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Web application for thermal comfort visualization and calculation according to ASHRAE Standard 55

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Web application for thermal comfort visualization and calculation according to ASHRAE Standard 55

Abstract

Thermal comfort is one of the fundamental aspects of indoor environmental quality and it is strongly related to occupant satisfaction and energy use in buildings. This paper describes a new web application for thermal comfort visualization and calculation according to ASHRAE Standard 55-2010 and 2013. Compared to existing software, the web application is free, cross-platform, and provides a visual and highly interactive accurate representation of the comfort zone. Its main features are: dynamic visualization of the comfort zone on psychrometric, temperature-relative humidity, and adaptive charts; new implementation of the Elevated Air Speed model; local thermal discomfort assessment; compliance document automation for LEED thermal comfort credits; metabolic activity and clothing insulation tables and dynamic models; and compliance with the standard. The tool can be used by architects, engineers, building operators, educators, and students.

Keywords

Thermal comfort, Predictive Mean Vote – Predicted Percentage of Dissatisfied (PMV/PPD), Adaptive Comfort, psychrometric chart, visualization, web application.

Acronyms and symbols

ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers
clo	Unit of clothing insulation [$m^2 \cdot K/W$]
HVAC	Heating, Ventilation and Air-Conditioning
LEED	Leadership in Energy and Environmental Design
met	Unit of metabolic activity [W/m^2]
MRT	Mean radiant temperature [°C]
PMV	Predicted Mean Vote [-]
PPD	Predicted Percentage of Dissatisfied [%]
rh	Relative humidity [%]
SET	Standard Effective Temperature [°C]

1 Introduction

Maintaining thermal comfort for building occupants is a primary goal of HVAC (heating, ventilation, and air conditioning) design engineers, architects and building operators. There is room for improvement. Thermal comfort is the second largest source of dissatisfaction (after sound privacy) in US office buildings; more than 50% of occupants are not satisfied with their thermal environment (Frontczak 2012). At the same time, the energy used for HVAC is high, approaching 71% of primary energy use in commercial building (18% of societal energy use) (U.S. Department of Energy 2011). There are many causes for this poor performance, including mechanical ones like building envelope, systems, and controls. But in addition there appears to be limited or outdated understanding among designers and operators of how comfort is affected by the full range of possible indoor thermal conditions. In the design and operation of buildings and HVAC systems, an understanding of human thermal comfort can create opportunities to save energy while improving, or at least not compromising, current levels of occupant satisfaction. Examples might be in extending thermostat heating and cooling setpoints (Hoyt 2009; Schiavon and Melikov 2008), or in the use of personal comfort systems (Zhang 2010) or in the avoidance of summer overcooling and winter overheating (Mendell and Mirer 2009). Using such approaches requires a clear understanding of how the human responds to each of the climate variables, and how their limits interact. Thermal comfort prediction and visualization tools may help designers, building operators to better design, operate and understand thermal comfort.

In this paper, after a brief introduction of thermal comfort models used in ASHRAE Standard 55-2010, we describe the limitations of existing thermal comfort visualization techniques and software, and present a new web application for thermal comfort visualization and calculation. The 'comfort tool' is based on the methods and models in ASHRAE Standard 55-2010 and 2013. In Section 2 the web-application software architecture and a new interpretation of the elevated air speed method are described. The thermal comfort visualization charts are shown and described in Section 3, while the main features of the tool are described in Section 4.

1.1 Thermal comfort models

The three relevant standards regarding thermal comfort are the international standard ISO 7730 (2005), the European standard EN 15251 (CEN 2007) and the ASHRAE 55 (2010). The web application described here work is based primarily on ASHRAE Standard 55-2010 and the forthcoming 2013, and their addenda. ASHRAE Standard 55 specifies the combinations of indoor thermal environmental factors and personal factors that produce thermal environmental conditions acceptable to a majority of the occupants within a space. Thermal comfort is based on the Predicted Mean Vote / Predicted Percentage of Dissatisfied (PMV/PPD) (Fanger 1970) and Standard Effective Temperature (SET) (Fobelets and Gagge 1988; Gagge 1986) comfort models. For elevated air speed levels (> 0.15 m/s), the Standard uses an integrated SET-PMV approach described in Section 2.2 and referred to as the Elevated Air Speed model. The Adaptive Comfort model (de Dear and Brager 1998) can be used to assess naturally conditioned spaces.

SET is a comfort index based on a dynamic two-node model of human temperature regulation, in which the body is modeled as two concentric cylinders, the inner representing the body core and the outer representing the thin skin shell. The SET is defined as the equivalent air temperature of an isothermal environment at relative humidity (rh) 50% in which a subject, wearing clothing standardized for the activity concerned, has the same heat stress and thermoregulatory strain as in the actual environment (ASHRAE 2009). The isothermal environment is at sea level, with air temperature equal to mean radiant temperature, and with still air. This means that the skin heat loss, temperature and wettedness provided by the SET model in the isothermal environment are equal to those of the person in the actual environment. The model applies to a lightly clothed person who is engaged in near sedentary activity. The SET lines generated with this model are used to extend the comfort zone boundaries across a range of air speeds.

According to ASHRAE Standard 55 the Adaptive Comfort model can be used in naturally conditioned buildings, with no mechanical cooling system installed and no heating system in operation. The standard specifies that the prevailing mean outdoor temperature should be greater than 10°C and less than 33.5°C, and the occupants should be engaged in near sedentary activities (met between 1.0 and 1.3) and have the freedom to adapt their clothing level at least in the range of 0.5 to 1.0 clo. The Adaptive Comfort model is based on the work of de Dear and Brager (de Dear and Brager 1998), which showed that occupants in naturally ventilated buildings preferred a wider range of temperatures that reflected the swings of the outdoor climate. The adaptation is due both to behavioral and physiological adjustments.

1.2 Visual representation of thermal comfort

The growing power of consumer computers and browser technology has enabled highly accessible applications capable of real-time scientific computation and visualization. Visualizations help users understand and act on data quickly and effectively. Providing designers, building operators and building science educators with thermal comfort prediction and visualization tools will contribute to the design, operation and investigation of more comfortable and energy efficient indoor spaces. A simple, interactive and complete visualization of thermal comfort is a benefit to professional practice designers.

To our knowledge, the first significant attempt of creating a single-figure comfort index was made by Houghten and Yaglou (1923) and named Effective Temperature (ET). This index combines temperature and humidity, so that two environments with the same ET should evoke the same thermal response even though they have different values of temperature and humidity, as long as they have the same air velocity (ASHRAE 2009).

An important pioneer of thermal comfort representations was Victor Olgyay, who used the previous work on the ET as the basis of his comfort diagram, the 'Bioclimatic Chart', shown in Figure 1a. This chart assumes the criterion that the perimeter of the comfort zone is defined by the conditions wherein the average person will not experience the feeling of discomfort, and it applies to moderate climate zones (Olgyay 1963). Four parameters are considered in his representation: air movement, vapor pressure, evaporation and radiation effect. Dry-bulb temperature is the ordinate and relative humidity (rh) the abscissa. The chart displays the comfort zone in the middle surrounded by curves that describe how climatic effects can be used to restore the feeling of comfort for conditions that fall outside of the boundaries. The bioclimatic chart is a powerful representation that combines several factors and considers their interaction and effects on thermal comfort (Givoni 1998). The thermal comfort area reported in the chart is not consistent with ASHRAE 55 thermal comfort areas. Givoni, the author of the 'Building Bioclimatic Chart' (Figure 1b), partially converted the Olgyay's representation to the psychrometric chart and added rules about passive heating and cooling strategies. The Building Bioclimatic Chart has two components: thermal comfort area and '*boundaries of climatic conditions within which various building design strategies and natural cooling systems can provide comfort*' (Givoni 1992). Limitations of the chart are reported by Lomas at al. (Lomas 2004).

