Optimizing Complex HVAC Systems with CFD – Role of Thermal Comfort

Anil Kapahi and Fengchang Yang
Learning Objectives

+ Understand thermal comfort – A key constituent to indoor environment quality
+ Recognize key contributing factors and a method to assess thermal comfort
  − ASHRAE 55
+ Understand science of Computational Fluid Dynamics (CFD) and how it can be applied to thermal comfort calculations
+ Understand external and internal heat sources and their impact on thermal comfort
+ Understand key outputs from CFD modeling to assess thermal comfort
Background

**Understanding Thermal Comfort**

- Buildings are responsible for 30-40% of global energy demand
  - Humans spend >80% of time indoors
  - Energy efficient buildings reduce carbon emissions

- Optimizing energy demand and ensuring human satisfaction can lead to sustainable and comfortable buildings

- Indoor Environment Quality (IEQ) comprehensively includes the conditions inside a building and their effects on patrons

Source: [https://www.healthyheating.com](https://www.healthyheating.com)
Background

Understanding Thermal Comfort

A principal purpose of HVAC is to provide conditions for human thermal comfort, “that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation” (ASHRAE Standard 55)

- judgement of comfort is a cognitive process
- purpose of this standard is to specify the combinations of factors that will produce thermal environmental conditions acceptable to a majority of the occupants
  - indoor thermal environmental factors
  - personal factors
- does not address other environmental factors which can improve indoor quality
- shall not be used to override any safety, health, or critical process requirements.

Source: https://www.ashrae.org
Key Thermal Comfort Factors

+ Thermal comfort: human body temp 36-38°C (96.8-100.4°F)
+ Achieved when Heat produced by metabolism = heat lost from body (Energy balance)

Personal Factors
- Activity (Metabolic rate)
- Clothing (Thermal resistance)

Environmental Factors
- Air temperature
- Mean radiant temperature
- Humidity
- Air flow speed

Source: https://www.simulationhub.com
**Indoor thermal environment factors**

+ Mean Radiant Temperature
  - Uniform temperature of an imaginary enclosure
  - Function of the position at which it is measured

Source: https://www.pok.polimi.it
How Do Standards Address Thermal Comfort?

**PPD/PMV**

assessment for thermal comfort can be done using ASHRAE 55 guidelines using PMV (Predicted Mean Vote) and PPD (Predicted Percentage Dissatisfied) indices.

![PMV Diagram](http://comfort.cbe.berkeley.edu/)

**Figure 1: Percentage of People Dissatisfied**

<table>
<thead>
<tr>
<th>Sensation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot</td>
<td>+3</td>
</tr>
<tr>
<td>Warm</td>
<td>+2</td>
</tr>
<tr>
<td>Slightly warm</td>
<td>+1</td>
</tr>
<tr>
<td>Neutral</td>
<td>0</td>
</tr>
<tr>
<td>Slightly cool</td>
<td>-1</td>
</tr>
<tr>
<td>Cool</td>
<td>-2</td>
</tr>
<tr>
<td>Cold</td>
<td>-3</td>
</tr>
</tbody>
</table>

Source: http://comfort.cbe.berkeley.edu/
Computational fluid dynamics (CFD)

+ CFD is a powerful tool for fluid flow analysis
+ Conservation of Mass, momentum, energy equations are solved
+ Coupled with heat transfer models
  - Heat generated due to equipment/people/lights
  - Heat gain/loss through enclosure boundaries
+ Incorporate design parameters: supply and return air velocity/temperature/RH; solar radiation
+ Visualize velocity, temperature, RH, MRT etc.
+ Steady state / Transient analysis

Fluid Flow
- Cooling and heating systems
- Gas and liquid leaks
- Ventilation system design
- Flow from moving systems (e.g. elevators)

Explosions & Dispersion
- Gas and dust hazards
- Leaks and migration
- Explosion potential and overpressures
- Venting design

Fire Dynamics
- Fire exposure, smoke movement
- Ignition, burning, and flame spread
- Buildings, ships, and other structures
- Wildland fires
Practical Problem

Do we need additional HVAC duct work at the gantry region to ensure patrons will be comfortable?

Gantry 2

Gantry 1
Three Dimensional CAD Model to Three Dimensional CFD Model
## Boundary Conditions

