GLAZING AND WINTER COMFORT

Part 1: An Accessible Web Tool for Early Design Decision-Making

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Glazing and Winter Comfort
Part 1: An Accessible Web Tool for Early Design Decision-Making

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Abstract

Of the factors that influence wintertime occupant thermal comfort, two are often of primary concern around cold windows: overall low mean radiant temperatures and localized downdraft currents. To prevent these from leading to a thermally uncomfortable environment in cold climates, the building industry has traditionally used perimeter heating – a system that is aesthetically unpleasing, costly to maintain and wasteful in its energy use. At present, quantifying discomfort from cold windows is either overly conservative, or relies on expensive and time-consuming simulation methods. Part 1 of this paper introduces the Glazing and Winter Comfort web tool, which identifies suitable glazing geometry and insulation performance criteria quickly and interactively to fully mitigate radiant and downdraft discomfort. Accordingly, this web tool aids designers in testing feasibility and iterating early in the design process, as well as informs the design team of critical thresholds during cost consideration exercises.

Nomenclature

Variable	*Description*	*Units*
PMV	Predicted Mean Vote (thermal sensation)	
PMV*	Average of PMV over two heights (0.6m and 1.1m from the ground for seated occupants, 1.1m and 1.7m for standing occupants)	
PPD_{Rad}	Predicted Percentage of Dissatisfied occupants associated to radiant discomfort	
PPD_{Draft}	Predicted Percentage of Dissatisfied occupants associated to downdraft discomfort	
MRT	Mean radiant temperature	K
F	View factor between occupant and surface	
ε	Surface emissivity	
T_{in}	Interior room temperature	°C
T_{out}	Exterior room temperature	°C
v_{ankle}	Downdraft speed at ankle height	m/s
x	Occupant distance to façade	m
H	Relevant downdraft height (H_{window} + H_{sill})	m
H_{window}	Height from bottom to top of window	m
H_{sill}	Distance from floor to top of window sill	m
h_{c_in}	Convective heat transfer coefficient along the interior window surface	W/m^2K
h_{r_in}	Radiative heat transfer coefficient along the interior window surface	W/m^2K
U_{window}	Window U-value	W/m^2K

Introduction

Because windows lose several times more heat than solid walls, their cold interior surface can be a source of wintertime occupant discomfort in cold climates. A common strategy to prevent occupants from feeling cold when close to a window is through the addition of perimeter heating, which elevates the temperature of the inner windowpane to mitigate radiant discomfort, eliminate cold downdraft currents, as well as minimize the risk of condensation.

The probability of an occupant experiencing discomfort associated with glazing depends on both on window's geometry and thermal performance, aspects defined in early stages of the design process. The need for perimeter heating is typically determined through a computational fluid dynamics (CFD) simulation. These simulations are often performed late in the design process for verification or minor design modifications, rather than as a design tool, due to it cost and time-intensity.

Because a poorly performing façade that requires the use of perimeter heating often leads to both unpleasing aesthetics as well as increased operational and maintenance costs, there is a need for a tool that informs the design team of the thresholds in window design and performance that ensure a comfortable space in the wintertime through passive means.

Two existing tools, developed by U.C. Berkeley's Center for the Built Environment, provide an easy way to quantify thermal comfort. The Thermal Comfort Tool (Hoyt et al., 2013) uses a set of given environmental and occupancy parameters to determine whether a space is comfortable or not. While this tool is very useful to quantify comfort levels when all environmental variables are known, it lacks the capability to relate the impact of any geometrical parameters of the space on comfort directly. The MRT tool (Hoyt et al. 2014), where MRT stands for mean radiant temperature, bridges this gap by allowing the user to draw a room with windows and understand the impact of glazing geometry. This tool, however, requires calculating the temperature of the window surface separately. The key shortfall of these two tools is that they provide no means to quantify thermal discomfort associated to downdraft, a critical source of thermal discomfort in glazed spaces.

