Designing For Comfort:
New Approaches for Detailed Window Modeling

BuildEnergy NYC, October 4, 2018
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Outline (45 mins)

• A Brief Introduction to Thermal Comfort
• Passive House Institute certification and thermal comfort limits
• Applying detailed modeling techniques to windows for Thermal Comfort analysis
• What’s next?
A (Brief) Introduction to Thermal Comfort
Perceptions of Thermal Comfort depend on:

- Air temperature
- Humidity level
- Velocity of air flows
- Surface temperatures
- Clothing level
- Activity Level
- Age, Gender, Body type
- Culture / Expectations
- Control over space
Isn’t it just up to the mechanical systems?
How do we improve comfort AND reduce energy consumption?

From: “Advancing Passive House Policy NAPHN 2016 policy session 1 presentations” John Lee. NYC Mayor’s Office of Sustainability
Thermal Comfort Standards

Ergonomics of the thermal environment — Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria

BS EN ISO 7730:2005

The European Standard EN ISO 7730:2005 has the status of a British Standard

ANSI/ASHRAE Standard 55-2017
(Supersedes ANSI/ASHRAE Standard 55-2013)
Includes ANSI/ASHRAE addenda listed in Appendix N

Thermal Environmental Conditions for Human Occupancy

See Appendix N for approval dates.

This Standard is under continuous maintenance by a Standing Standard Project Committee (SSPC) for which the Standards Committee has established a documented program for regular publication of addenda or revisions, including procedures for timely, documented, consensus action on requests for change to any part of the Standard. The change submittal form, instructions, and deadlines may be obtained in electronic form from the ASHRAE website (www.ashrae.org) or in paper form from the Senior Manager of Standards. The latest edition of an ASHRAE Standard may be purchased from the ASHRAE website (www.ashrae.org) or from ASHRAE Customer Service, 1791 Tullie Circle, NE, Atlanta, GA 30329-2305. E-mail: orders@ashrae.org. Fax: 678-539-2129. Telephone: 404-636-8400 (worldwide), or toll free 1-800-527-4723 (for orders in the U.S. and Canada). For reprint permission, go to www.ashrae.org/permissions.

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“The predicted mean vote (PMV) model uses heat balance principles to relate the six key factors for thermal comfort to the average response of people on the ... scale.”

1. Air temp
2. Air Relative Humidity
3. Air Speed
4. Occupant Metabolic Rate
5. Occupant Clothing Level
6. Mean Radiant Temperature

From: ASHRAE 55, 2017. Appendix H3
Radiant Temperature?
### ISO 7730: 2005

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Warm Ceiling</td>
</tr>
<tr>
<td>A</td>
<td></td>
<td>&lt; 6%</td>
<td>-0.2 &lt; 0.2</td>
<td>&lt; 2</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td>&lt; 10%</td>
<td>-0.5 &lt; 0.5</td>
<td>&lt; 3</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td>&lt; 15%</td>
<td>-0.7 &lt; 0.7</td>
<td>&lt; 4</td>
</tr>
</tbody>
</table>

The diagram illustrates the thermal comfort body model with two temperatures, $T_1$ and $T_2$.
Mechanically Conditioned Spaces
Section 5.3
Any conditioned space

Compliance is achieved by demonstrating:
-0.5 < PMV < +0.5
(same as 'Class B' in ISO 7730)

‘Naturally’ Conditioned Spaces
Section 5.4 but only IF...

- No mechanical cooling in the space
- 1.0 - 1.3 Met.
- Occupants can control clothing level (0.5 – 1.0 Clo.)
- Outdoor temp is > 50-F and < 92.3-F
Overall PMV and Occupant Dissatisfaction

PPD = 100 - 95 \times \exp(-0.03353 \times \text{PMV}^4 - 0.2179 \times \text{PMV}^2)

From: ASHRAE 55, 2017. Appendix H, Figure H3

We can’t make ALL people comfortable, ALL of the time. 
There is a ‘floor’ of 5% Dissatisfied no matter what.
Localized thermal discomfort

Window to Wall
Sheer Wall
Corner

Source: Justin Downey, RWDI
Window Surface Temperature Effect

PD as a function of a 'Cool Wall' Surface

From: ISO 7730 Section 6.5, Equation 10: \[ PD = \frac{100}{1 + \exp(6.61 - 0.345 \times \Delta T [^\circ C])} \]
Entire industries of products have developed in order to fix the comfort problems caused by poor quality windows.
“A **Passive House** is a building, for which thermal comfort . . . can be achieved solely by *post-heating or post-cooling* of the fresh air mass [supply air], which is required to fulfill sufficient indoor air quality conditions . . . without a need for additional recirculated air.”