The psychrometric chart is the most complete representation of the factors involved in the study of moist air (ASHRAE 2009). It represents an equation of state and it allows all the parameters of moist air to be determined from any three independent parameters.

In the psychrometric chart the atmospheric pressure is fixed, the dry-bulb temperature is on the x-axis, and the humidity ratio is on the y-axis. Vertical lines represent constant dry-bulb temperature, and horizontal lines represent constant humidity ratio values. Curved lines climbing from left to right represent equal relative humidity. The upper boundary of the chart is known as saturation line, i.e. at 100%, the points at which moisture in the air begins to condense. These points correspond to the dew-point temperatures at a given humidity ratio, or conversely, the maximum amount of moisture that can be held by the air at a given temperature. The psychrometric chart is used for many applications, including thermal comfort assessment.

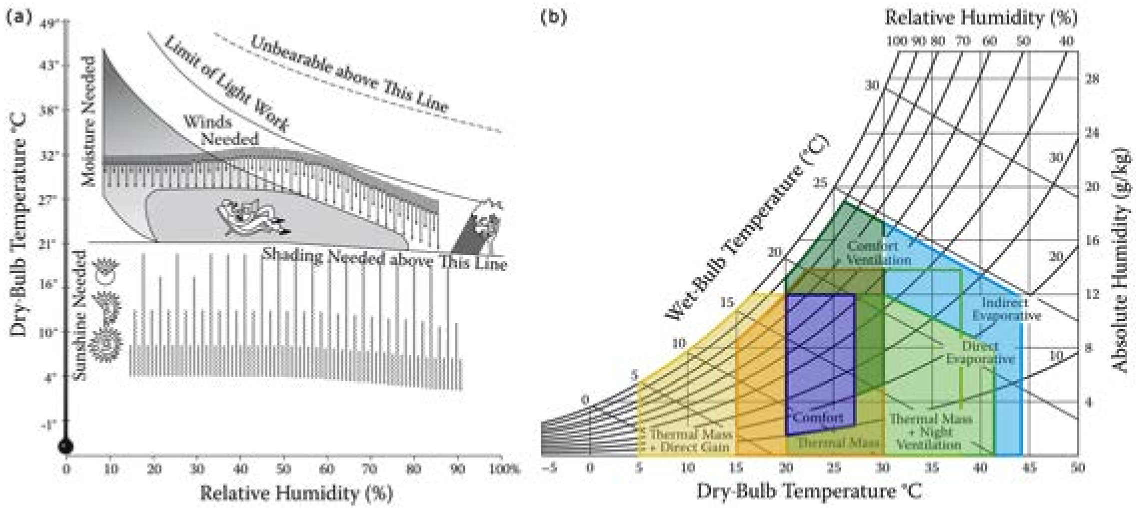

Figure 1. Representations of thermal comfort zones and passive design strategies, such as natural ventilation, solar radiation, shading, evaporative cooling and thermal mass. (a) Olgyay's bioclimatic chart, adapted from (Olgyay 1963). In this chart relative humidity is on the horizontal axis and dry-bulb temperature on the vertical axis. (b) Givoni's building bioclimatic chart, adapted from La Roche (2012). It is based on a psychrometric chart, with dry-bulb temperature on the horizontal axis and humidity ratio on the vertical axis.

According to ASHRAE Standard 55-2010 (and 2013), the comfort zone is defined by the combinations of the six key factors of thermal comfort for which the PMV is within the required limits (-0.5 and +0.5). To determine the comfort zone for the PMV model, Standard 55-2010 provides two ways. First, a graphical method can be used, which defines two comfort boundaries for 0.5 and 1.0 clo – assumed to be summer and winter conditions – and allows interpolation between these limits. As shown in Figure 2, the two zones are represented in grey for a metabolic activity of 1.1 met, with no lower humidity limit and a maximum of 0.012 kg_w/kg_{da}. A computer model method is allowed for a more flexibility (e.g. metabolic activity or clothing insulation can be changed) and release from the maximum humidity constraint. Both representations can be rendered on the psychrometric chart. However, in the graphical method the standard does not allow the use of dry-bulb temperature alone, and the operative temperature is plotted on the x-axis instead. The boundary conditions in the graph have been obtained with the MRT exactly equal to the dry-bulb temperature for each of the points considered. This approach is reasonable for spaces in which the dry-bulb and mean radiant temperatures can be considered equal or very close to each other (e.g. core zones). If operative temperature is calculated as the average of the dry-bulb and mean radiant temperatures and these two differ, then the accuracy of the graphical method is reduced. This is because the same operative temperature can be obtained with different combinations of dry-bulb and mean radiant temperatures. These different combinations can affect the calculated humidity ratio, changing the underlying chart. For example, an operative temperature equal to 24°C can be obtained with the T_{bd}=22°C and MRT=26°C or T_{bd}=26°C and MRT=22°C. From the chart reported below the humidity ratio is equal to 11 g_w/kg_{da} when the rh=60%. This value is significantly different from both the two cases presented above (9.8 g_w/kg_{da} with T_{bd}=22°C and 12.4 g_w/kg_{da} with T_{bd}=26°C) if the rh is kept equal to 60%.

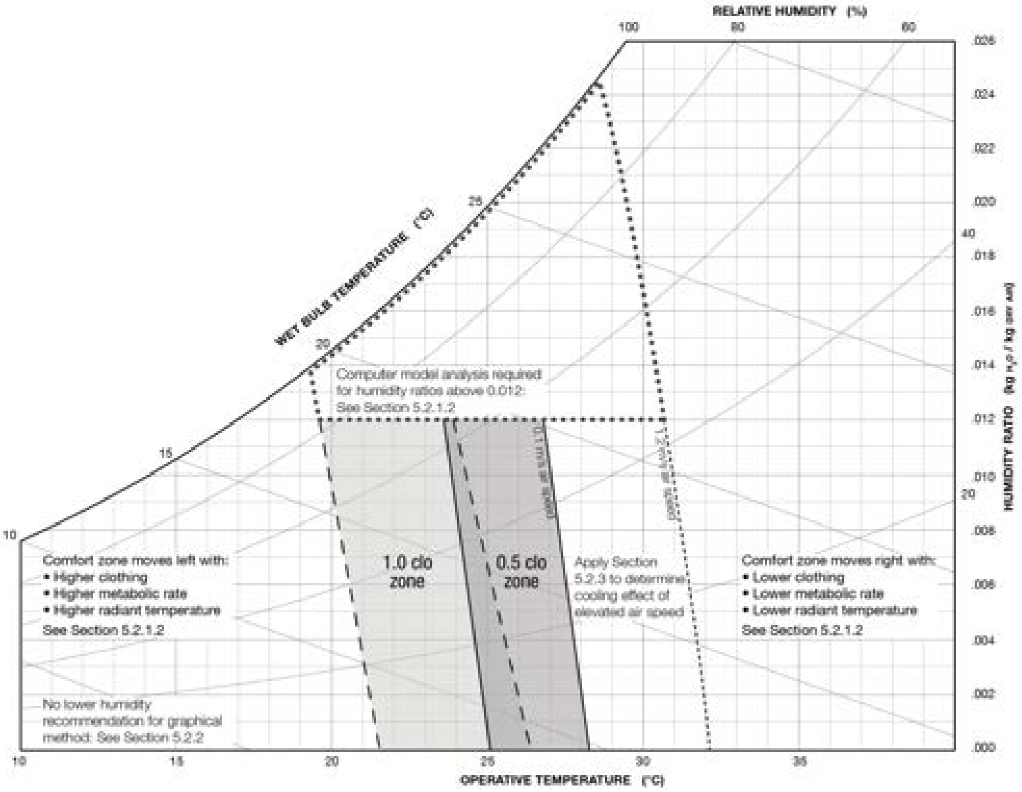

Figure 2. Psychrometric chart with superimposed comfort zones for 0.5 and 1.0 clo (summer and winter conditions), 1.1 met, air speed below 0.2 m/s, provided by ASHRAE Standard 55-2010 for the graphical method.

