Air movement: its role in conditioning building interiors efficiently

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Armstrong World Industries
CBE
Presentation outline

- Building environment and human comfort
  - Cooling of the indoor environment
  - The energy problem with existing approaches
  - The comfort problem with existing approaches
- Energy-efficient cooling: the role of air movement
  - Human response
  - Practical issues of how to implement air movement indoors
- Air movement and air quality, perceived and real
- Barriers for fan adoption in practice
- Future opportunities for air movement in buildings
Air movement related to thermal comfort and energy
4 environmental factors affect thermal comfort

- Air temperature
- Surrounding surface temperature
- Humidity
- Air speed

- Design has always focused on the first three (use of operative temperature and the psychrometric chart)
- Air speed has largely been seen as a problem to be avoided (draft) in conditioned spaces
ASHRAE Standard 55 comfort zones

- Winter and summer zones
- Zones satisfy 80% of people
- Require still air

- Setpoint ranges in US are narrower — winter temperatures year-round; buildings are overcooled in summer

In practice there is often a narrow zone year-round:

\[ \sim 71 - 75^\circ F \]
Actual temperatures lower than setpoints (BASE data: 95 office buildings, 1994 – 1998)
The cost of maintaining range of indoor conditions

https://escholarship.org/uc/item/13s1q2xc
Air movement: building occupants often want more

Air Movement Preference, ASHRAE Sensation -0.7 to 1.5 (n = 3230)

- Want More: 52%
- No Change: 45%
- Want Less: 

Air movement acceptability, and preferences

Acceptable Air Movement
- 71%

Unacceptable Air Movement

Want More: 84%
Want Less: 7%
No Change:

ibid
Example of what is possible: a zero net energy building in Phoenix Arizona, $82^\circ F$ ($28^\circ C$)

But is it OK for its white-collar occupants?
Thermal satisfaction ranking 91% in the CBE database
Windows (aka ‘natural ventilation’) and fans

Operable windows

Operable windows and fans
Standard 55 comfort zone for naturally ventilated buildings

- Empirical adaptive comfort model (adopted 2004)
- Limited to buildings with operable windows
- Local conditioning of environment—air movement cooling
- 13 degree F range!
- Causes not fully known; occupants’ personal control of air movement seems to be a major factor

Elevated air movement ASHRAE standard (2013,4)


*There is no upper limit to air speed when occupants have local control.*
Implementing air movement within a space

- Overhead fans are the most general source
- Design guidance is lacking
- Objective of CARB study: determine cooling effectiveness under several conditions at 82.5°F
  - With and without desks
  - Fan fixed and oscillating
  - Low and medium fan speed levels
  - Varying distance from the fan
- Added tests to cover hotter and more humid environmental conditions

Image from Armstrong World Industries
Study 1: test of fixed and oscillating fan 82.5°F

Oscillating fan, front positions

Oscillating fan, side positions

Summer clothing with short-sleeve shirts; 0.5clo
Office tasks
Test condition—comfort and energy

ASHRAE Standard 55

82.5°F
50% RH
## Air flow configurations

<table>
<thead>
<tr>
<th>Subject position</th>
<th>Fan mode</th>
<th>Power level</th>
<th>Configuration code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front</td>
<td>Fix</td>
<td>2</td>
<td>2 Fix Front</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>3 Fix Front</td>
</tr>
<tr>
<td>Oscillating</td>
<td>2</td>
<td>2 Oscillating Front</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>3 Oscillating Front</td>
</tr>
<tr>
<td>Side</td>
<td>Fix</td>
<td>2</td>
<td>2 Fix Side</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>3 Fix Side</td>
</tr>
<tr>
<td>Oscillating</td>
<td>2</td>
<td>2 Oscillating Side</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>3 Oscillating Side</td>
</tr>
<tr>
<td>Below</td>
<td>Fix</td>
<td>2</td>
<td>2 Fix Below</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>3 Fix Below</td>
</tr>
</tbody>
</table>
Whole-body thermal comfort
Velocity profiles for “oscillating” configuration
Results of the first study

- Both the fixed and oscillating fans provided comfort at the test condition.
- However the oscillating mode was not statistically different from the base case without a fan.
- The chosen oscillation frequency was too low, causing discomfort in the ~15 second period that air movement was absent. The recurrence interval should be shortened.
Study 2 and 3: Ceiling and floor fan comfort studies in warm and humid environments

<table>
<thead>
<tr>
<th>Study 2: Vertical airflow</th>
<th>Study 3: Horizontal airflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceiling fan</td>
<td>Floor fan</td>
</tr>
<tr>
<td>No control</td>
<td>Control</td>
</tr>
<tr>
<td>Six environmental conditions</td>
<td>Six environmental conditions</td>
</tr>
</tbody>
</table>
Test conditions

When applying this Graphic per Section 5.2.1.1, the following limitations apply:
- Applies to Operative Temperature only – cannot be applied based on dry bulb temperature alone. See Appendix C for acceptable approximations.
- Applies only when requirements of Sections 5.2.3 through 5.2.5 are met.

For other compliance paths, see Section 5.2.1.2 for the Computer Model Method and Section 5.3 for the Optional Method for Naturally Conditioned Spaces.

For further compliance requirements, see Sections 6 and 7.

