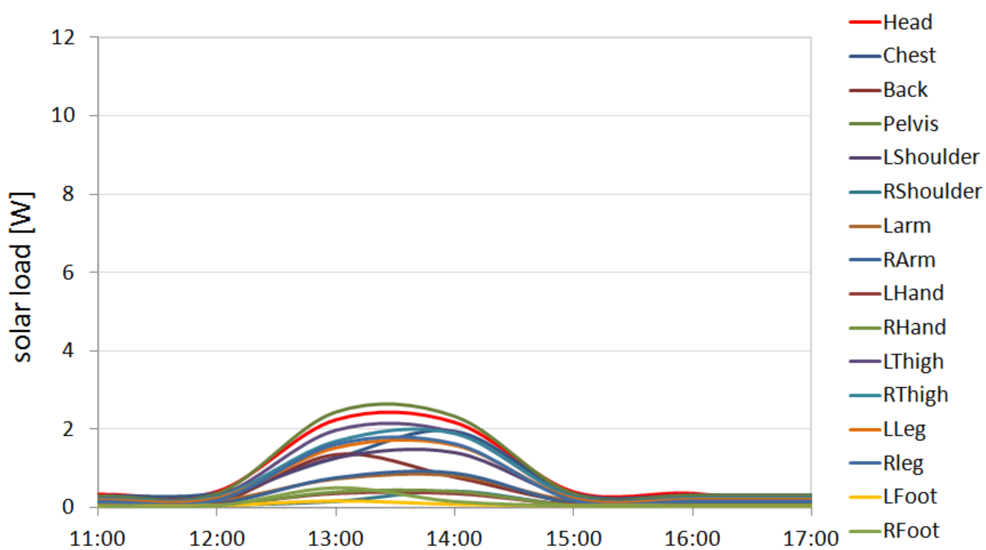

Figure 6: Solar load on body parts for the solar coating plus the exterior shade

6.2 Sensation and comfort

In Fig. 7a and 7b the dark red line shows the overall sensation of the occupant for the case without exterior shade. The metric “overall sensation” represents the vote that a normalized person would give if asked for the perception of temperature conditions in the room.[5] At noon the predicted vote would be “slightly warm”, from 1 pm to 3:30 pm the conditions would be perceived as “hot” before the overall sensation rating drops to “warm” at 4 pm and to “slightly warm” at 5 pm.

The other curves represented in the Fig. 7a and 7b correspond to the metric “local sensation”, i.e. how warm a specific body part is perceived. When comparing the overall sensation to the local sensation curves, it becomes obvious that the overall sensation is not equal to the mathematical average (mean) sensation: body parts have different impacts on the overall sensation.

In Fig. 7a, the highlighted local sensations are those of the left leg and left foot. These are the body parts that receive most of the direct radiation before noon. As the lower extremities are less sensitive to heat, their influence on the overall sensation is not very strong.