All of the above comfort zone representations have the limitation of being static, which means that no interaction is provided and the comfort zone is based on fixed values of, for example, clothing insulation and metabolic activity. An interactive visualization would allow the users to dynamically change the input variables and to see the results directly on the chart.

1.3 Existing software: features and limitations

We found three tools that perform thermal comfort calculations, two of which are also able to visualize comfort conditions: *Climate Consultant*, *Autodesk Ecotect Weather*

Tool and the *ASHRAE Thermal Comfort Tool*. These tools are described below, and their interfaces and visualizations are shown in Figure 3.

Climate Consultant is an excellent graphics-based, free, stand-alone computer program that helps users understand weather data used for building performance software. Its main goal is to help users create more energy-efficient and sustainable buildings, each of which should be suited to its particular climate (Milne 2009). The program reads a weather file for building performance simulations and shows a summary of the weather data as an overview of the selected climate. *Climate Consultant* is graphic-based computer program that helps architects, builders, contractors, homeowners and students understand their local climate. It allows the user to plot climate data on the Building Bioclimatic Chart, where each dot represents the temperature and humidity for each hour of the year. It uses standardized weather data for energy simulation software. Regarding thermal comfort visualization, *Climate Consultant* does not allow the user to control the level of air movement and does not include the SET model. The other parameters can be controlled but they are in a separate screen, making it difficult to apply changes. Three thermal comfort options are available: California Energy Code, ASHRAE Fundamentals and ASHRAE Standard 55-2004. To run the tool, it needs to be downloaded, installed or updated. The limitations described above arise from the generalized approach of most design tools of this kind, which are easy to use but little customization is available (Steinfeld 2012).

The *Ecotect Weather Tool* is a flexible and iteractive add-on for *Autodesk Ecotect* that provides the user with visualizations of weather data depending on the location and the 3D model of the building, imported into or created in *Ecotect*. In the thermal comfort section of this tool, a comfort zone is overlaid on weather data plotted on the psychrometric chart. By changing the activity level of the occupants (from sedentary to heavy) the user can modify the position of the comfort region, but the rest of the parameters – clothing insulation, air speed, and MRT – cannot be modified. It is possible to partition the data in several ways, which allows the user to assess how often outdoor air temperature and relative humidity are considered comfortable. The tool does not provide information related to thermal comfort standard compliance. The algorithm or basis of determining the comfort zones is not publicly available and there are no references to standards. Furthermore, as opposed to *Climate Consultant*, it is not freely available and it runs only on Microsoft Windows.

These tools do not reflect the latest standards, focusing on climate analysis rather than thermal comfort design. Neither of them properly accounts for air movement, MRT, nor do they allow the use of the SET method, which is included in the ASHRAE Standard 55-2010.

In 1997 ASHRAE published the ASHRAE Thermal Comfort Tool (Fountain and Huizenga 1997) to provide a simplified, consistent method for evaluating thermal comfort under a range of thermal conditions. The software was consistent with ASHRAE Standard 55-1992 and indicated whether a set of environmental conditions was in compliance with that standard. ASHRAE subsequently published Standard 55-2004 and Standard 55-2010, which incorporated several important changes. In 2010, ASHRAE released Version 2 of the ASHRAE Thermal Comfort Tool (Huizenga, 2010). The ASHRAE tool can be used only in computers using Microsoft Windows, and it was updated following major ASHRAE revisions (e.g. 2004 and 2010). It is difficult to keep it up to date with the new continuous-maintenance form of the standard, where addenda are frequent. This tool does not provide visualizations of thermal comfort (Figure 3c).

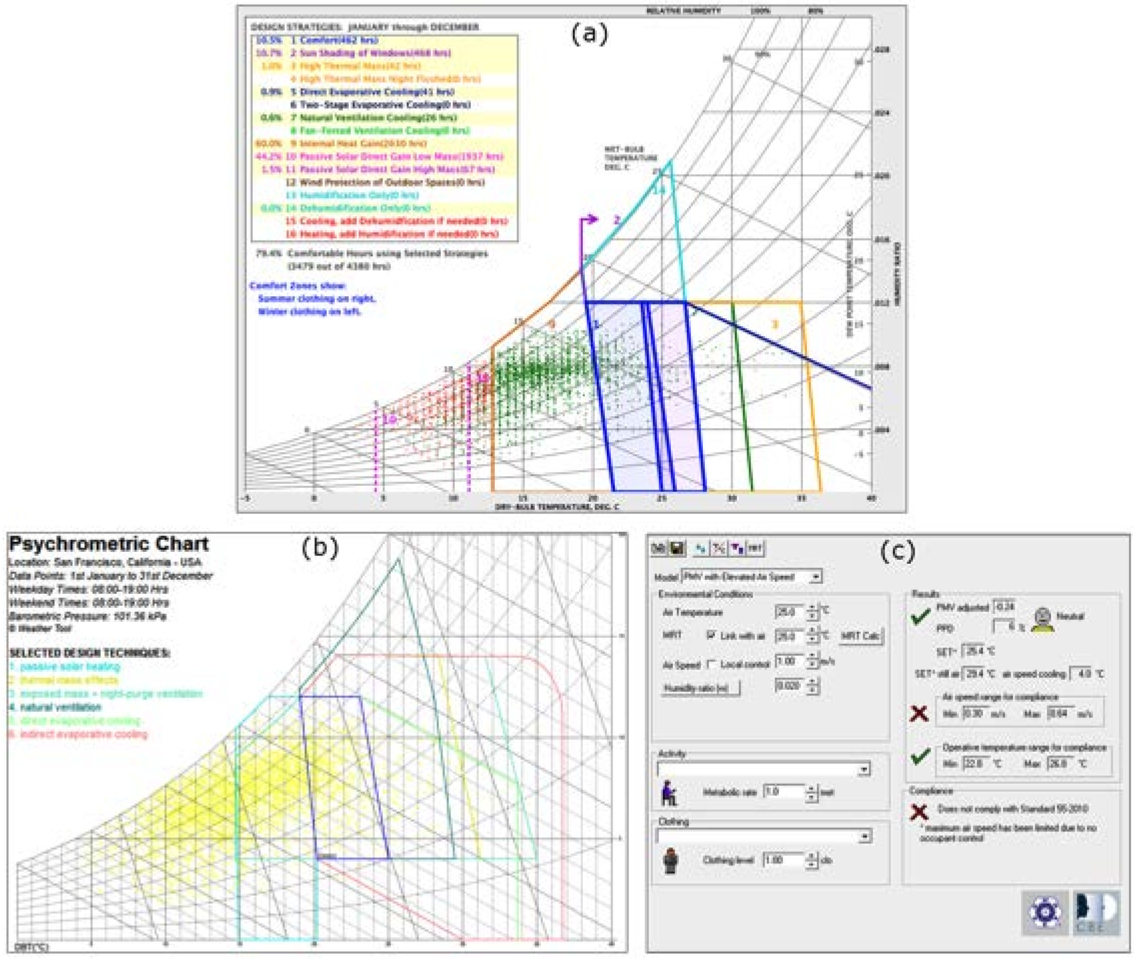

Figure 3. Screenshots of the three existing tools with thermal comfort assessment. (a) Climate Consultant: psychrometric chart showing the ASHRAE Standard 55-2004 comfort zone calculated with the PMV/PPD method and thermal zones corresponding to relevant design strategies for the San Francisco climate. (b) Ecotect Weather Tool: representation of the comfort zone and potential additions using passive design strategies, and hourly weather data for San Francisco. (c) ASHRAE Comfort Tool interface, with compliance messages but no visualization provided.