- Dr. Wolfgang Feist. 2006
Eliminate Perimeter Supply?

Often supply air (and therefore heating) is restricted to the 'core' of the building for reasons of economy. This is only possible if the exterior surfaces have surface temperatures within the comfort zone.
PHI Certification Requirement

Minimum Thermal Protection:
“For the arctic to warm-temperate climate zones interior surface temperatures of the standard cross-sections of walls and ceilings as well as the average interior surface temperatures of windows may not be more than 7.6 F [4.2 K] below the operative indoor temperature 71.6 F [22 C].

The ‘operative’ temperature is a simplified combination temp that results from the air temp, mean radiant temp and air speed.

...The requirements will be checked in the PHPP with an indoor temperature of 71.6 F [22 C] and a minimum outdoor temperature taken from the climate data set for the building's location.”

For PHI certification this is the mean temp over the coldest 12 hour period for the building’s climate. For PHI certification projects in NYC this is +10.4F [-12C]

From: “Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standard, version 9f, revised 15.08.2016"
7.6 F Radiant Temp. Asymmetry?


“Radiation temperature asymmetry: In DIN 1946 Part 2 a limit value of 14.4 F [8 k] (10 K in ISO 7730) is given for radiation temperature asymmetry ($\Delta T_{si}$) value for cold wall surfaces. The wording of the standard indicates some uncertainty around this value; due to practical experience with the comfort in residential areas, a lower limit must be required [for Passive House certification]. As a benchmark, half of the limit value of DIN 1946 could be used: in the designated spaces, the radiation temperature asymmetry should be below 7.2 F [4 K].”

From: “Highly insulating window systems: examination and optimization in the installed state” Dr. Rainer Pfluger, Dipl.-Phys. Jürgen, Schnieders, Dr. Berthold Kaufmann, Dr. Wolfgang Feist. Passivhaus Institut 2003
4.2 K Radiant Temperature Asymmetry?

In [Pfluger 2003] numerous further variants for the placement of cold structural elements were calculated. As long as the criterion $\Delta T_{si} < 7.6 \degree F [4.2 \degree K]$ was met, no inadmissibly high temperature stratifications resulted, even when the ceiling and window heights were increased.

![Temperature Stratification Diagrams]

$U_W = 1.6 \text{ W/(m}^2\text{K)}$

$U_W = 0.5 \text{ W/(m}^2\text{K)}$

From: “Comfort standards for passive-house windows.” Jürgen Schnieders, Dr. Wolfgang Feist, Passivhaus Institut 2007
Air Temperature Stratification?

TYPICAL WINDOW ($R_w \approx 3.6$ (hr-ft$^2$-F)/Btu )

Source: PHI

62.6°F

68 °F

EXT.

INT.

Source: PHI
### PHI Max Allowable Window $U_{W-Installed}$ (NYC)

<table>
<thead>
<tr>
<th></th>
<th>Vertical</th>
<th>Sloped</th>
<th>Horizontal Roof</th>
<th>Horizontal Floor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W/m^2-k$</td>
<td>0.950</td>
<td>1.100</td>
<td>1.200</td>
<td>0.520</td>
</tr>
<tr>
<td>Btu/hr-ft²-F</td>
<td>0.167</td>
<td>0.194</td>
<td>0.211</td>
<td>0.092</td>
</tr>
</tbody>
</table>

The following exemptions from the thermal comfort requirements apply in addition:

- The requirements do not apply for areas which are not adjacent to rooms with prolonged occupancy or for separate isolated areas which are smaller than 1 m².
- For windows and doors, exceeding the limit value is permissible if low temperatures arising on the inside are compensated by means of heating surfaces or if, for other reasons, there are no concerns relating to thermal comfort.
- Alternatively, the criteria for thermal comfort will be deemed to have been fulfilled if evidence of the comfort conditions is provided in accordance with DIN EN ISO 7730.

$U_W$-Installed?

