Thermal Comfort
DEA 3500 - Human Factors: Ambient Environment

Thermal comfort scales
- Thermal comfort and thermal sensation are not the same
- Thermal sensation depends on skin temperature (cold through hot)
- Users can be comfortably hot or cold!
- Thermal comfort is a psychological concept that depends on the desired physiological state (uncomfortable through comfortable).

Thermal Comfort Variables

Thermal comfort variables
- Air temperature
- Radiant temperature
- Relative Humidity
- Air velocity
- Activity
- Clothing

Thermal comfort: Clothing
- Clothing insulation is measured in Clo units ($I_{cl}$)
  - One clo is the amount of thermal resistance which is necessary to maintain thermal comfort for a sitting-resting subject in a normally ventilated room (air movement 20 ft/min or 10 cm/sec) at a temperature of 70°F (21.1°C) and a RH<50%.
  - $1 \text{ clo} = 0.155 \text{ m}^2 \cdot \text{°C}/\text{W}$
  - Lowest clo value is 0 (naked body)
  - Highest practical clo value = 4 clo (Eskimo clothing, fur pants, coat, hood, gloves etc.)
  - Summer clothing ~ 0.6 clo
  - Winter clothing ~ 1 clo
  - $I_{cl} \text{ passive} \sim 0.15 \times \text{weight of clothes (lbs)}$ (10 lbs clothing~1.5 clo)
  - $I_{cl} \text{ active} = I_{cl} \times (0.6 + 0.4/M) \quad 1.2 \text{ Met}<M<2.0 \text{ Met}$

Thermal comfort: Clothing
- ASHRAE clothing ensembles

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Thermal comfort: Clothing
- 1 clo maintains sedentary man (1 met) indefinitely comfortable at 21°C, 50% RH, 0.01 m/sec.
- Wind speed effects clothing insulation
- Porosity - water vapor transfer through clothing affects its insulation value
- Permeation efficiency factor ($F_{pc}$) ranges from 0 = completely impermeable fabric
  - $1 = \text{absence of clothing}$
- Thickness - effects insulation value
- Tog - European unit of thermal insulation $1 \text{ tog} = 0.645 \text{ clo}$

Thermal comfort: Clothing
- ASHRAE 55-2010
Japan's “Cool Biz” Initiative
- 2005 – Japan launches “Cool Biz” initiative – thermostats set at 28°C (82.4°F) in
government offices from 21st of June and the 23rd of September – casual dress code, no
tie - saved 460,000 tons of CO₂ emissions in 1st year.
- 2006 - an estimated 1.14 million-ton reduction in CO₂ emission, the equivalent to the CO₂
emissions by about 2.5 million households for one month.
- Spawned new clothing lines – lightweight, low clo values
- Now spread to Korea and U.K.

Thermal comfort: Clothing
- Aerogel gives the greatest insulation value: it is flexible, has good compression resistance,
and so it is ideal for footwear insoles for extreme cold or hot environments.

Thermal Insulation of Chairs
- Tested the insulation value for 7 chairs. Value ranged between 0.1 – 0.3 clo for chairs with
solid seats, full backs and heavy cushioning.

Thermal Insulation of Chairs
- ASHRAE 55-2010 includes an insulation adjustment chair type.

Thermal Comfort Standards
Climate Chamber Studies (Rohles)
ASHRAE 55-1992 approach
- ASHRAE 55-1992:
  - Assumed similar air and radiant temperatures
  - Standard ET (SET*) - incorporates different levels of activity and clothing.

- New ET (ET*) - incorporates a correction for skin wettedness. ET* is equivalent to
SET* for sedentary activity (1.1 met), light clothing and low air speed.

- ET* defines a winter comfort zone and a summer comfort zone (modular comfort
envelope).