2 Web application: software architecture and Elevated Air Speed algorithm

The aim of this project has been to develop a comprehensive web application for thermal comfort calculation, visualization, design, and compliance according to the latest ASHRAE Standard 55, suitable for all operative system platforms and frequently updated according to new addenda and main revisions of the Standard.

The web application is freely available at http://cbe.berkeley.edu/comforttool. In the following two sections, we briefly describe the structure of the tool and the previously unpublished algorithm for the Elevated Air Speed model that merges the SET and PMV models for thermal comfort assessment when the air velocity is higher than 0.15 m/s. Figure 4 shows the interface of the web application. On the left hand side, the user can select the comfort model to be used (PMV and Adaptive Comfort) and specify the inputs for the parameters affecting thermal comfort. Further options and features can also be selected. On the right hand side, compliance messages and results from the calculations are shown. Below these outputs there is the representation of the thermal comfort zone on interactive charts (psychrometric, temperature-relative humidity, adaptive charts).

The web application is an application created with JavaScript, HTML and CSS.

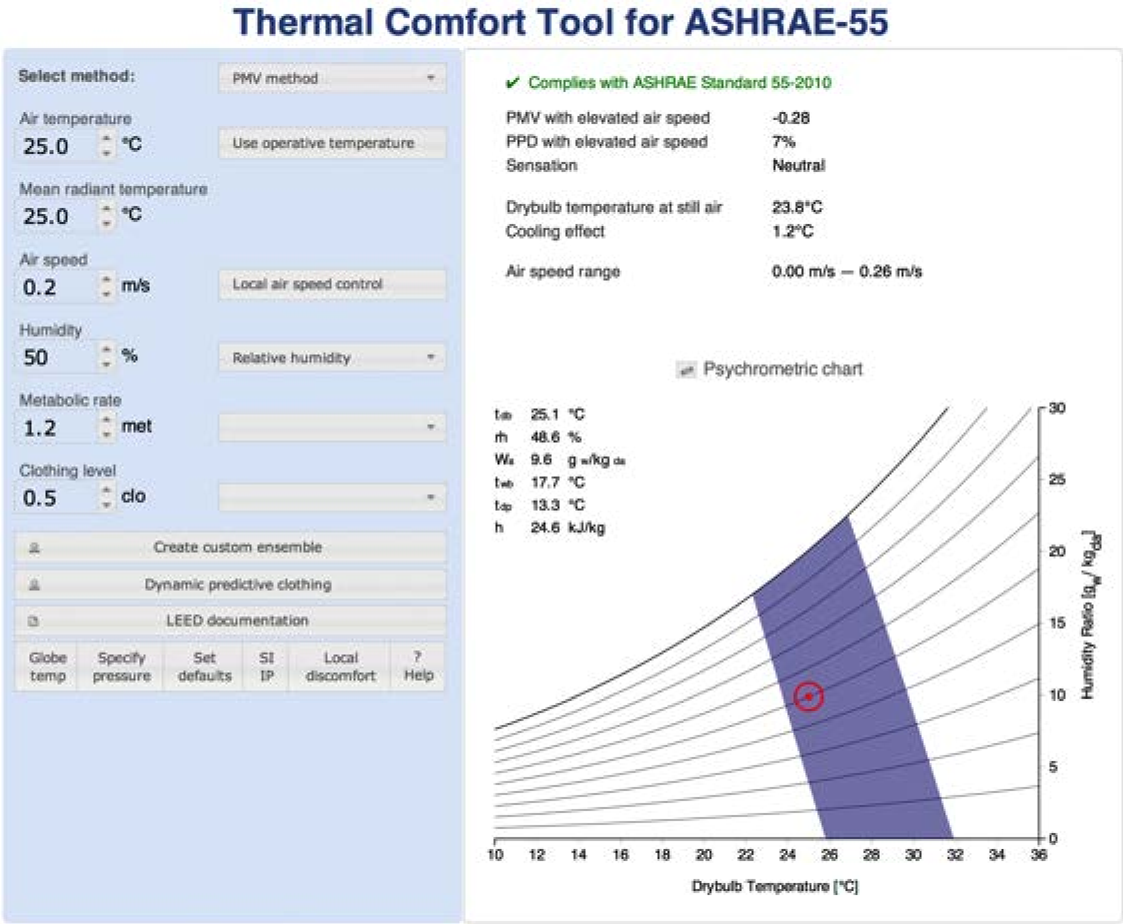

Figure 4. Interface of the CBE Thermal Comfort Tool for ASHRAE-55 (web application). On the left hand side, the user interface with the inputs for the six parameters, selection of method to be used and further options and features. On the right hand side, compliance messages and results from the calculations are shown. An interactive representation of the comfort conditions in the inputs is provided, depending on the selected method.

2.1 Structure of the web application

Browser based applications have the advantages of being cross-platform and centralized, as well as having readily available, powerful, and easy-to-use visualization and user interface libraries. The tool employs several open source JavaScript libraries, including d3, jQuery, and jQueryUI. The d3 library enables interactive browser-based visualizations of data (Bostock 2012). It provides a powerful interface for manipulating the Document Object Model (DOM) and mapping data to visual attributes of DOM elements such as polygons, lines, or circles. For example, a point on a scatter plot may be rendered as a circle located according to raw data mapped by d3 functions. The visualizations are Scalable Vector Graphics (SVG) objects, with elements that are dynamically controlled by the user input. For example, the location of the red circle in the psychrometric chart (see Figure 4) is determined by the user input of dry-bulb temperature and humidity. The blue comfort zone, defined as the region satisfying -0.5 < PMV < 0.5, is an SVG polygon with vertices mapped from the result of iterative solutions locating the comfort boundary. jQuery is a widely used library for manipulating HTML and creating interactive interfaces. It provides a concise syntax for selecting DOM elements, binding functions to events, and developing Ajax applications. jQueryUI is a library of widgets and interactive elements that enable interfaces to be created easily (The jQuery Foundation 2013a; The jQuery Foundation 2013b). For example, the buttons, select menus, number boxes, and modal dialogs in the tool are all jQueryUI elements.

The computational engine of the tool consists of two main JavaScript objects. One contains all functions relating to comfort model computation, including the PMV model, SET model, Adaptive Comfort model, and the Elevated Air Speed model. The other contains psychrometric conversion utilities, which enables the five humidity indices (relative humidity, humidity ratio, wet-bulb temperature, dew-point temperature, and vapor pressure) to be used interchangeably. The user interface code consists of visualizations driven by d3, interface interactions, and input and output processing. Advanced applications and visualizations of the comfort models and psychrometric described below utilize the same libraries and core JavaScript as the primary application.