- $U_g$: U-Value of the Glass
- $U_f$: U-Value of the Frame
- $U_w$: U-Value of the Window
- $U_{w-installed}$: U-Value of the Window in the specific wall type
$$U_{w\text{-installed}} = \frac{(U_g \times A_{\text{glass}}) + (U_f \times A_{\text{frame}}) + (\Psi_{\text{spacer}} \times L_{\text{spacer}}) + (\Psi_{\text{install}} \times L_{\text{install}})}{A_{\text{window}}}$$

The addition of the Psi-Install (calculated separately) is used to calculate the $U_{w\text{-INSTALLED}}$.
psi_{\text{Install}}: +0.043 \text{ W/mK}
In the Passive House Planning Package (PHPP) the $U_{W\text{-installed}}$ is calculated uniquely for EACH window. These values are used for both energy analysis and a thermal comfort check.
$U_{W}$-Installed: Window Size

$U_f = 0.14 \text{ Btu/(hr-ft}^2\text{-F)}$

$U_g = 0.08 \text{ Btu/(hr-ft}^2\text{-F)}$

2’ x 6’

$U_w = 0.185$

4’ x 6’

$U_w = 0.169$

10’ x 6’

$U_w = 0.159$
\[ T_{\text{surface-int}} = T_i - (R_{si} \times U_{\text{surface}} \times (T_i - T_e)) \]

In NYC this is +10.4 F [-12C]

- \( U_w = 0.185 \), \( T_{\text{surface}} = 63.2 \) F
- \( U_w = 0.169 \), \( T_{\text{surface}} = 64.0 \) F
- \( U_w = 0.159 \), \( T_{\text{surface}} = 64.4 \) F
Issues with Simplified Surface Temp. Check

Probably a good conservative solution for the most part. But...

1. **Prescriptive**: Doesn’t allow for creative solutions
2. **Coarse**: Doesn’t take all the specific parameters of the actual situation into account:
   - Window and Room Geometry [View Factors]
   - Localized low-temps [Asymmetric Psi-Installs]
   - What about complex situations [corner glass, double height]
   - Is a single design-day calculation suitable or is annual evaluation better?
   - What about summer comfort?
Detailed Window Thermal Comfort Modeling
**Goal:** Develop a more detailed methodology and tool for Passive House designers to utilize for thermal comfort analysis and design related to windows.
Existing Modeling Tools

http://comfort.cbe.berkeley.edu/

CBE Thermal Comfort Tool

Select method: PMV method

Air temperature
25 °C

Mean radiant temperature
25 °C

Air speed
0.1 m/s

Humidity
50 %

Metabolic rate
1.1 met

Clothing level
0.5 clo

Complies with ASHRAE Standard 55-2017

PMV
-0.13

PPD
5%

Sensation
Neutral

SET
24.6°C

Psychrometric chart (air temperature)

NOTE: In this psychrometric chart the abscissa is the dry-bulb temperature, and the mean radiant temperature (MRT) is fixed, controlled by the input box. Each point on the chart has the same MRT, which defines the comfort zone boundary. In this way you can see how changes in MRT affect thermal comfort. You can also still use the operative temperature button, yet each point will have the same MRT.
Existing Modeling Tools

Existing Modeling Tools

- Ladybug
- Honeybee

Operative Temperature

Adaptive Comfort

°C

°C From Comfort Temperature

20  22  24

-3  0  +3
Can it be used for Passive House certification?

- Relies on surface temps from an hourly (Energy+) model rather than PHI design day Exterior temps
- Uses Energy+ simplified U-Factor method for whole windows (no Psi-Install)
- Doesn’t output asymmetry result by default
- Uses AHSRAE 55 targets not PH thresholds
- Doesn’t calculate bi-directional asymmetry
Example: Candela Lofts Passive House

Penthouse Corner Glass

Lobby Double-Height
Example: Localized low temperatures
Detailed Radiant Temp Asymmetry Calc.

Base Mean Radiant Temperature Calculation
A visualization of the view factor and MRT calculation for a point and surface.

\[
MRT = (\text{Srf1 Temp})(\text{Srf1 View Factor}) + (\text{Srf2 Temp})(\text{Srf2 View Factor}) + (\text{Srf3 Temp}) * (\text{Srf3 View Factor}) + \ldots
\]

View Factor = \frac{\text{(Intersect Vectors)}}{\text{(Total Vectors)}}

From: “PAN CLIMATIC HUMANS: Shaping Thermal Habits in an Unconditioned Society by Chris Mackey"
Example: Analysis Model

Detailed Window Method

U_w-installed Method
Radiant Temperature Asymmetry Map [-12 C Ext.]
Radiant Temperature Asymmetry Map [-12 C Ext.]
Reporting analysis-point data