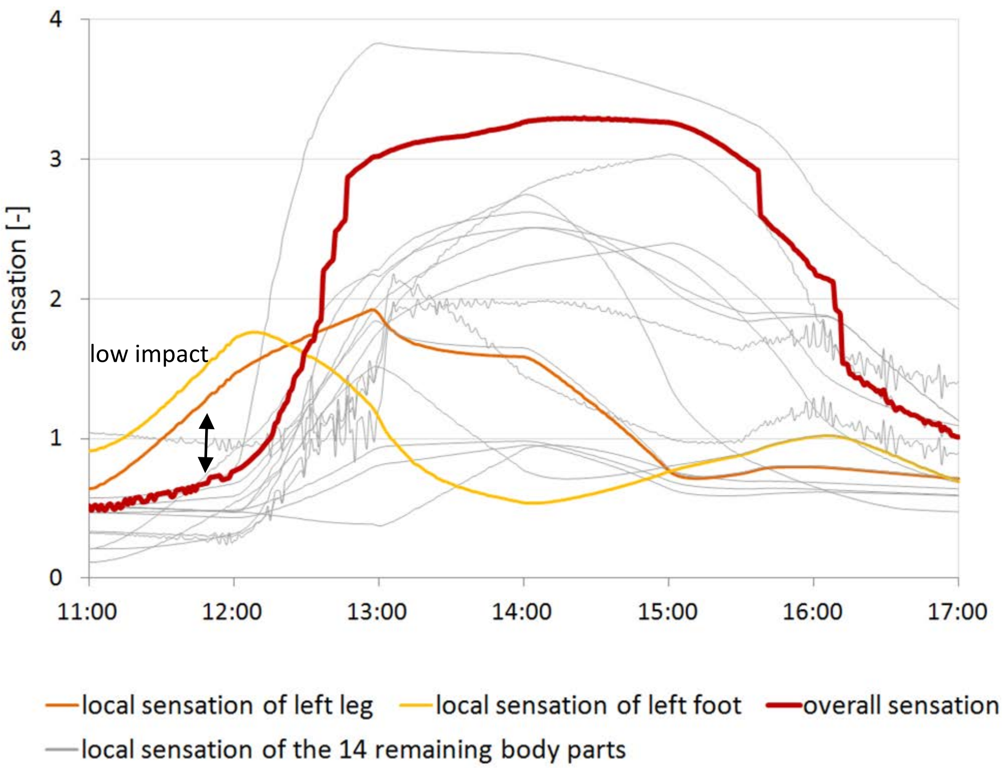

Figure 7a: Local and overall sensation for solar coating without exterior shade, left leg and foot highlighted

5 The modeling of the occupant’s thermal state starts a couple of hours earlier (e.g. around the time when the person enters the office and gets started with sedentary work) and it is assumed that prior to the occurrence of direct radiation the person is in a thermally neutral state, i.e. she or he is neither too hot nor too cold, i.e. overall sensation = 0.

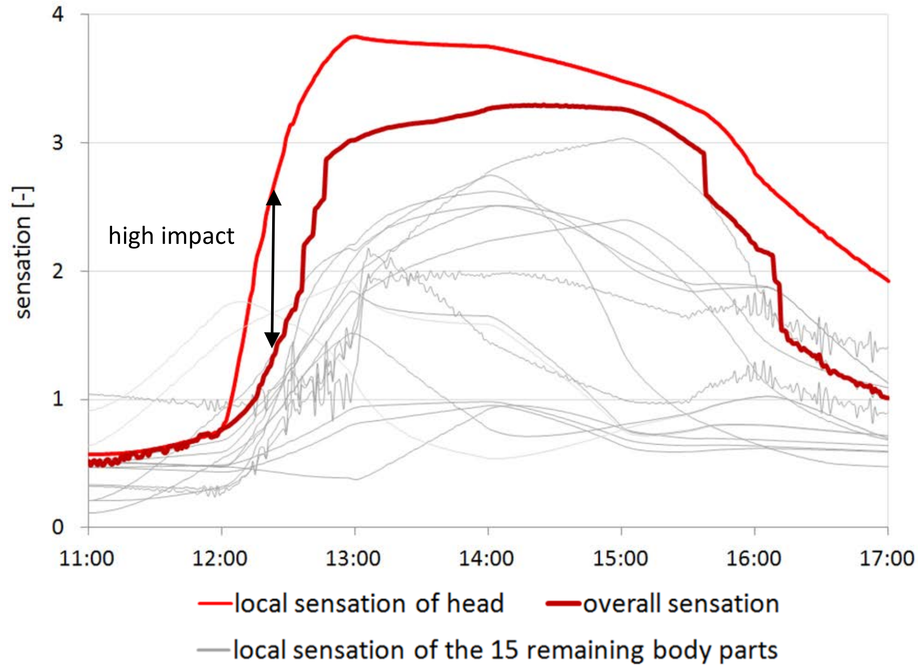

Figure 7b: Local and overall sensation for solar coating without exterior shade, head highlighted

In contrast to the low influence of the lower extremities, Fig. 7b shows how strongly the head reacts to the solar radiation and how the overall sensation follows the slope of the head's local sensation.