2.2 Elevated air speed algorithm

Comfort models employed in the tool include the PMV model, the Elevated Air Speed model and the Adaptive Comfort model. PMV and Adaptive Comfort algorithms are available in (ANSI/ASHRAE 2010) and therefore are not described in detail here. For air speed below 0.15 m/s the PMV model is used, and for higher air speed the Elevated Air Speed model is used. The model is based on the idea that equal heat balance and skin wittedness for different air speeds can be plotted in terms of SET contours. If one starts with the underlying PMV comfort zone, these SET contours form the boundaries of an air-movement comfort zone (Arens 2009). The Elevated Air Speed algorithm is not described in the 2010 standard and our implementation is different from the ASHRAE Thermal Comfort Tool (2010). We think that the following implementation is more accurate and we predict that it will be included in the ASHRAE Standard 55-2013.

Suppose T_{db} is the dry-bulb temperature, and v_{elev} is the air velocity such that $v_{elev} > 0.15\ m/s$. Let $v_{still} = 0.15\ m/s$. Consider functions PMV and SET which take six parameters, which we will denote with the shorthand $PMV(.,*)$ and $SET(.,*)$. The variables of importance will be listed explicitly while the variables that are invariant will be denoted with the $*$ shorthand. The variables we will refer to explicitly are dry-bulb temperature (T_{db}), mean radiant temperature (MRT), air velocity (v), and relative humidity (rh).

The web application instead uses the SET model to find the equivalent dry-bulb temperature at still air that produces the same SET output as the elevated air speed condition. To define the adjusted dry-bulb temperature T_{adj}, we assert that it satisfies the following:

$$SET(T_{db}, v_{elev}, *) \ = \ SET(T_{adj}, v_{still}, *) \qquad [1]$$

That is, the adjusted dry-bulb temperature yields the same SET given still air as the actual dry-bulb temperature does at elevated air speed. In order to determine T_{adj} an iterative solver must be employed. We use both the secant and bisection iterative methods to find a solution quickly and reliably. The root of the error function satisfies the definition of T_{adj}:

$$E(T) \ = \ SET(T_{db}, v_{elev}, *) \ - \ SET(T, v_{still}, *) \qquad [2]$$

The cooling effect is equal to $T_{db} - \ T_{adj}$ and always greater than or equal to zero. The adjusted PMV is given by

$$PMV_{adj} = PMV(T_{adj}, v_{still}, *) \qquad [3]$$

A core application of the PMV/PDD and Elevated Air Speed models is to find the boundary of comfort for a given input condition. The result of this computation determines the vertices of the comfort zone polygons shown in the psychrometric and temperature-relative humidity charts. This is another case of employing a root-finding process to find the condition that satisfies a constraint. In this case, we iterate over a set of relative humidity values $rh = \{0, 10, 20, \dots, 100\}$, each time solving for the dry-bulb temperatures $T_{left,i}$ and $T_{right,i}$ for which the pair ($T_{left,i}$, rh_i) lies on the left comfort boundary ($PMV = -0.5$) and ($T_{right,i}, rh_i$) lies on the right comfort boundary ($PMV \ = \ 0.5$). Thus $T_{left,i}$ satisfies $PMV(T_{left,i}, rh_i, *) \ \ = \ -0.5$ while $T_{right,i}$ satisfies $PMV(T_{right,i}, rh_i, *) = 0.5$ and the boundaries are the roots of

$$E_{left,i}(T) = PMV(T, rh_i, *) + 0.5 \qquad [4]$$

$$E_{right,i}(T) = PMV(T, rh_i, *) - 0.5 \qquad [5]$$

The collection of solutions defines the vertices of the comfort zone.

3 Visualizations in the web application

There are three main charts in the web application, two for the PMV and Elevated Air Speed methods and one for the Adaptive Comfort method. All visualizations are for both the metric and imperial systems, and the units can be toggled easily.

3.1 Psychrometric chart

For the PMV method, the main visualization of the comfort conditions is the psychrometric chart (Figure 5a). The inputs are the six primary factors that affect thermal comfort. The comfort zone displayed in blue represents the combination of acceptable dry-bulb temperature and humidity values according to the standard, given the other four parameters kept constant. In particular, the comfort boundary contains the conditions for which PMV is between -0.5 and +0.5, representing 90% of satisfied occupants in the space. The red dot represents the dry-bulb temperature and humidity values in the inputs. Both the comfort zone and the red dot are interactive and their position can be modified by changing the input variables. In this chart, each point has a different dry-bulb temperature and humidity, while the MRT is constant. This is different from the ASHRAE Standard 55-2010 chart provided for the graphical method, since the latter assumes equal dry-bulb and mean radiant temperatures for each single point. In the web application, the user can select to use the operative temperature instead of dry-bulb and mean radiant temperatures separately; by doing so, these two variables will be set equal. The chart can be interpreted in the same way, where the MRT is fixed and the x-axis indicates the dry-bulb temperature. The user can examine the psychrometric variables by hovering over the chart. The mouse position determines the dry-bulb temperature and the humidity ratio, from which the other psychrometric variables can be derived. Dry-bulb temperature, relative humidity, humidity ratio, wet-bulb temperature, dew point temperature, and air enthalpy are displayed above the chart.

The Adaptive Comfort model is not represented on the psychrometric chart because the version reported in the Standard does not account for humidity and the dependent variable is the indoor operative temperature. A separate chart has been developed for this model.

3.2 Temperature – relative humidity chart

A simplified version of the psychrometric chart is included in the tool, displaying humidity on the y-axis in terms of relative humidity instead of humidity ratio (Figure 5b). The results are similar to those displayed by the psychrometric chart, but it may be easier to understand for those not familiar with the psychrometric chart.

The environmental and personal factors are the same for both representations and the comfort regions are similar, as can be noticed by comparing Figure 5a and 5b. This chart uses basically the same graphic space as Olgyay's bioclimatic chart, but the axes are inverted to be a bit more similar to the psychrometric chart, both now having different forms of humidity on the vertical axis.

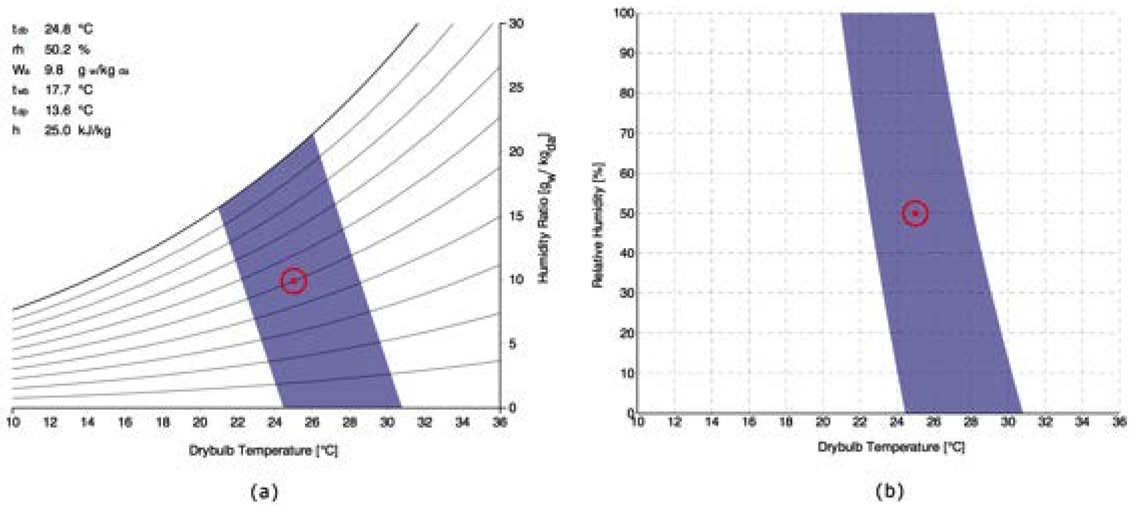

Figure 5. Visualizations of thermal comfort zone for the same input conditions. (a) Psychrometric chart. (b) Temperature–relative humidity chart.