There is, therefore, a need to provide a way for design teams to quantify the impact of designing a glazed façade on the occupant's thermal experience that accounts for both radiant and downdraft discomfort. Part 1 of this set of papers introduces the Glazing and Winter Comfort design tool, a web-based calculator that allows the design team to quantify the risk of occupant discomfort in the wintertime associated to a given glazing scenario. This tool allows modelling rectangular, horizontally spaced windows of any dimensions, for a point-in-time condition. Part 2 will cover the development of a Grasshopper plugin that allows predicting thermal comfort conditions over an entire season associated to complex glazing and space geometries, as well as unique interior conditions such as radiant heating.

Glazing and Thermal Comfort

Occupants close to a window may feel cold in the wintertime due to two factors: radiant discomfort and downdraft discomfort. This section will cover how to quantify these two types of discomfort, and how they relate to window design and performance.

Radiant Discomfort

Radiant discomfort is encountered when an occupant loses heat beyond a certain threshold to one or multiple colder surfaces. The impact of this radiant loss on overall comfort can be quantified using the Predicted Mean Vote (PMV) model developed by P.O. Fanger (1973) and currently adopted by ASHRAE Standard 55 (ASHRAE, 2010).

This model relies on heat balance principles to correlate six environmental and occupancy parameters (metabolic rate, clothing insulation, air speed, air temperature, air humidity and mean radiant temperature) to a value, PMV, within a predicted thermal sensation scale and a predicted percentage of occupants dissatisfied (PPD_{Rad}[1]). The procedure to calculate PMV can be found in Fanger (1973). PPD_{Rad} is obtained according to:

$$PPD_{Rad} = 100 - 95 * \exp(-0.03353\, PMV^4 - 0.2179\, PMV) \quad (1)$$

ASHRAE Standard 55 recommends that spaces like offices keep a PPD below 10%.

Mean radiant temperature is the variable within the PMV model that helps correlate the presence of a cold pane of glass to a person's overall thermal sensation. It depends on the view factor (F) between the person and each surface, as well as on the temperature such surface (Figure 1). Equation 2 describes the MRT for a human interacting with the interior space (temperature T_i, in Kelvin), a solid exterior wall (temperature T_w) and the interior pane of glass (temperature T_g, interior emissivity ε_g). This equation is based on the definition of mean radiant temperature defined in Fanger (1970), and it assumes that the solid wall and the glass do not have any radiant exchange and that the surface emissivity of the wall and interior are 1. The emissivity of the interior pane of glass can be lass then 1 when the window has a low-emissivity (low-e) coating on the interior surface. The view factor calculation can be found in Tredre (1965).

$$MRT^4 = F_s T_s^4 + [F_i + (1 - \varepsilon_g)F_g]T_i^4 + \varepsilon_g F_g T_g^4 \quad (2)$$

Downdraft Discomfort

Downdraft discomfort originates from occupant exposure to cold air currents falling parallel to the cold window and spreading to a horizontal surface. This discomfort is particularly exacerbated if parts of the occupant's body are not covered by clothing, such as ankles or hands.

Downdraft discomfort was, for a long time, quantified by using P.O. Fanger's risk of downdraft model (Fanger and Christensen, 1986; Fanger et al, 1988), which was developed by evaluating a person's tolerance to draft on the back of the neck. Early research suggested that these results could be used as a conservative prediction for discomfort at ankle level. One of the shortfalls of this model is that it does not account for the cross-effect of an occupant's thermal sensation and the discomfort associated to draft. As a result, the model has been found to overestimate draft (Toftum et al. 2003). While this draft risk model is still used by European standards (CEN, 2007), it was removed from ASHRAE Standard 55 as of 2010. Other attempts to quantify discomfort associated to window-originated downdraft have been proposed (Olesen, 1995), but have been deemed too conservative when tested under a larger range of thermal scenarios (Schellen et al., 2012).

