MODULE 150

HVAC&R SKILLS WORKSHOP

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SELECTING INDOOR DESIGN CONDITIONS FOR THERMAL COMFORT

Skills summary

What?

A guide to the different aspects of thermal comfort and how these affect design decisions.

Who?

Relevant for anyone involved in the design of air conditioning systems.

Human comfort is a subjective concept which varies from person to person and changes over time. Internal conditions that are considered universally comfortable in a temperate climate do not need to be exactly replicated in a tropical climate. Clothing differences, cultural difference and outdoor air humidity levels all must be considered.

By varying indoor humidity, dew point and air speed, designers can create comfortable conditions that are more practical and relevant to a specific environment, application or culture.

This Skills Workshop looks at the different factors affecting thermal comfort, and how to design for them.

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Factors affecting thermal comfort

Human comfort depends on a range of factors including temperature, humidity, air movement, clothing, and the type of activity, as well as cultural factors and personal preferences. Thermal comfort is a subjective experience that varies from person to person and over time. Historically, air conditioning controls have targeted a set room air temperature (DBT) and sometimes relative humidity (RH) level. We now understand that many other factors affect human comfort and their control can be exploited to optimise comfort air conditioning at greater energy efficiency. The ASHRAE 55 thermal comfort standard provides a mechanism for analysing human thermal comfort.
The factors that affect comfort include:

- Air temperature (DBT/WBT)
- Humidity levels (per cent RH)
- Mean radiant temperature (MRT)
- Air velocity (Air V)
- Activity level (MET)
- Clothing (CLO)
- Seasonal variation
- Geographic location
- Adaptation
- Workplace and local culture.

A CLO is a non-SI unit of clothing insulation, defined as the thermal insulation necessary to keep a sitting person comfortable in a normally ventilated room at 21°C and 50 per cent relative humidity. The thermal resistance of one CLO is equal to 0.155m^2.K/W. A typical combination of garments for 0.5CLO would be underpants, shirt with short sleeves, light trousers, light socks and shoes. See Table 1 for typical CLO factors.

Garment description[a]	I_{cl} clo[b]
Underwear	
Men's briefs	0.04
Panties	0.03
Bra	0.01
T-shirt	0.08
Full slip	0.16
Half slip	0.14
Long underwear top	0.20
Long underwear bottoms	0.15
Footwear	
Ankle-length athletic socks	0.02
Calf-length socks	0.03
Knee socks (thick)	0.06
Panty hose	0.02
Sandals/thongs	0.02
Slippers (quilted, pile-lined)	0.03
Boots	0.10
Shirts and blouses	
Sleeveless, scoop-neck blouse	0.12
Short-sleeved, dress shirt	0.19
Long-sleeved, dress shirt	0.25
Long-sleeved, flannel shirt	0.34
Short-sleeved, knit sport shirt	0.17
Long-sleeved, sweat shirt	0.34
Trousers and coveralls	
Short shorts	0.06
Walking shorts	0.08
Straight trousers (thin)	0.15
Straight trousers (thick)	0.24
Sweat pants	0.28
Overalls	0.30
Coveralls	0.49

Garment description[a]	I_{cl} clo[b]
Suit jackets and vests (lined)	
Single-breasted (thin)	0.36
SIngle-breasted (thick)	0.44
Double-breasted (thin)	0.42
Double-breasted (thick)	0.48
Sleeveless vest (thin)	0.10
Sleeveless vest (thick)	0.17
Sweaters	
Sleeveless vest (thin)	0.13
Sleeveless vest (thick)	0.22
Long-sleeved (thin)	0.25
Long-sleeved (thick)	0.36
Dresses and skirts[c]	
Skirt (thin)	0.14
Skirt (thick)	0.23
Long-sleeved shirtdress (thin)	0.33
Long-sleeved shirtdress (thick)	0.47
Short-sleeved shirtdress (thin)	0.29
Sleevless, scoop neck (thin)	0.23
Sleeveless, scoop neck (thick)	0.27
Sleepwear and robes	
Sleveless, short gown (thin)	0.18
Sleeveless, long gown (thin)	0.20
Short-sleeved, hospital gown	0.31
Long-sleeved, long gown (thick)	0.46
Long-sleeved pyjamas (thick)	0.57
Short-sleeved pyjamas (thin)	0.42
Long-sleeved, long wrap robe (thick)	0.69
Long-sleeved, short wrap robe (thick)	0.48
Short-sleeved, short robe (thin)	0.34

a "Thin" garments are summerweight, "thick" garments are winterweight.
b 1clo = 0.155 (m^2.K/W) **c** Knee-length

Table 1 – Typical CLO factors for typical garments

MET is the unit of metabolic rate of people. One MET is defined as 58.15W/m^2, which is equal to the energy produced per unit surface area of a person seated at rest. The surface area of an average person is about 1.8m^2. MET rates for typical people undertaking particular activities are provided in Section 8.