3.3 Thermal comfort comparison

Having a visual comparison of the thermal comfort implications of alternative design or operating strategies may lead to better informed decisions.

How the thermal comfort comparison was implemented in the tool is shown in Figure 6. The comfort zones are represented using the same comfort models (PMV and Elevated Air Speed) but with different environmental or personal variables. The second zone will overlay the first one in a different color. The results of the calculations, including the ASHRAE Standard 55-2010 compliance results, are shown above the visualization (either the psychrometric or temperature-relative humidity chart). If the user modifies temperature or humidity in the inputs, the point representing the selected condition will move. In Figure 6, the second condition (on the right in the chart) has greater air speed, dry-bulb temperature and mean radiant temperature than the first one, but the comfort conditions (represented here by PMV) are the same. This can be easily assessed with this interactive representation, since the user can rapidly change the input parameters to redraw the comfort zone for the new condition and see the PMV results above the chart. Up to three comfort conditions can be displayed, and all of them can be hidden or shown with the respective toggle button.

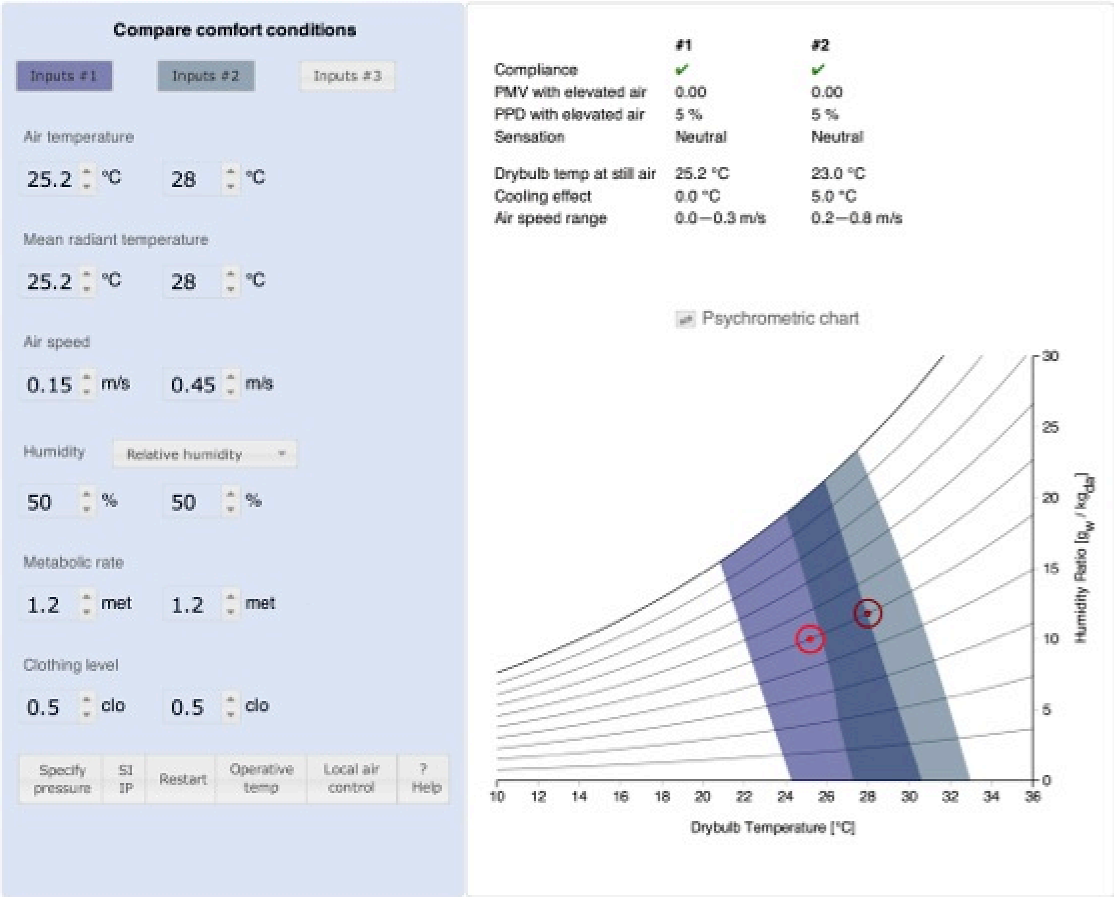

Figure 6. Thermal comfort comparison page. Two scenarios with equal thermal sensation (PMV=0) are shown. The input parameters can be seen on the left hand side, while on the right there are the results from the PMV equations, the Elevated Air Speed outputs in case of air speed > 0.15 m/s, and the visualization of the two conditions on the psychrometric chart.

3.4 Thermal comfort ranges

An enormous challenge in designing for thermal comfort is the recognition that conditions are rarely uniform over space or static over time, and that the people in the space all may have different thermal preferences. By necessity, comfort models describe the average conditions that such a group of people might feel, for a single set of conditions. For example, PMV and Elevated Air Speed thermal comfort calculations are performed with a fixed set of the six input parameters (e.g., it is assumed that all the occupants in a space are exposed to the same environmental conditions, that they are wearing the same clothing insulation and have the same activity level). This might be a necessary assumption for design purposes, but is far from reality during building operation and in building performance simulations. People do not wear the same level of clothing nor do they perform the same activity and they may be exposed to different environmental conditions within the same zone.

To overcome this limitation of existing tools, we developed a new thermal comfort

visualization in which one of the four input parameters (MRT, air velocity, clothing and metabolic activity) can be changed gradually within a range. A comfort region is drawn for each step between the minimum and the maximum of the given range decided by the user. The visualization that we developed is based on the assumption that only one parameter may vary.
An example of the visualization is shown in Figure 7a. Air speed is varied in 0.05 m/s steps between 0.20 and 0.60 m/s, while the remaining factors are kept constant. In Figure 7a, two new thermal comfort areas can be determined, an inner and an outer area. The inner area (i.e., the darkest shaded area) is composed of the dry-bulb temperature and humidity values for which comfort will be obtained for any of the air speeds (i.e., all of the comfort zones overlap this region). The outer area is composed of the dry-bulb temperature and humidity values for which comfort is obtained if one specific air speed within the given range is provided to the occupants. From this example two design considerations can be developed: (i) If the occupants have the possibility of using personal fans, where the full range of air velocities could be achieved for a single person, then a wider temperature range can be set in the HVAC system (i.e., the area represented by all of the shaded regions); and (ii) if the air velocity in the space cannot be controlled and is allowed to freely vary within the given range, than the only comfort region that would satisfy everyone will be the inner one.

Another meaningful example of the inner comfort area is the case of metabolic activities in a restaurant. Since customers and waiters have significantly different activity levels, it is problematic to find a comfort area that satisfies all the occupants. Usually, waiters have higher metabolic activity levels than the customers. With the ranges feature, one can explore the intersection of comfort zones between the lower and higher metabolic levels, to see if there are opportunities to satisfy both categories of occupants. The inner area represents the conditions for which occupants of both types will be comfortable assuming all the other variables (e.g. clothing insulation) are held constant.