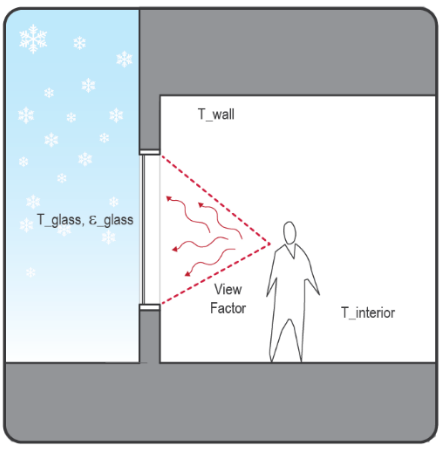

Figure 1. Factors influencing radiant discomfort close to a glazed façade.

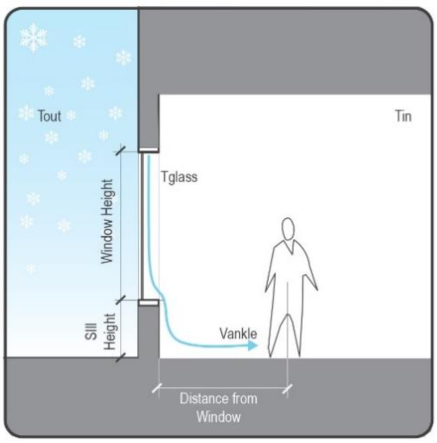

Figure 2. Factors influencing downdraft discomfort close to a glazed façade.

[1] This value is commonly known as PPD. In this paper we have labeled it PPD_{Rad} to distinguish it from the PPD associated to downdraft (PPD_{Draft}).

A new experimental thermal comfort model developed specifically to quantify draft discomfort bare ankles has been proposed by Liu et al. (2016). It was obtained through experimental testing of 110 subjects, male and female, exposed to ankle-level draft speeds ranging from 0.1 to 0.7 m/s, and draft temperatures from 17 to 22 Celsius. It quantifies the percentage of occupants dissatisfied (PPD_{AD}) based on two factors: the speed of the air at ankle level (v_{ankle}) and the average of the occupant's thermal sensation (PMV*) over two heights (0.6m and 1.1m from the ground for seated occupants, 1.1m and 1.7m for standing occupants), as outlined in Equation 3.

$$PPD_{Draft} = \frac{\exp(-2.58 + 3.05\, v_{ankle} - 1.06\, PMV^{*})}{1 - \exp(-2.58 + 3.05\, v_{ankle} - 1.06\, PMV^{*})} \quad (3)$$

While draft temperature is not explicitly included in this model, note that in the case of downdraft it is directly related draft speed. A threshold PPD_{Draft} of 20% was originally recommended by ASHRAE Standard 55 (versions prior to the 2010 edition), and is still used to date by industry and academia, though there is no recent experimental data justifying this subjective value.

The draft air velocity at ankle level depends on several variables, such as height and temperature of the inner pane of glass, indoor air temperature and distance from the façade to the occupant (Figure 2).

The air speed at ankle level at a distance x from the façade can be estimated using the experimental results obtained by Manz and Frank (2003) when simulating the development and spread of cold downdraft originating along a cold window of height H and surface temperature T_{glass} , with a room temperature T_{in} (Eq. 4).

$$v_{ankle} = \begin{cases} 0.083\sqrt{H\,\Delta\Theta}\ [m/s],\ x < 0.4m \\ \frac{0.143}{x+1.32}\sqrt{H\,\Delta\Theta}\ [m/s],\ 0.4m \le x \le 2m \\ 0.043\sqrt{H\,\Delta\Theta}\ [m/s],\ x > 2m \end{cases} \quad (4)$$

$$\Delta\Theta = T_{in} - T_{glass}\ [C]$$

In the presence of a window sill the relevant height to use in Eq. 4 is the sum of the window height and the sill height (Rueegg et al., 2001).