ASHRAE Standard 55

- **Studies 2,3**
- **Study 1**
Thermal comfort with ceiling fan

Vertical air movement maintains thermal comfort

![Graph showing thermal comfort levels with different effective temperatures and fan speeds.](image-url)
Perceived air quality with ceiling fan

Air movement maintains perceived air quality

Effective temperature (°F)

Perceived air quality

Very acceptable

Very unacceptable

79°F 60%
79°F 80%
82°F 60%
82°F 80%
86°F 60%
86°F 80%

-3
-2
-1
0
1
2
3

78 80 82 84 86 88 90 92

No fan

0.3 m/s
0.7 m/s
0.85 m/s
1.2 m/s
1.6 m/s
1.8 m/s
Preferred air speed for comfort

- With vertical air flow, subjects’ preferred air speed can exceed ASHRAE 55 limit (existing no-control limit is 0.8 m/s)
- Air speed chosen by subjects with horizontal air flow vary but can also exceed the ASHRAE 55 with-control limit of 1.2 m/s)
Measured power consumption of fans

Power consumption of both ceiling and floor fans is very low. Fan power per occupant was around 3W at 79°F, 5W at 82.4°F, and around 10W at 86°F.
Study 4 – air movement cooling in sport facilities

Objectives
- Study air movement cooling at higher than sedentary activity levels (met rates)

Approach
- Physiological tests
- Comfort surveys
Test conditions

68, 72, 75, 78°F, 50%

base condition
(68°F, 50%, no fan)
Study design

Metabolic level: 2, 4, 6 met
Subjects: 10 males, 10 females
20 minute rides for each met level
Fans provided comfort at high temperatures
Summary of related work: near-body air movement within a heated/cooled chair (lab study at 84°F 50% RH)

<table>
<thead>
<tr>
<th>Comfortable rate (%)</th>
<th>91</th>
<th>19</th>
</tr>
</thead>
</table>

Fan
Control unit
Field study of chair in a campus building

Cesar Chavez Student Union: Summer and winter

Building

- No mechanical cooling

Objective

- Provide occupant thermal comfort

Approach

- Installed wireless temperature sensors in each of 18 workstations
- Survey finished

- Without PCSs (Sept. 25, 2013, base case)

- About 1300 survey responses received

Funding

CIEE through SPEED program

CBE chair

PCS chair

USB fan

PCS chair
Acceptability rates with and without chairs (summer)

Without PCS, acceptability rate is about 50 – 75%
With PCS, acceptability rate is about 75 – 90%
Summary of air movement studies in the literature

Zhang, H., E. Arens, Y. Zhai 2015, “Review of the corrective power of personal comfort systems in non-neutral ambient environments” Building and Environment, April
Occupant satisfaction rates under air movement cooling
Air movement and perceived air quality
Study of air movement cooling

- 2 tests/day
- 2 people/test
- 28°C (82.4F), 50%RH
Impact of airspeed on perceived air quality
Thermal comfort versus acceptability of perceived air quality
Investigating body plume effects

Collar can deflect the plume effectively
Creating body odor; isolating body plume
Scent intensity: collar versus airspeed disruption
Human convective boundary layer and its impact on personal exposure

Body plume affects inhaled air quality

Boundary layer air is 1 – 2°F higher than the ambient air temperature
Interaction of the human CBL with the downward ventilation flow from above

Interaction of the human CBL with the ventilation flow from front
Normalized concentration of cough released from 3 m distance from the manikin — Influence of the CBL, the direction and magnitude of invading airflow
Radiant cooling + acoustical panels + fans
Problem: heat transfer is blocked by suspended panels

- 60% Radiant heat exchange
- 40% Convective heat exchange
Goals and method

Goals

- Investigate the impacts of acoustical ceiling panels on radiant slab systems
- Study the ability of ceiling integrated fan to increase the ceiling convection coefficient

Method

- CFD model of a portion of office equipped with radiant ceiling

Funded by CBE and CARB in collaboration with Armstrong
Configurations tested

- Baseline with no fan and no panels

- Five different levels of acoustical panel coverage (26%, 35%, 43%, 56%, 68%)

- Two fan configurations (fan blowing up or down). Air speed at the blade level equal to 98.4 fpm
Results

<table>
<thead>
<tr>
<th>Panels coverage</th>
<th>No fan</th>
<th>Fan down</th>
<th>Fan up</th>
</tr>
</thead>
<tbody>
<tr>
<td>0% (baseline)</td>
<td>100%</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>26%</td>
<td>96%</td>
<td>144%</td>
<td>144%</td>
</tr>
<tr>
<td>35%</td>
<td>91%</td>
<td>139%</td>
<td>153%</td>
</tr>
<tr>
<td>43%</td>
<td>88%</td>
<td>139%</td>
<td>154%</td>
</tr>
<tr>
<td>56%</td>
<td>88%</td>
<td>139%</td>
<td>151%</td>
</tr>
<tr>
<td>68%</td>
<td>89%</td>
<td>132%</td>
<td>152%</td>
</tr>
</tbody>
</table>

Velocity [fpm]

Fan down

Fan up
Overcoming barriers to fan use; future prospects
Contributions to ceiling fan design and evaluation

Objective

- Work with industry to produce a standard ceiling fan performance index
- Guidance for designers about fan placement and the effects of workstation furniture

Test facilities

- CBE environmental chamber
- Thermal manikin

Funding

CEC/PIER *Changing the Rules* project, CBE
Quantifying airflow interaction with furniture

- No furniture
- With table
- With partition

0R, 0.5R, 1R, 2R
Airspeed distributions with furniture
Focusing fans within the workstation
Progress in the industry and future prospects

- Appearance—major progress in the fan industry
- Power efficiency improved with DC motors
- Intelligent controls for comfort and energy effectiveness—links with internet building automation

- We believe the momentum is underway for cooling with air movement
- An elevated air speed should be the base condition before compressor cooling is initiated—this requires a fundamental change to the practice of the last 50 years, but is not beyond reach
Creating architectural acceptance
Thank you!