Comfort zones

Comfort zones, or envelopes of acceptable internal comfort conditions, have been developed for refrigerative air conditioning, evaporative air cooling and naturally ventilated or fan assisted ventilative cooling applications. The evaporative air cooling comfort zone differs from the refrigerative air conditioning comfort zone because of the different air velocities used and because of the differences in how indoor humidity is considered.

An advanced understanding of human comfort presents opportunities to save energy while still keeping occupants comfortable. The standard convention of attempting to maintain a narrow temperature band can be an energy-intensive practice. Instead, using ASHRAE Standard 55 as a guide, designers may find that a wider temperature band will provide adequate comfort, saving a significant amount of energy.

The ASHRAE-developed comfort zones shown in Figure 1 indicate a wide humidity tolerance.

The operative temperatures have been determined based on the following criteria:

- Light, primarily sedentary activity
- A metabolic rate ≤1.1MET
- 50 per cent relative humidity
- Mean air speed ≤0.15m/s.

Accommodating a range of CLO, MET and air speed within comfort zones can be achieved using the analytical methods contained in ASHRAE 55. Comfort is not the only performance criteria applied to systems, however, and indoor air quality, condensation risk and operating costs all need to be considered.

ASHRAE Standard 55 is strictly limited to thermal comfort considerations, so mould issues and health issues such as dry throat or eyes at low RH are not accommodated in the ASHRAE 55 thermal comfort recommendations.

With adaptation, an even greater psychrometric region may be accepted as comfortable, particularly if summer indoor air velocities are increased above winter velocities, see Figure 1.

Thermal comfort, air temperature and operative temperature

Temperature is usually the most important environmental factor affecting thermal comfort. If the temperature changes are small (e.g., <1°C) and occur slowly over the course of a day, they are unlikely to prompt dissatisfaction. Larger diurnal changes can be acceptable if they are within the control of the building occupant, i.e., they can move to a different area, change clothing levels, operate blinds or shade curtains, turn on a personal fan, or open windows (when air conditioning is off). Temperature changes over longer time periods (e.g., in a summer heat wave) can be acceptable if they occur sufficiently gradually to allow building occupants to adapt to the change. Seasonal temperature changes are reflected by changed clothing.

The air temperature inside an occupied space can be measured on a standard (mercury-in-glass) dry-bulb thermometer. This measurement of air temperature is representative for internal rooms where room surfaces are close to air temperature. This condition is described in Equation 1:

$$t_a = t_{mr}$$

Equation 1

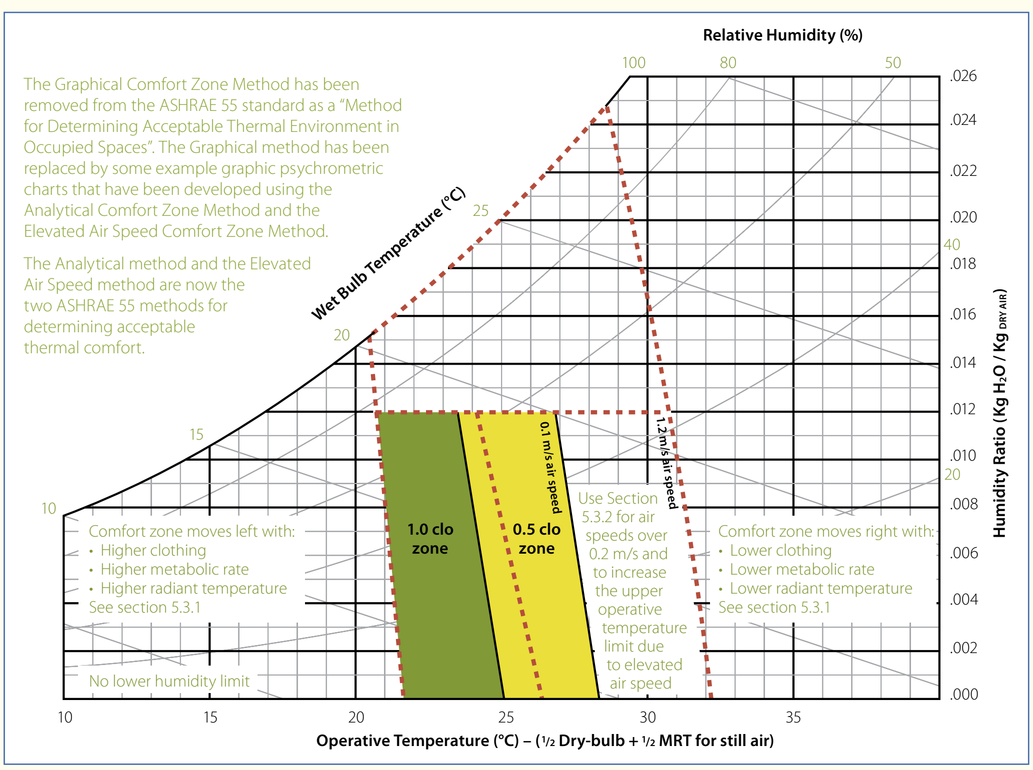
Where:

t_a = air temperature; and

t_{mr} = mean radiant temperature.

However, if an air conditioned space is subjected to direct solar radiation through a window, or infrared radiation through a poorly insulated roof or ceiling, then a simple mercury-in-glass thermometer measurement would be misleading if the temperature measurement is used to assess indoor thermal comfort.

Comfort assessment under these conditions must also consider the radiant temperature of the surrounding surfaces. This radiant temperature (tr) can be calculated from a measurement using a standard mercury-in-glass thermometer



Note that "Operative temperature" is not the same as the space temperature measured by a thermometer or temperature sensor.

Figure 1 – Extending comfort zones

enclosed in a hollow black sphere referred to as a *globe thermometer* in ISO 7726.

Psychrometric charts are the tool of choice for many air conditioning assessments. The psychrometric chart used in ASHRAE 55 for visualising indoor thermal comfort is different to the AIRAH psychrometric charts in that the scale along the bottom is in operative temperature not air temperature. Air temperature and radiant temperature are combined as operative temperature. Operative temperature is not the same as actual/measured space temperature as measured by a thermometer or temperature sensor. Operative temperature (t_{op}) is defined as the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non-uniform environment. Operative temperature can be shown mathematically as:

$$t_{op} = \frac{h_r t_{mr} + h_c t_a}{h_r + h_c}$$

Equation 2

It is also acceptable to approximate this relationship for occupants engaged in near sedentary physical activity (with metabolic rates between 1.0MET and 1.3MET), not in direct sunlight, and not exposed to air velocities greater than 0.20m/s.

$$t_{op} = \frac{t_a + t_{mr}}{2}$$

Equation 3

Where:

t_{op} = operative temperature

h_c = convective heat transfer coefficient hr
= linear radiative heat transfer coefficient ta
= air temperature (DBT)

t_{mr} = mean radiant temperature (MRT)

Most people have experienced the difference between air temperature and operative temperature. Recall the perceived temperature on a hot summer day when there is no breeze under a metal roof (without insulation) of say a park shelter. Then compare that to the lower perceived temperature under the shade of a nearby large and leafy tree. The difference is largely due to the greater protection from radiant heat offered by the leafy tree.

Typically, radiant temperature in a room becomes noticeable when a surface temperature of the space exceeds the air temperature by more than 4°C.

Thermal comfort and air movement

The cooling effect of moving air is well known, and operative temperature can be increased to take advantage of this cooling effect, associated with differences between air temperature and radiant temperature, see Figure 2. Comfort is a function of both temperature and air velocity, and humans can be comfortable over a range of conditions. By increasing the velocity or air movement, the air feels cooler even though the air temperature has not changed.