The impact of mullions or a deep sill on the development of downdraft has been studied by Svidt and Heiselberg (1995), Heiselberg at al. (1996) and Larsson and Moshfegh (2002). Their experimental results indicate that horizontal obstructions larger than 7-15 cm break down the cold current. However, several factors, such as impact of mullion temperature and air speed patterns after the obstruction, still need to be evaluated in order to be able to confidently estimate the ideal obstruction depth to mitigate downdraft.

The impact of dynamic infiltration on occupant thermal comfort is not modeled in this tool.

Methods

This section outlines the calculations and assumptions made in the Glazing and Winter Comfort tool.

In order to predict the risk of occupants feeling too cold close to a window on a winter day given a glazing scenario, radiant discomfort and downdraft discomfort must be quantified separately and then compared to one another to identify which measure of discomfort dominates.

The variables that are available to the design team early in the design process include:

- window geometry (height, width, sill height)
- room geometry (floor-to-ceiling height, width)
- façade thermal performance (exterior wall R-value, window U-value, interior windowpane emissivity)
- occupancy profile (metabolic rate, clothing levels, thermal comfort (PPD) threshold, distance to façade)
- outdoor temperature (T_{out})
- indoor conditions (air temperature and humidity)

To quantify both radiant and downdraft discomfort, it is necessary to know the temperature of the interior windowpane (T_{glass}), which can be obtained from the following energy balance:

$$T_{glass} = T_{in} - (T_{in} - T_{out})\left(\frac{h_{c\_in} + h_{r\_in}}{U_{window}}\right) \quad (5)$$

Where h_{c_in} and h_{r_in} are the convective and radiative heat transfer coefficients, respectively, between the glass and the interior air. A simple interpolation of the surface film coefficients for vertical windows of different interior emissivities ε in (ASHRAE, 2013) leads to the following two expressions for heat transfer coefficients:

$$h_{c\_in} = 0.305\left[\frac{W}{m^2K}\right] \quad (6)$$

$$h_{c\_in} = 5.82\,\varepsilon\left[\frac{W}{m^2K}\right] \quad (7)$$

Given all inputs cited above, and using Equations 1-7 and the expressions to estimate PMV, the algorithm in the tool estimates the change in PPD_{Rad} and PPD_{Draft} with occupant location from the façade (x).

The following assumptions have been made during the calculations:

- The temperature of all surfaces that are not along the exterior façade are assumed to be the same as the room air temperature.
- The surface emissivity of all surfaces but the glass is assumed to be 1.
- The resulting PPD values correspond only to negative values of thermal sensation.
- For occupants that are offset laterally to the right or left of the window the downdraft speed is assumed to decrease linearly, and is equal to zero 0.9 m away from the window or farther, with respect to the center of the occupant.
- Since the tool is intended to identify the coldest conditions for a space, no solar radiation is assumed.