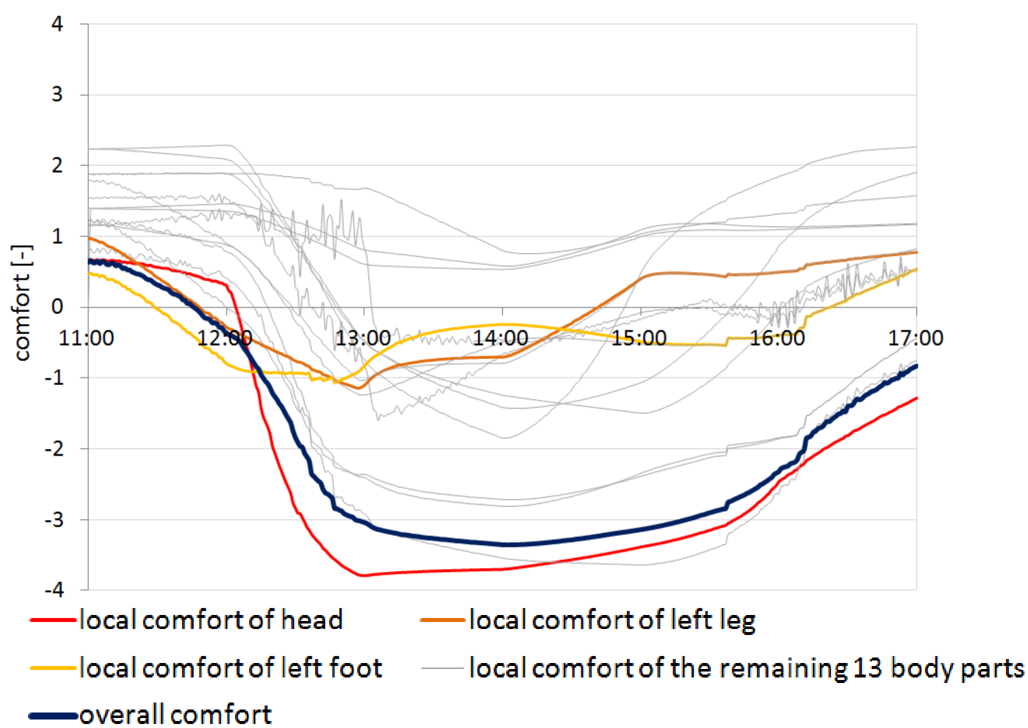

Figure 8: Local and overall comfort for solar coating without exterior shade, head, left leg and left foot highlighted

Fig. 8 shows how local and overall sensation translates to local and overall comfort. Any comfort value above -0.5 corresponds to the vote "comfortable" or better. Although Fig. 7a shows the left leg and left foot experiencing a warm sensation the occupant does not become uncomfortable. The head, which is more sensitive to heat, not only experiences a sensation of "very hot" in the presence of direct radiation (Fig. 7b) but it also becomes "very uncomfortable" (Fig. 8). The most uncomfortable body parts determine the overall perception of comfort; hence the overall vote drops to "very uncomfortable" at 1 pm and only reaches a comfortable level again at 5 pm.

6.3 The decision making process – comparing options

While the results presented in 6.2 demonstrate the process of assessing comfort based on a detailed solar load calculation, it is usually of greater interest to know how different project options compare to each other in terms of comfort. In this case study the main question to answer was whether an external shade as shown in Fig. 4 is needed to provide a satisfying comfort level, or if the use of a solar coating alone is sufficient.

In order to assess the effects of the solar coating alone without exterior shade, a base case with a clear glass IGU (w/o coating) was used as a reference (black lines).