A third example is shown in Figure 7b. In this case the clothing insulation was changed between 0.65 to 0.9 clo. If people are allowed to adapt their clothing to achieve thermal comfort, then the designer or building operator can widen the comfort range substantially. In this case, the heating setpoint can be set to 18°C and the cooling setpoint to 27.3°C. If occupants are not allowed to adapt their clothing, for example if there is a restrictive dress code in the building, then the designer or building operator should set a much smaller temperature range, i.e. the inner area, where all occupants wearing 0.65 to 0.9 clo will find thermal comfort. In this case, the heating setpoint should be set to 21.3°C and the cooling setpoint to 25.0°C. This has significant implications on energy use and HVAC system sizing.

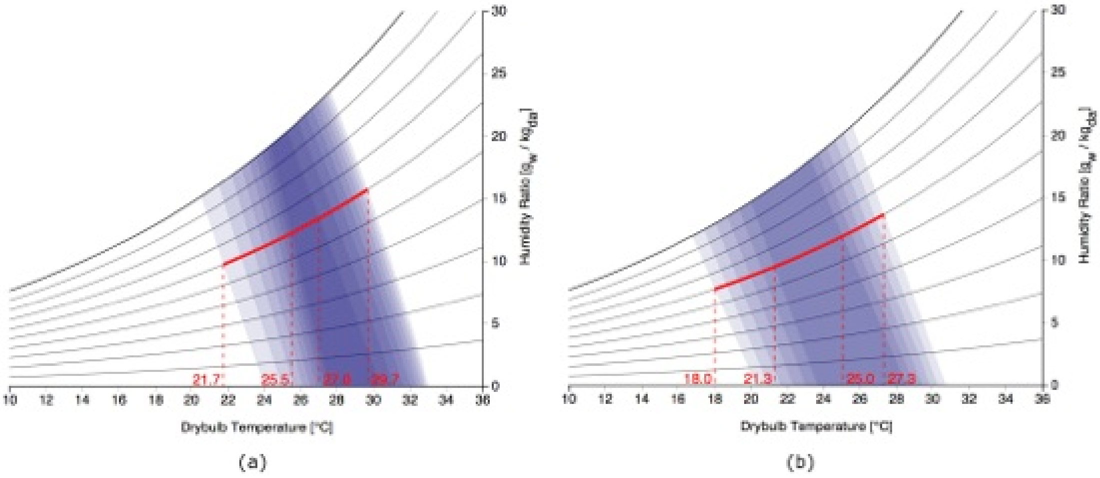

Figure 7. Thermal comfort ranges on psychrometric chart. (a) Range of air speeds (0.2 to 0.6 m/s), rh of 60%, clothing of 0.7 clo, activity level of 1.1 met, MRT of 26°C. (b) Range of clothing levels (0.65 to 0.9 clo), rh of 60%, air speed of 0.15 m/s, activity level of 1.2 met, MRT of 23.5°C.

3.5 Adaptive Comfort visualization

For the ASHRAE Standard 55-2010 Adaptive Comfort model (de Dear and Brager 1998), the comfort zone can be represented on a chart with indoor operative temperature as ordinate and prevailing mean outdoor temperature as abscissa. The comfort zones displayed in Figure 8 represent the 80% and 90% acceptability levels of satisfied occupants. The red dot is the input condition, which complies with the standard if it is found within the 80% acceptability limits. In this visualization, the comfort zone changes only in response to the air speed input (see Figure 8), which offsets the upper comfort boundary by a fixed amount, depending on the intensity of the air, as explained in a table in the standard.

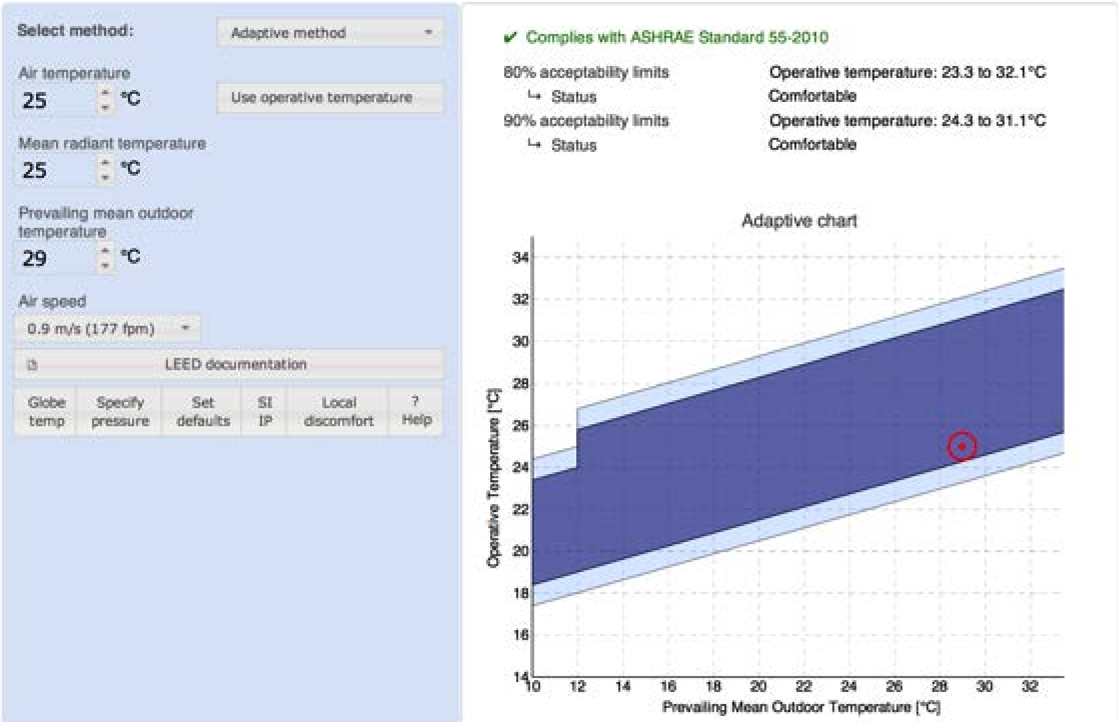

Figure 8. Visualization of the input, thermal comfort ranges and compliance according to the Adaptive Comfort model when the air speed is 0.9 m/s.

4 Web application main features

4.1 Local discomfort assessment

While the PMV and Elevated Air Speed models describe whole-body thermal comfort, thermal dissatisfaction may also occur to a particular part of the body, due to local sources of unwanted heating, cooling or air movement (ISO 2005). According to ASHRAE Standard 55-2010 there are four main causes of local thermal discomfort to be considered: radiant temperature asymmetry, vertical air temperature difference, floor surface temperature, and draft. We implemented the models and constraints required in ASHRAE Standard 55-2010 within the web application as a modal dialog (Figure 9). This feature allows the users to verify the compliance of their indoor spaces to the standard as regards local thermal discomfort. By feeding the dialog with measurements or estimations of the inputs, one can see whether the discomfort effect in the space is likely to exceed the ASHRAE Standard 55-2010 PPD acceptability limits. The implemented algorithms are described in ISO 7730 (ISO 2005). To comply with the Standard, all the four sections must comply with the acceptability limits in the Standard.