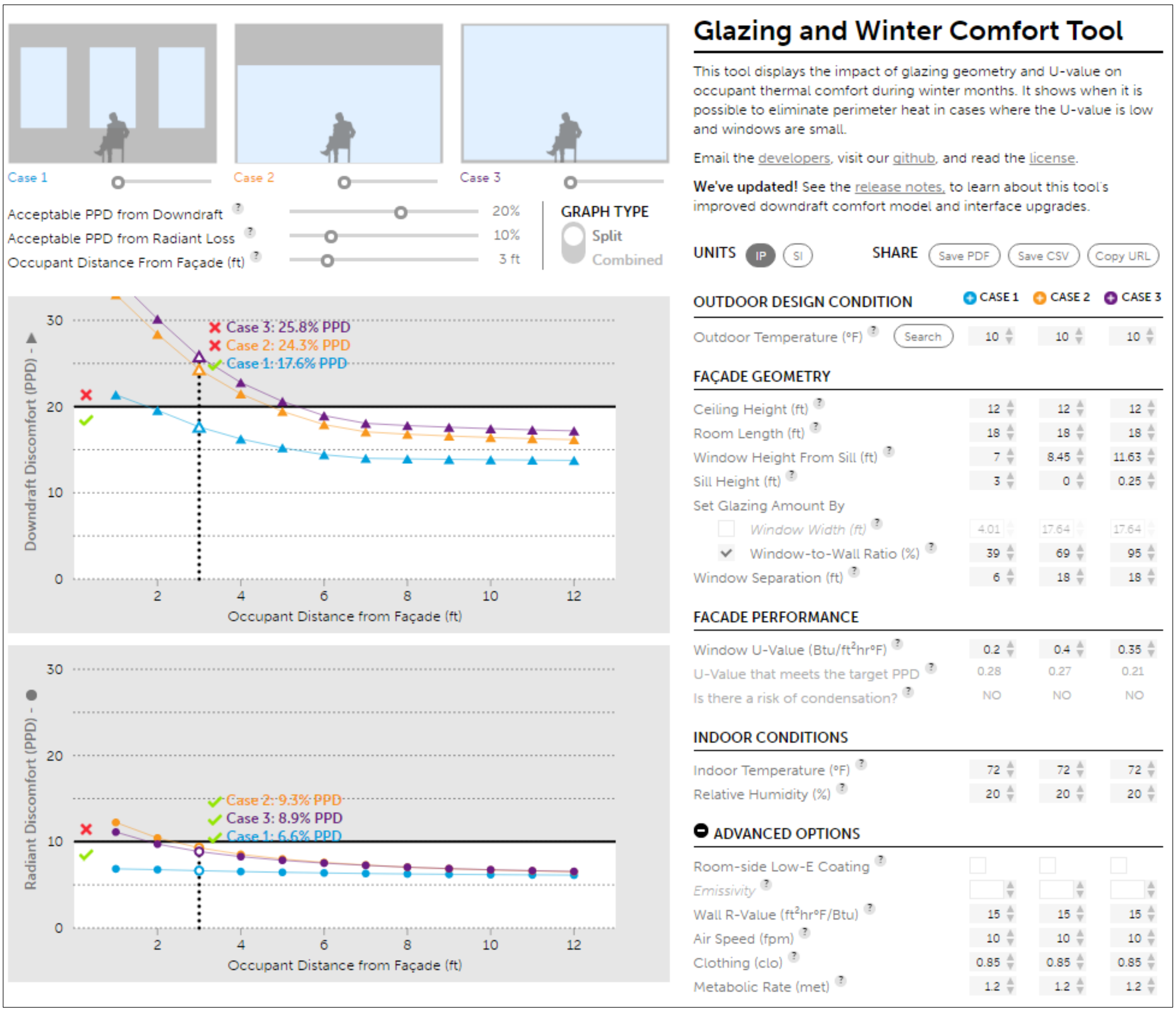

Figure 1. Thermal and Winter Comfort Tool Interface

User Interface

Figure 3 illustrates the web interface.

Most inputs (and a few outputs) are located along the right side of the page, while most outputs are laid out on the left.

Façade Geometry

In this section all aspects of window and room geometry are specified, Window dimensions can be entered either as a set window-to-wall ratio at a given window height, or to set window width and height. Multiple windows can be modelled by specifying a horizontal separation between windows. Only horizontally-spaced coplanar rectangular windows can be modeled with this tool.

Façade Performance

The only input in this section is window U-value, which is recommended to be center-of-glass, but assembly U-value could be used for a window where the frame is prominent and can significantly influence the inner window pane temperature. Two pieces of information are provided as feedback to the user:

- Critical window U-value at which the limiting PPD threshold is met
- Potential for condensation along the interior windowpane, based on interior conditions. If the interior windowpane is within 3 °C from the air dew point temperature, the user is informed that there is potential for condensation. If the dew point meets or exceeds the interior saturation point the user is told there will certainly going to be condensation. (This is particularly relevant for window assemblies with an interior low-e coating where the glass surface temperature is considerably lower than in other window units).