ASHRAE 55-1992 zones
- Winter:
  - activity 1.2 met
  - clothing = 0.9 clo (sweater, long sleeve shirt, heavy pants)
  - air flow = 30 fpm (0.15 m/sec)
  - mean radiant temperature = air temperature
  - Optimum Operative Temperature \( t_{op} \) = 22.7°C (73°F)
- Summer
  - clothing = 0.5 clo
  - air flow = 50 fpm (0.25 m/sec)
  - Optimum Operative Temperature \( t_{op} \) = 24.4°C (76°F)
  - Minimum clothes (0.05 clo), \( t_{op} \) = 27.2°C (81°F)

Psychrometric Chart
- Dry bulb temperature
- Water vapor pressure
- Wet bulb temperature
- Relative humidity
- Effective temperature
- Assumes that radiant temperature = air temperature
- ET is the isothermal sensation equivalent to the sensation for a air temperature at 50% RH
- Different charts for different airs speeds and clothing ensembles.

**ASHRAE 55-2010**
- ASHRAE 55-2010: Thermal Environmental Conditions for Human Occupancy

**ASHRAE 55-2010**
- “Thermal comfort is that condition of mind that expresses satisfaction with the thermal environment”
- Standard only addresses “steady state” thermal comfort (not necessarily immediate experiences upon entering a space)
- Focus is on sedentary activity level (1.0-1.3 met), which is where most data has been gathered.
- Does not apply to sleeping or bed rest.
- Range of Operative Temperatures presented are for 80% occupant acceptability (assumes 10% whole body dissatisfaction and 10% partial body dissatisfaction).
- Assumes clothing between 0.5-1.0 clo
- Assumes air speeds <= 20 m/s (40 ft/min)

**ASHRAE 55-2010 standard**
- Operative Temperature \( t_{op} \) is equal to the dry-bulb temperature that would result in the same heat loss from an unclothed, reclining human body in a hypothetical environment where the wall and air temperatures are equal and the air movement is 7.6 centimeters per second (15 fpm).
  \[
  T_{op} = 0.48t_r + 0.19\sqrt{v}t_a - (\sqrt{v} - 2.76)t_s
  \]
  where:
  - \( t_a \) = mean air temperature (°C)
  - \( t_r \) = mean radiant temperature (°C)
  - \( t_s \) = mean skin temperature (°C)
  - \( v \) = air velocity (cm/s)
  
  \( 1\text{cm/s} = 1.97 \text{ fpm} \)

**ASHRAE 55-2010 standard**
- Operative Temperature \( t_{op} \)
  - When the difference between radiant and air temperatures is <4°C (~7°F) and when air speed is small (<0.2 m/s, 40 fpm) then
  \[
  t_{op} = A t_a + (1-A) t_r
  \]
  where:
  - \( t_a \) = air temperature
  - \( t_r \) = radiant temperature
  - \( A \) is:
    - \( A = 0.5 \) (<0.2 m/s; <40 fpm)
    - \( A = 0.6 \) (0.2-0.6 m/s; 40-120 fpm)
    - \( A = 0.7 \) (0.6-1 m/s; 120-200 fpm)
ASHRAE 55-2010 Comfort zones

Effect of elevated air speed - lines represent equal levels of heat loss from the skin
When radiant temperature is low and air temperature is high, elevated air speed is less effective at increasing heat loss.

ASHRAE 55-2010

No lower humidity limit
Humidity ratio (the ratio between the actual mass of water vapor present in moist air - to the mass of the dry air) should be \( \leq 0.12 \)
- At 1 clo \( \sim 80\% \text{ RH} @ 72^\circ\text{F} \) to \( \sim 70\% \text{ RH} @ 74^\circ\text{F} \)
- At 0.5 clo \( \sim 65\% \text{ RH} @ 74^\circ\text{F} \) to \( 55\% \text{ RH} @ 80^\circ\text{F} \)

ASHRAE 55-2010

Acceptable operative temperatures and air speeds

International Thermal comfort Standard

ISO 7730, 2005: Ergonomics of the thermal environment – “That condition of mind which expresses satisfaction with the thermal environment”
ISO 7730 views thermal comfort as a specific combination of thermal conditions that will elicit the desired physiological state of comfortable (thermal comfort temperature).
ISO 7730 accepts the criteria that 80% satisfaction is adequate.