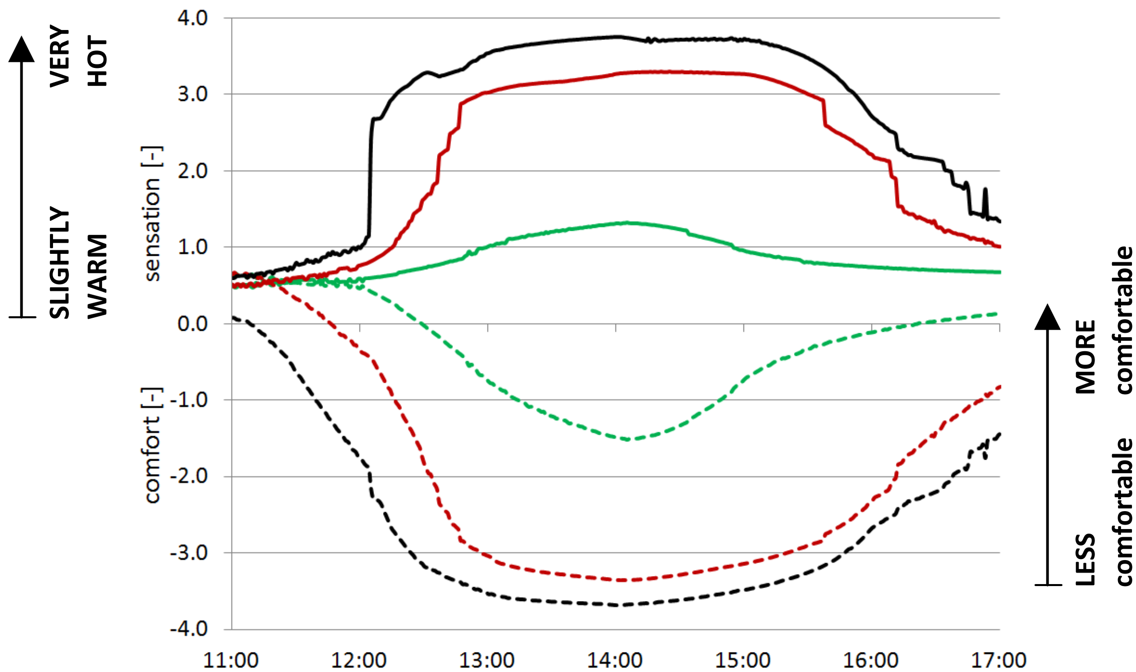

Figure 9: Overall sensation (bold) and overall comfort (dashed) for different options

Black: Clear glass IGU
Red: HP solar coating
Green: HP solar coating + exterior shade

While a person sitting in the patient room without an exterior shade would feel hot for most of the afternoon, adding the shade would make the person feel only “slightly warm” and therefore more comfortable. Although the solar coating with an SHGC of 33 % can reduce the heat load into the room substantially compared to a non-coated IGU, it does not reduce the thermal discomfort significantly. The direct radiation that hits the occupant on sensitive body parts such as the head leads automatically to a perception of the room conditions as very uncomfortably hot.

6.4 Discussion of the results

The presented results of the case study are the first ones in a series of calculations which will be published in a future paper in the Journal of Building Physics. In this paper a single, extremely clear summer day with maximum radiation was chosen in order to demonstrate the methodology and the outcome. In the next step, different sky conditions including more cloudy days and different seasons (fall, winter, spring) will be assessed.

As with all modeling, each of the used simulation tools is subject to assumptions which imply a certain uncertainty in the results. As these assumptions do not change within one set of simulation runs, numerical approaches are generally well-suited for parametric studies and the comparison of different options, but they may be less reliable in terms of absolute values. Comparing simulation results with observations in the field will increase the confidence when interpreting numerical values.

In this paper the focus lies on the assessment of thermal comfort. Other determining areas such as the general load on the HVAC system and the influence on daylight conditions in the room have to be investigated separately. Although a solar coating alone might not be favorable in terms of thermal comfort because it permits direct radiation in the perimeter zone, it is still efficient to reduce the solar load in the room and might be sufficient when no occupants are significantly exposed to the sun. On the other hand a certain shading system might be rejected for its impact on the daylight conditions in the room though it provides a thermally comfortable indoor climate. Which solution to choose and which trade-offs to make always depends on the specifics of the buildings and the priorities of the client.

7 CONCLUSIONS

The presented example (Section 4) and the case study (Section 6), as well as results from previous studies show that the comfort level in a building is higher when direct sun impinging on the occupant is avoided. Diffusing shading systems improve best the quality of the indoor conditions, especially in buildings with large transparent areas and unfavorable orientations, because they reduce direct radiation on sensitive body parts and local discomfort.

The newly developed software tool *SoLoCalc* together with a multi-segment physiology model and the corresponding comfort equations allows quantifying the effects of different shading systems, solar coatings, frits etc. on the occupants' perception of thermal comfort in the room. The innovation of *SoLoCalc* is the use of bi-directional scattering distribution functions for complex fenestration systems (exterior and interior venetian blinds, coatings, frits etc) as provided by the *Window6* software.