Environmental Conditions

Three environmental conditions can be modified by the user in this section: outdoor air temperature, room air temperature, and indoor air humidity. The choice of the right outdoor temperature for a given climate is left to the user (see Part 2 of this paper for further discussion on the topic.)

A search feature allows the user to specify the 99% heating design temperature as outdoor temperature from any TMY weather data file in the world without having to manually search for this value.

Advanced Options

This section contains variables that should be only modified by users who are deeply familiar with their influence on the output:

- Variables that can affect the outcome significantly include occupant metabolic rate, clothing value and room air speed.
- Windows with room-side low-e coatings can be modeled by changing the emissivity of the inner windowpane from the default value of 1 to a lower value. This variable can be different for each scenario.
- Finally, the R-value of the exterior wall can also be modified in this section. In a well-insulated building this value has a negligible impact on the thermal comfort conditions of the space, however, it is more relevant in spaces with uninsulated exterior walls.

Façade Elevations

The upper left corner of the page displays the façade elevations being modeled in each scenario, and allows the user to define the relative location of the occupant with respect to the window, parallel to the façade.

Outputs

Two output charts for PPD distribution with distance from façade are shown on the left part of the screen (for downdraft and radiant discomfort at the top and bottom, respectively). Each case is identified by a curve of a different color, and text informs the user whether the minimum comfort threshold is being met. In order to ensure a comfortable space, the space must meet an acceptable condition in both charts.

The PPD thresholds for both sources of discomfort can be set either above the outputs area or by manually dragging the solid black line in each chart.

Similarly, the distance of the occupant from the façade can be modified either above the chart or by dragging the dotted vertical line left or right in either chart.

There is also the option to combine both charts into one, where only the dominant source of discomfort for each occupant location is represented.

Units

Calculations can be completed in either SI or IP units.

Sharing / Exporting

Results can be shared or exported in three formats:

- Through a unique URL
- By printing to a pdf file
- By exporting the data to a .csv file

Warning Messages

Certain scenarios may lead to a condition that will never be comfortable to the users. In these cases, a warning message is displayed. Examples include conditions where the indoor air temperature is too low to ever satisfy acceptable comfort levels, or the PPD threshold is too strict.

Case Studies

Case Study 1: Glazing Design

Consider the situation in which a project in early design stages has a goal 40% window-to-wall ratio for its façade, with a double-pane window with a U-value of 2.0 W/m²K. The team wants to understand the impact of glazing geometry on indoor thermal comfort conditions, hoping to avoid the use of perimeter heating.

Three cases are evaluated (Figure 4):

1. Floor-to-ceiling windows (H: 4 m, W: 0.7 m)
2. Shorter punched windows (H: 3 m, W: 0.9 m, 0.5 m from floor)
3. Ribbon windows (H: 1.63 m, W: 4.9 m, 1 m from floor)

Figure 4. Three glazing scenarios with 40% window-to-wall ratio

Environmental conditions included outdoor and indoor temperatures of -12 °C and 23 °C, respectively, and indoor relative humidity is 20%. The room is 4 m high and 5 m wide. The occupancy type is an office (1.2 met, 0.85 clo). The thermal comfort thresholds defined by the team are PPD_{Rad} of 10% and PPD_{Draft} of 20%.