<table>
<thead>
<tr>
<th>Category</th>
<th>PPD %</th>
<th>PMV</th>
<th>DR%</th>
<th>Local Discomfort</th>
<th>PD% from...</th>
<th>Radiant Temp</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Vertical air temp. difference</td>
<td>warm or cool floor</td>
</tr>
<tr>
<td>A</td>
<td>&lt;6</td>
<td>-0.2</td>
<td>&lt;+0.2</td>
<td>&lt;10</td>
<td>&lt;3</td>
<td>&lt;10</td>
</tr>
<tr>
<td>B</td>
<td>&lt;10</td>
<td>-0.5</td>
<td>&lt;+0.5</td>
<td>&lt;20</td>
<td>&lt;5</td>
<td>&lt;10</td>
</tr>
<tr>
<td>C</td>
<td>&lt;15</td>
<td>-0.7</td>
<td>&lt;+0.7</td>
<td>&lt;30</td>
<td>&lt;10</td>
<td>&lt;15</td>
</tr>
</tbody>
</table>

AHRAE 55--->

| Point 1  | 5.1   | -0.08 | 4.5 | 0.6 | 6.1 | 0.2 | 12.1 | 4.7 | 1.2 |
| Point 2  | 5.3   | -0.12 | 4.6 | 0.6 | 6.1 | 0.3 | 12.5 | 4.7 | 2.0 |
| Point 3  | 5.3   | -0.12 | 4.6 | 0.6 | 6.1 | 0.3 | 12.6 | 4.7 | 2.0 |
| Point 4  | 5.5   | -0.15 | 4.6 | 0.7 | 6.1 | 0.3 | 13.3 | 4.8 | 2.2 |
| Point 5  | 5.7   | -0.18 | 4.6 | 0.8 | 6.1 | 0.3 | 14.2 | 4.9 | 2.1 |
| Point 6  | 5.1   | -0.07 | 4.5 | 0.6 | 6.1 | 0.2 | 10.7 | 4.7 | 0.9 |
| Point 7  | 5.1   | -0.08 | 4.5 | 0.6 | 6.1 | 0.2 | 10.8 | 4.7 | 1.1 |
| Point 8  | 5.2   | -0.09 | 4.5 | 0.6 | 6.1 | 0.2 | 10.8 | 4.7 | 1.4 |
| Point 9  | 5.2   | -0.11 | 4.6 | 0.6 | 6.1 | 0.2 | 11.1 | 4.7 | 1.6 |
| Point 10 | 5.4   | -0.14 | 4.6 | 0.7 | 6.1 | 0.2 | 13.0 | 4.8 | 1.7 |
| Point 11 | 5.1   | -0.06 | 4.5 | 0.5 | 6.1 | 0.2 | 10.3 | 4.6 | 0.6 |
| Point 12 | 5.1   | -0.06 | 4.5 | 0.5 | 6.1 | 0.2 | 10.4 | 4.6 | 0.9 |
| Point 13 | 5.1   | -0.07 | 4.5 | 0.5 | 6.1 | 0.2 | 10.4 | 4.6 | 0.9 |
| Point 14 | 5.1   | -0.08 | 4.5 | 0.6 | 6.1 | 0.2 | 10.8 | 4.6 | 1.0 |
| Point 15 | 5.1   | -0.08 | 4.5 | 0.6 | 6.1 | 0.2 | 10.9 | 4.6 | 1.2 |
| Point 16 | 5.1   | -0.05 | 4.5 | 0.5 | 6.1 | 0.2 | 10.3 | 4.5 | 0.7 |
| Point 17 | 5.1   | -0.06 | 4.5 | 0.5 | 6.1 | 0.2 | 10.4 | 4.5 | 0.7 |
Next Steps
Predicted Mean Vote [PMV]

“The predicted mean vote (PMV) model uses heat balance principles to relate the six key factors for thermal comfort to the average response of people on the ... scale.”

1. Air temp = ?
2. Air Relative Humidity = ?
3. Air Speed = ?
4. Occupant Metabolic Rate = ?
5. Occupant Clothing Level = ?
6. Mean Radiant Temperature = ?

Operative Temp. = 71.6 F [22C]

From: ASHRAE 55, 2017. Appendix H3
• Input boundary conditions for PHI Cert?
• Need an easy way to calculate temp. stratification without complex simulation
• What about summer?
  • ASHRAE 55 2017 now has a “Procedure for Calculating Comfort Impact of Solar Gain on Occupants” – should that be included as a requirement?
• What radiant temp asymmetry values should be used as targets?