Fanger's Thermal comfort equation

Estimated by taking a weighted sum of the various temperatures and other relevant variables.
Thermal comfort meter.
Computer models used to calculate comfort predictions.
For many indoor settings, the predicted temperature is around 25.6°C (78°F).

Climate Chamber Studies (Fanger)

PMV and PPD

ISO 7730-2005 (Fanger's) approach

Equation containing following variables:
- Environment - air temperature, radiant temperature, air velocity, water vapor pressure
- Activity - metabolic heat, metabolic free energy
- Clothing - insulation, clothed area/nude area
Predicted mean vote (PMV)
- Mean vote on ASHRAE scale (Hot; Warm; Slightly warm; Neutral; Slightly cool, Cool; Cold) by a group of people
Predicted Percentage Dissatisfied (PPD)
- Based on PMV can predict the % of the group that will report thermal discomfort
Comfort temperature \( \sim 25.6^\circ\text{C} (~78.1^\circ\text{F}) \)
Thermal Comfort Meter
- Thermographic image of a standing and seated person.
- Thermographic image of the thermal comfort probe.
- Thermal comfort meter

Radiant Asymmetry

Thermal Comfort - ISO 7730-2005
- Radiant temperature asymmetry:
  - cold windows, walls, ceiling < 10°C (~18°F)
  - warm walls (no limit)
  - heated ceiling < 5°C (~9°F) asymmetry 0.6 m above floor (~2 ft)
- Air velocity (draft):
  - Winter - < 0.15 m/s (30 fpm)
  - Summer - < 0.25 m/s (~50 fpm)
- Vertical air temperature difference (< 3°C (~5°F) from feet to head when sitting - 0.1m-1.1 m (0.3 – 3.6 ft), or standing - 0.1 m-1.7 m (0.3-5.6 ft)
- Floor temperature - between 19°C (~66°F) and 29°C (84°F)
- PMV and PPD values for <20% dissatisfied

Thermal Comfort Software (ASHRAE)

Thermal Comfort Software

Thermal Comfort Software

Thermal Comfort Factors
- Age effects - nonsignificant - any age effect relates to activity and clothing)
- Ethnicity - nonsignificant
- Gender - mainly nonsignificant, some short term effects, depends on clothing and activity
- Time-of-day effects - mostly nonsignificant
- Ventilation system - variability in acceptable temperatures (Osland, 1998):
  - air-conditioned: winter = 2.6°C (~5°F)
  - air-conditioned: summer = 2.4°C (~4 5°F)
  - naturally ventilated: winter = 4.9°C (~9°F)
  - naturally ventilated: summer = 3.9°C (~7°F)

Draft Dissatisfaction
- 100 sedentary Ss participated in 3 experiments at an air temperature of 20, 23 and 26°C and exposed to six mean air velocities ranging from 0.05 to 0.40 m/s.
- The percentage of people predicted to be dissatisfied because of a draft may be calculated by using the following equation:
  \[ DR = (34 - t_a)(v_a - 0.05)^{0.62}(37*SD + 3.14) \]
- where:
  - DR Draft Rating [%]
  - \( t_a \) Air Temperature [°C]
  - \( v_a \) Local Mean Air Velocity [m/s]
  - SD Standard Deviation of air velocity [m/s]
- To describe how fluctuating the air velocity is, we often use the term "Turbulence Intensity" which is defined as:
  \[ Tu = 100 * SD/ v_a \%
- The head region was the most draught-sensitive part of the body for persons wearing
normal indoor clothing. No significant differences between the draught sensitivity of men and women.

**Air Velocity (Wigo & Knez, 2005, Ergonomics, 48, 1086)**

- 2 exps. tested the effects of 2 velocity conditions in a classroom during an 80 min. exposure:
  - V1 - constant low velocity
  - V2 - variations of low and high velocity
- Exp. 1: air temperature was increased from 21°C to 24°C
- Exp. 2: air temperature was increased from 25°C to 27°C
- 24 Ss (12 females; 12 males), aged 16 to 18 years
- No significant effects on attention, long-term memory or problem solving.
- In both experiments Ss in V2 said the air temperature decreased (while it increased).
- In Exp. 2, V2, Ss reported more pleasant conditions
- Air velocity variations induce a perceived cooling effect, and improve the perceived pleasantness of higher room temperatures.