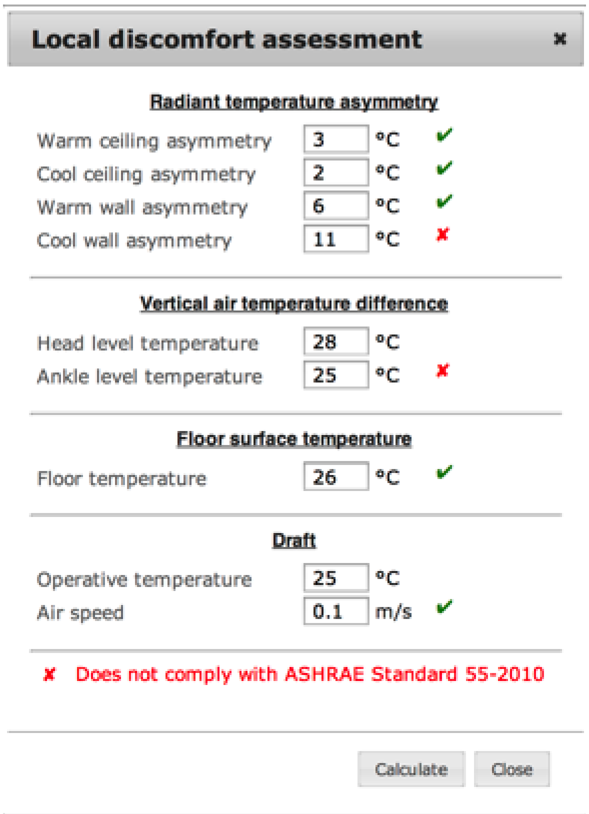

Figure 9. Local discomfort assessment dialog box for radiant temperature asymmetry, vertical air temperature difference, floor surface temperature, and draft.

4.2 LEED compliance documentation

The web application includes the capability of automating the creation of a compliance document for LEED certification credits related to thermal comfort. LEED (Leadership in Energy and Environmental Design) is a voluntary, consensus-based, market-driven program that provides third-party verification of green buildings. There are several rating systems depending on the class of building in question (U.S. Green Building Council 2013). LEED for New Construction addresses design and construction activities for both new buildings and major renovations of existing buildings, which includes major HVAC improvements, significant envelope modifications, and major interior rehabilitation (U.S. Green Building Council 2007).

One of the credit categories is indoor environmental quality. Within this category, in the current version of LEED (v2009), thermal comfort can earn two points: one in design (EQc7.1) and one in verification (EQc7.2). In LEED version 4 one point can be earned for thermal comfort, both for new construction (EQc5) and existing buildings (EQc3). The main intent of this section is to provide the building with quality thermal comfort according to the main standards on the subject, such as ASHRAE Standard 55, ISO 7730 (ISO 2005), EN 15251 (2007), in order to promote occupants' productivity, comfort and well being (U.S. Green Building Council 2013). LEED v2009 refers to ASHRAE Standard 55-2004, while the new version LEED v4 refers to the ASHRAE Standard 55-2010.

The LEED documentation feature of the web application is based on LEED guidelines (U.S. Green Building Council 2013) and ASHRAE Standard 55-2010 (appendix C). The first part of the compliance page is about the personal factors related to the occupants of the space to be rated. Subsequently, there are two separate sections for the PMV and the Adaptive Comfort models, which require different information and return results from the calculations and visualizations of comfort zones created by the web application. Representing the comfort zone on the chart – instead of reporting the results of the calculations alone – is instrumental to better understand each set of conditions. At the end of the PMV section, the local discomfort effects are reported and, in case they are likely to occur, the user has to demonstrate that calculations have been made to verify that those discomfort levels are predicted to be within the standard limits. This can be done with the local discomfort assessment dialog described above.

For the last section of the compliance page, if the Adaptive Comfort model is selected, the user has to specify the weather file used and verify that the prevailing mean outdoor temperature does not exceed the limits of applicability set by the standard. The result is then shown on the adaptive chart, which is included in the compliance document.

4.3 Auxiliary features

Globe to MRT converter: This feature of the web application allows the users to convert the globe temperature measured with a globe thermometer into MRT. It is a modal dialog window that takes dry-bulb temperature, air speed, globe temperature, globe diameter and emissivity as inputs, and calculates the correspondent MRT according to the equation for forced convection provided by standard ISO 7726 (ISO 1998). The result can then be used as an input.

Metabolic activity table: The metabolic rate varies for different activities. It is usually not measured but either estimated during the design phase, or assessed for occupied buildings through occupant surveys or researcher's observations. The user can either choose a level from the list next to the input box or type a value directly.

Custom ensemble creator: The web application allows the user to select clothing insulation values for common clothing ensembles by the list on the right of the input box, or to create a custom ensemble by choosing every garment that composes it, by clicking on the button just beneath the list. This meets the methods provided by ASHRAE Standard 55-2010 to evaluate the clothing insulation. Once the ensemble has been created, the clothing insulation can be used as an input.

Dynamic predictive clothing calculator: In ASHRAE Standard 55-2013, clothing insulation may be correlated with outdoor air temperature. A model predicts clothing insulation as a function of outdoor dry-bulb temperature at 6 o'clock in the morning of the day in question. The implemented model is described in Schiavon and Lee (Lee and Schiavon 2013; 2012).

Shortwave (solar) gain calculator: The web application includes a method to convert solar gain (direct, sky-diffuse, and ground-reflected shortwave radiation) to its equivalent longwave effect on the human body, as represented by MRT. For building occupants in the vicinity of direct sun through windows, the shortwave component is added to the longwave component. Accounting for shortwave radiation on occupants is not yet considered in Standard 55.

Links to Wikipedia: To enhance the user-friendliness, technical terms in the interface have a link to relevant Wikipedia pages that we reviewed and edited. These pages include: thermal comfort, clothing insulation, dry-bulb, mean radiant and operative temperature, and psychrometric.

4.4 Future work

In this paper we have described the first version of the tool. We are planning to add the following features: (a) ability to upload measurements of the indoor thermal environment and visualize them in the dynamic charts; (b) ability to upload EnergyPlus weather files, and use them to calculate and then visualize the allowable indoor operative temperatures according to the Adaptive Comfort model, and the variable clothing insulation values according to the dynamic predictive clothing model; (c) thermal comfort compliance and visualization for other thermal comfort standards (e.g. ISO 7730 and EN 15251); (d) mean radiant temperature calculations for 3D space; and (e) stochastic simulation of thermal comfort to assess uncertainty.

5 Discussion and Conclusions

The web application described in this paper has a large spectrum of applicability. It can be used by designers during the programming and schematic design phases to assess different thermal control strategies (e.g. natural ventilation, elevated air speed or radiant systems). It can be used in the construction documentation phase of the design to predict the comfort of the occupants and the compliance with the standard. It can be used by HVAC engineers to find evidence to determine more elaborate control strategies (e.g. daily zone temperature reset). The tool can also be used for existing buildings or new construction to verify the compliance with the comfort requirements and seamlessly develop the needed documentation for LEED thermal comfort credits. Moreover, it can be a useful resource to analyze existing building performance and assess which strategies can be used to improve thermal comfort. Another application of the web application, given its free availability and high interactivity, is in graduate and undergraduate building science/technology classes, or in design studios, where students can assess the thermal comfort implications of their design.

The web application fills the gaps of existing software described in section 1.3, as it allows an accurate representation of the comfort zone, complies with ASHRAE Standard 55-2010, provides a visual and dynamic representation of the comfort zone, and is free and works regardless the operative system. ASHRAE Standard 55 is a continuous maintenance standard. This means that every approved addendum becomes immediately part of the official standard. As a web application, the updates driven by new addenda can be easily deployed and do not oblige the user to update the tool.

To our knowledge, the web application is the most up-to-date and interactive tool for ASHRAE Standard 55-2010 and 2013.

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