As shown in the case study, it is now possible to rank options for a given project by running parametric studies of solar load, thermal sensation and comfort while accounting for all important project conditions such as the geographic location of the building, the facade orientation, room geometry, window-to-wall ratio and the occupant's position in the perimeter zone.

ACKNOWLEDGMENTS

Several organizations contributed in one way or another to this project:

- California Energy Commission Public Interest Energy Research (PIER)
  – project funding.
- Center for the Built Environment (CBE)
  – *Berkeley Comfort Model* and *SoLoCalc* project co-funding.
- Lawrence Berkeley National Laboratory (LBNL)
  – *Window6*
- National Institute of Standards and Technology (NIST)
  – *View3D*
- ZGF Architects Portland
  – funding for the case study

REFERENCES

Arens, E., and H. Zhang, 2006. "The Skin's Role in Human Thermophysiology and Comfort." *Thermal and Moisture Transport in Fibrous Materials*, Eds. N. Pan and P. Gibson, Woodhouse Publishing, London, pp 560-602, October.

Fanger, P. O., "Thermal Comfort", Danish Technical Press, 1970 (republished by McGraw-Hill, New York, 1973)

Hoffmann, S., Jedek, C. "Advanced Tool for Assessing Comfort near Glass Facades: Calculation of solar load on occupant." University of California, Berkeley, CBE meeting, Oct 2011

Hoffmann, S., Jedek, C., WraNielsen, M., Arens, E., Zhange, H. Yu, T. "Advanced Tool for Modeling Comfort near Glass Facades" University of California, Berkeley, CBE meeting, April 2011

Huizenga, C., H. Zhang and E. Arens, 2001. “A Model of Human Physiology and Comfort for Assessing Complex Thermal Environments.” *Building and Environment*, Vol. 36, pp. 691-699.

Huizenga, C., H. Zhang, E. Arens, and D. Wang, 2004. "Skin and Core Temperature Response to Partial- and Whole-Body Heating and Cooling," *Journal of Thermal Biology* Vol. 29 (2004) pp. 549–558

Huizenga, C., H. Zhang, P. Mattelaer, T. Yu, E. Arens, and P. Lyons, 2006. “Window Performance for Human Thermal Comfort.” Final Report to the National Fenestration Rating Council, Center for the Built Environment, University of California, Berkeley, February 2006.

Klems, J.H. 1994a. “A New Method for Predicting the Solar Heat Gain of Complex Fenestration Systems I”. Overview and Derivation of the Matrix Layer Calculation. ASHRAE Transactions V.100, Pt. 1

Kohler, C., 2009. “WINDOW6 detailed overview”, Complex Glazing Workshop, June 1st, 2009, Windows and Daylighting Research Group, Lawrence Berkeley National Laboratory

Siegel, R., J. R. Howell, 1972 „Thermal radiation heat transfer“ McGraw-Hill, Inc., ISBN 07-057318-2

Stolwijk, J.A.J., 1971. “A mathematical model of physiological temperature regulation in man.” Washington, D.C.: NASA Contractor Reports CR-1855.

Tanabe, S., S. Horikawa, M. Kin, H. Tsutumi, 1998. “Comparison of physiological values calculated by a 65 node thermoregulation-model with subjective experiments.“ Proceedings of SHASE, pp. 989-992, 1998.

Voelker, C. 2011. “Entwicklung und messtechnische Validierung der Kopplung von CFD-Simulation mit einem thermophysiologischen Modell zur Bestimmung der thermischen Behaglichkeit” PhD Thesis, Bauhaus-Universiteat Weimar, Germany, Nov. .
Zhang, H. 2003. "Human Thermal Sensation and Comfort in Transient and Non-Uniform Thermal Environments,” PhD Thesis, Center for Environmental Design Research (CEDR), University of California at Berkeley, December.

Zhang H., E. Arens, C. Huizenga, and T. Han, 2009. “Thermal Sensation and Comfort Models for Non-Uniform and Transient Environments:
Part I: Local Sensation of Individual Body Parts,” *Building and Environment*, 9 pp.
Part II: Local Comfort of Individual Body Parts,” *Building and Environment*, 10 pp.
Part III: Whole-Body Sensation and Comfort,” *Building and Environment*, 12 pp.