**Boundary conditions add physics to the model**

<table>
<thead>
<tr>
<th>Boundaries</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Air inlets</strong></td>
<td>Velocity inlets:</td>
</tr>
<tr>
<td></td>
<td>Stage area  ( v_{air} = 58 \text{FPM} )</td>
</tr>
<tr>
<td></td>
<td>Seats area  ( v_{air} = 49 \text{FPM} )</td>
</tr>
<tr>
<td></td>
<td>Temperature – 62 F</td>
</tr>
<tr>
<td></td>
<td>Humidity – 63% RH</td>
</tr>
<tr>
<td><strong>Air outlets</strong></td>
<td>Pressure outlets</td>
</tr>
<tr>
<td></td>
<td>(flow to outside of room)</td>
</tr>
<tr>
<td><strong>Human body</strong></td>
<td>Constant heat flux:</td>
</tr>
<tr>
<td></td>
<td>Seating people  ( Q'' = 60 \text{W/m}^2 )</td>
</tr>
<tr>
<td></td>
<td>Stage performer  ( Q'' = 70 \text{W/m}^2 )</td>
</tr>
<tr>
<td></td>
<td>Humidity from human body:</td>
</tr>
<tr>
<td></td>
<td>Water mass fraction = 0.014 (35% RH at skin temperature)</td>
</tr>
<tr>
<td><strong>Walls/Ceiling</strong></td>
<td>External walls/ceiling</td>
</tr>
<tr>
<td></td>
<td>( T_{air} = 90.1 \text{F} )</td>
</tr>
<tr>
<td></td>
<td>Heat transfer coefficient = 22.7 \text{W/(m}^2 \cdot K)</td>
</tr>
<tr>
<td></td>
<td>Solar radiation from sun July 15\text{th}</td>
</tr>
<tr>
<td></td>
<td>Thermal network calculated effective thermal conductivity for layered wall</td>
</tr>
<tr>
<td><strong>Lights</strong></td>
<td>( Q_{upper} = 17600 \text{W} )</td>
</tr>
<tr>
<td></td>
<td>( Q_{small} = 4576 \text{W} )</td>
</tr>
<tr>
<td><strong>Equipment</strong></td>
<td>20000 W on stage</td>
</tr>
</tbody>
</table>
Boundary Conditions

AV Equipment

Lights

Supply

Return
SIMULATION RESULTS

Air Temperature Distribution in Auditorium

- Hot air flows upward due to buoyancy effect
- Cold air supplied from inlets located on floor
- Detailed temperature distribution throughout auditorium
- Identify design challenges and solutions
- Inform design decisions
SIMULATION RESULTS

Relative Humidity Distribution in Auditorium

- Higher relative humidity near patrons
- Separation of RH as a function of height
- Great details of RH in the whole auditorium
**Thermal Comfort Assessment**

**PMV and PPD calculations**

- Assess thermal comfort at different locations
- Velocity, temperature and RH used at individual locations
- MRT calculated for individual location using view factors

![Diagram showing a 3D thermal comfort assessment model with locations labeled from #1 to #12.](image)
### PMV + PPD

<table>
<thead>
<tr>
<th></th>
<th>Patron #1</th>
<th>Patron #2</th>
<th>Patron #3</th>
<th>Patron #4</th>
<th>Patron #5</th>
<th>Patron #6</th>
<th>Patron #7</th>
<th>Patron #8</th>
<th>Patron #9</th>
<th>Patron #10</th>
<th>Patron #11</th>
<th>Patron #12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Temp (F)</td>
<td>77.27</td>
<td>76.55</td>
<td>77.09</td>
<td>77.09</td>
<td>70.0</td>
<td>72.23</td>
<td>75.47</td>
<td>75.47</td>
<td>75.38</td>
<td>76.73</td>
<td>75.38</td>
<td>76.91</td>
</tr>
<tr>
<td>Flow velocity (ft/min)</td>
<td>35.24</td>
<td>25.4</td>
<td>31.9</td>
<td>36.4</td>
<td>17.7</td>
<td>17.7</td>
<td>18.5</td>
<td>19.68</td>
<td>19.68</td>
<td>15.33</td>
<td>14.37</td>
<td>19.29</td>
</tr>
<tr>
<td>Relative humidity (%)</td>
<td>47.6</td>
<td>48.7</td>
<td>47.1</td>
<td>47.5</td>
<td>53</td>
<td>51.5</td>
<td>48.3</td>
<td>48</td>
<td>43</td>
<td>43.4</td>
<td>43</td>
<td>42.7</td>
</tr>
<tr>
<td>MRT (F)</td>
<td>81.46</td>
<td>81.18</td>
<td>81.48</td>
<td>81.33</td>
<td>80.4</td>
<td>80.67</td>
<td>81.19</td>
<td>81.06</td>
<td>81.07</td>
<td>81.34</td>
<td>81.2</td>
<td>81.5</td>
</tr>
<tr>
<td>PMV</td>
<td>0.06</td>
<td>0.17</td>
<td>0.13</td>
<td>0.01</td>
<td>-0.59</td>
<td>-0.31</td>
<td>0.08</td>
<td>0.05</td>
<td>0</td>
<td>0.20</td>
<td>0.03</td>
<td>0.2</td>
</tr>
<tr>
<td>PPD (%)</td>
<td>5</td>
<td>6</td>
<td>5</td>
<td>5</td>
<td>12</td>
<td>7</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>6</td>
<td>5</td>
<td>6</td>
</tr>
</tbody>
</table>

**Cloth factor = 0.61**

**Met rate = 1.0**
Summary

**Thermal Comfort Assessment using CFD**

- Thermal comfort is a key constituent of indoor environment quality
- PMV and PPD indices (CBE Tool) addresses thermal comfort
- CFD can visualize complex systems
- Assumptions/Boundary conditions play a large role in results
- Model results can help to make informed decision
- Teaming architectures, HVAC engineers and CFD engineers at the design phase can address the problem comprehensively

Source: https://www.healthyheating.com