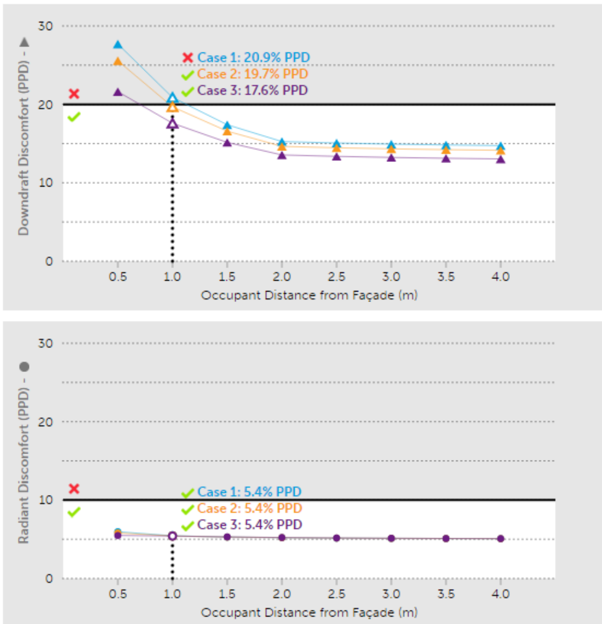

Figure 5 Thermal comfort conditions for three scenarios (blue, orange and purple curves for tall, punched and ribbon windows, respectively) with 40% window-to-wall ratio, double pane windows (U=2 W/m2K), outdoor temperature of -12 °C and indoor temperature of 23 °C. Tall windows generate too much downdraft to ensure a comfortable environment.

Figure 5 shows the expected PPD levels in the space, with respect to downdraft and radiant discomfort (top and bottom, respectively). In all three scenarios it is downdraft that dominates the potential for occupant discomfort. As one would expect, both PPD_{Rad} and PPD_{Draft} levels drop as the occupant is located further away from the exterior façade.

For an occupant located 1 m from the façade (indicated by a dotted line), only Case 3 (ribbon windows) meets the minimum comfort threshold in both charts.

In contrast, for an occupant 1.5 m away from the façade, the discomfort associated to downdraft is reduced for all three cases, achieving a PPD below the minimum threshold.

Radiant discomfort in not an issue for any of these cases.

Case Study 2: Window Performance

Now consider the scenario in which the glazing geometry has already been defined, and the team is looking for guidance in terms of which window unit to purchase in order to mitigate the need for perimeter heating.

Three cases are evaluated (Figure 6):

1. Double-pane window, U-value: 1.7 W/m^{2}K
2. Triple-pane window, U-value: 1.1 W/m^{2}K
3. Double-pane window with low-e coating (ε=0.2) on interior surface, U-value: 1.1 W/m^{2}K

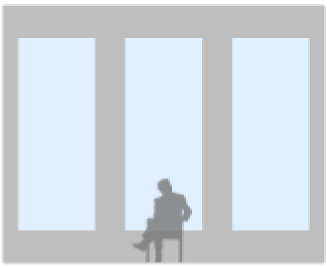

Figure 6. Evaluating three scenarios same window geometry but different window thermal performance

The room geometry, occupancy and environmental conditions are the same as in the previous case study. Indoor air temperature is 22 °C. The windows are 3 m tall and 1.2 m wide (54% window-to-wall ratio), and are located at 0.5 m from the floor.

Figure 7 shows the expected PPD levels in the space, with respect to downdraft and radiant discomfort (top and bottom, respectively). Once again, in all scenarios downdraft is the driving factor.

For an occupant sitting at 1 m from the façade (dotted line), only the triple-pane scenario is a viable option if the design team wants to avoid the use of perimeter heating. The window unit with an interior low-e coating will lead to the highest potential downdraft condition, because the coating works by blocking radiant heat transfer to the glass and thus lowering the inner windowpane temperature.

Similar to Case Study 1, radiant discomfort is not an issue for any of the cases analyzed.