**Adaptation and Context Effects**

- Thermal comfort testing shows evidence of context effects:
  - Malay subjects in a London climate chamber preferred a temperature of 25.7°C (78.2°F)
  - Chinese subjects in a Malaysian climate chamber preferred a temperature of 28°C (82.4°F)
  - Malay subjects in a Malaysian climate chamber preferred a temperature of 28.7°C (83.7°F)


**Adaptive Model (Auliciems,1981)**

**Thermal Comfort Adaptation**

- The mean of the monthly mean minimum and the monthly mean maximum temperatures predicts the indoor comfort temperature in free running buildings (Humphreys, 1981)

**Adaptive Models**

- Best fit model to thermal sensation data (Auliciems,1981):
  \[ Tn = 9.22 + 0.48Ta + 0.14 Tmmo \]
  - \( Tn \) = neutral temperature
  - \( Ta \) = air temperature
  - \( Tmmo \) = mean monthly outdoor temperature

- Best fit model to thermal sensation data for climate controlled and non-climate controlled buildings (Humphreys,1994):
  \[ Tn = 23.9 + 0.295(Tmmo – 22) \]
Adaptive Thermal Comfort

- Nicol et al. (1999) - with a continually changing indoor temperature Pakistani buildings were comfortable between 20 and 30°C with no cooling apart from fans.

Adaptive Thermal Comfort

- Humphreys & Nicol (2000) have shown that for free-running buildings comfort temperature ($T_c$) can be approximated:

$$T_c = 13.5 + 0.54 \, T_o$$

Where $T_o$ is the monthly mean of the outdoor air temperature.

- For air-conditioned buildings the relationship is more complex.

Adaptive Thermal Comfort

- Nicol & Humphreys (2002) - seasonal changes in mean comfort temperature $T_c$ in Islamabad, Pakistan and its relation to mean daily maximum, minimum and mean outdoor temperatures $T_o$.

Adaptation and Context Effects

Evaluating Adaptive Models (de Gear et al., 1997)

- Modeled 21,000 datasets on thermal conditions in 160 buildings
- Found that PMV can be useful in climate controlled buildings, and for 90% acceptability:
  - Winter: $T_{op} = 22.5 \pm 1.2K$
  - Summer: $T_{op} = 23.5 \pm 1.2K$
- PMV leads to substantial errors in non-climate controlled buildings. Here, for 90% acceptability:
  $$T_{op} = 18.9 + 0.255 \times (\text{outdoor mean ET*}) \pm 1.2K$$

ASHRAE 55-2010

- Acceptable operative temperature ranges for naturally conditioned spaces based on the adaptive model.

Field Study of Fanger’s Equation

- Howell et al. (1979, Human Factors, 21(2), 229) studied 521 adults in a variety of buildings and compared predicted comfort with actual rated comfort.
- Results showed that Fanger’s equation accounted for only 6% of the variance in thermal judgments.
- Demographic variables (age, sex) were insignificant.
- Psychological variables (e.g. perceptions of being warm or cold-natured may have much more potent effects.

Standard Classification of Office Serviceability

- ASTM E2320–04 presents a standard classification of the serviceability of an office facility in terms of Thermal Comfort and Indoor Air Conditions
- Serviceability is rated in terms of:
  - Temperature and Humidity
  - Indoor Air Quality Conditions
  - Ventilation (Air Supply)
Local adjustment by Occupants
Ventilation with Openable windows

**Standard Classification of Office Serviceability**
- ASTM E2320–04 – Temperature & Humidity

**Color, Noise and Thermal Comfort**
- Subjects sat in red or blue light conditions of low or high noise (noise stress).
- Color did not interact with noise.
- Subjects preferred lower ambient temperature in red light than in blue light (Fanger et al., 1977 Ergonomics, 20(1):11)