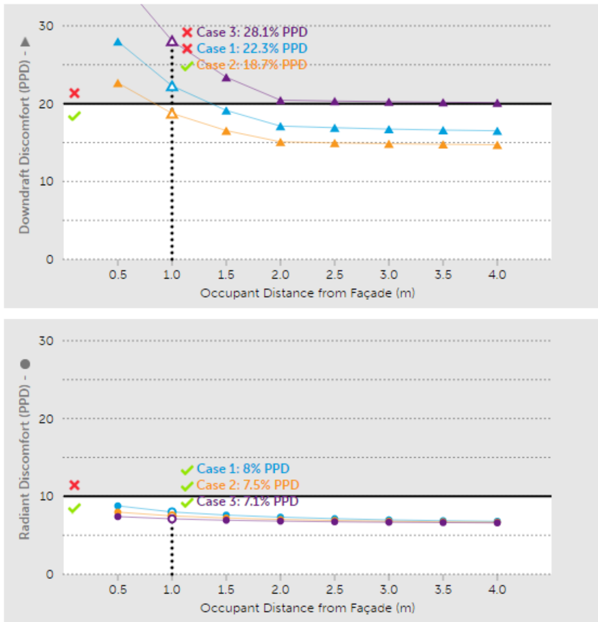

Figure 7. Thermal comfort conditions for three scenarios (blue, orange and purple curves for cases with double-pane, triple-pane and double-pane with interior low-e coating, respectively) with outdoor temperature of -12 °C and indoor temperature of 22 °C. Triple pane glass is the only configuration that ensures a comfortable environment for an occupant sitting 1 m from the façade.

Discussion

The Glazing and Winter Comfort tool is, to our knowledge, the first of its kind to provide quick feedback to designers and engineers regarding the thresholds beyond which thermal comfort may be compromised for a given glazing scenario.

Findings from using the tool indicate that downdrafts is often the limiting factor to ensure a thermally comfortable space, but that it can often be overcome by selecting the right window geometry. The relevance of selecting a high window thermal performance is particularly relevant in climates with very low temperatures in the winter time. In mild climates, the likelihood of encountering occupant discomfort associated to cold glazing is less likely.

This dominance of the downdraft effect suggests that tall windows, which are often encouraged to bring daylight into a space, are the most prone to triggering the need for perimeter heating, regardless of the window-to-wall ratio.

Findings also shed light on the fact that double-pane windows with an interior low-e coating, an increasingly popular technology, should be specified with caution, particularly if they are tall or installed in very cold climates.

Radiant discomfort appears to be only an issue in full glazing scenarios. Most other glazing conditions will not cause significant discomfort on occupants, and will instead show a minimal variation in PPD_{Rad} with distance from the façade.

The value of PPD_{Rad} however, is extremely sensitive to changes on a few inputs such as clothing values or room air temperature. Any tool using the PMV model encounters the same challenge, and the users should be very careful when defining these parameters.

This tool was designed to model simple facades with rectangular windows. Evaluating discomfort with more complex façade designs or spaces where interior surface temperatures may not be the same as ambient temperature (such as radiant flooring / ceilings, or thermal mass) are outside of the scope of this web tool, but are addressed in Part 2 of this paper (Mackey et al., 2017).

Conclusion

Facade design has increasingly more and more glass. While glass provides a connection to the outdoors for occupants and allows for daylight penetration, it is detrimental not only to the energy use of a building but also indoor thermal comfort levels. The Glazing and Winter Comfort tool was developed to provide architects and engineers with simple guidance on how to design glazed facades that are less prone to causing occupant thermal discomfort in the winter time.

Based on the latest research in the field, the tool evaluates the two most important sources of discomfort: low mean radiant temperatures and cold downdraft currents. It allows users to compare multiple glazing scenarios and assess the impact of window geometry and thermal performance on an occupant's thermal experience.

We hope that this tool can raise awareness within the design community on the relevance of glazing design on occupant winter comfort, and that it will assist project teams to make informed decisions regarding the options available to eliminate the use of perimeter heating when so desired.

Acknowledgements

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The code to calculate PMV thermal comfort in this work originates from the UC Berkeley's Center for the Built Environment (CBE) Thermal Comfort online tool, available under an open source GPL license. As a result, the tool presented in this paper is also open source.

Additionally, the authors would like to thank the CBE thermal comfort research group for their feedback on this project, in particular by sharing unpublished results of their recently-developed model to estimate downdraft discomfort.

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