The principal physical factors for thermal comfort described in ASHRAE Standard 55 for office type spaces are environmental factors: air temperature, radiant temperature, air speed, and humidity; and additional personal factors: metabolic rate and clothing insulation. Given that psychrometric charts are two dimensional, displaying temperature versus humidity, the other physical factors, PULLOUT

i.e., the radiant temperature (t_r) and an assumed air speed factor (A) are accommodated by combining them with the air temperature (t_a), as an operative temperature (t_{op}). The simplest form of this combination is described in ASHRAE 55 as:

$$t_{op} = At_a + (1 - A)\, t_{mr}$$

Equation 4

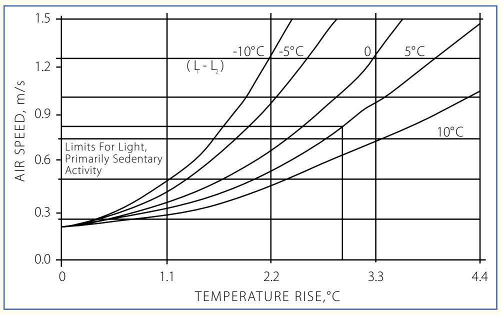


Figure 2 – Air speed required to offset increased air and radiant temperature

The values for air speed factor (A) range from 0.5 for air speed less than 0.2m/s to 0.7 for air speeds from 0.6–1.0m/s.

Assuming uniform velocity airflow, turbulent airflow with a gusting frequency of around 0.5Hertz can significantly increase the cooling effect of air movement at the same velocity.

The effect of air movement on the comfort of a person can be determined by comparing standard effective temperatures (SET).

Thermal comfort and humidity

Human comfort depends on temperature, air movement and the ability of the body to warm or cool itself to maintain a required body temperature. High levels of humidity generally lead to a feeling of discomfort as the increased levels of moisture in the air impede the body's ability to perspire and cool itself through evaporation (evaporative body heat exchange). The high humidity levels in tropical climate areas must be considered.

Unlike sunlight and temperature, humidity is a factor that is much harder to design for in the built environment. Humidity cannot be controlled through shade as we do the sun or insulated against as we do for the heat and cold. Instead, ventilative cooling by ventilation and air movement, or comfort cooling by air conditioning becomes the essential design consideration for controlling humidity. Although it is harder to avoid humidity by building design, good cross ventilation or assisted air movement using ceiling or wall mounted fans can improve the comfort levels at higher levels of room humidity.

Relative humidity is most relevant to body heat exchange and thermal comfort at operative temperatures above 30°C, refer to Figure 3. This accounts for significant differences between effective temperature (ET) and standard effective temperature (SET) values, see *"Effective temperature and standard effective temperature"*.

Figure 3 shows the following:

- At an operative temperature of about 25.5°C for light clothed person (and 31°C for an unclothed person), there is minimal body heat exchange when the metabolic rate is about 1MET.
- When the operative temperature drops to lower values, the dry heat exchange is increased and the evaporative heat loss is mainly respired vapour loss. The skin temperature and the temperature of superficial and deep tissues drop, resulting in a negative heat storage.
- When the operative temperature exceeds 29°C, the rate of evaporative heat loss is significantly increased in order to counterbalance the reduction of dry heat exchange to maintain the thermal equilibrium.
- The body temperature tends to rise only when the body is entirely wet, and the evaporative heat loss is inadequate. There exists a positive rate of heat storage.

Body temperature above 43°C may cause death.

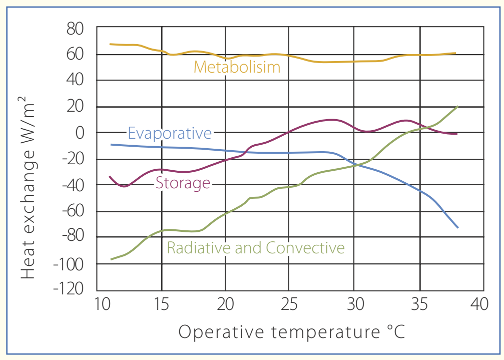


Figure 3 – Effect of operative temperature on human body heat exchange mechanisms

Effective temperature and standard effective temperature

Effective temperature (ET) combines operative temperature and humidity into a single index. Two different environments with the same ET should have a similar comfort response even though temperature and humidity levels are different. For the analysis to be valid, air movement and velocity, skin wettedness and clothing moisture permeability must also be the same. Some modified commercial versions of ET have been developed to better model human response to humid tropical and arid environments.

Standard effective temperature (SET) is the effective temperature (ET) under a set of standard conditions (clothing, skin wettedness and activity) intended to represent typical indoor applications or activities. SET is based on a laboratory study with a large number of subjects using empirical equations for skin temperature and skin wettedness. SET is calculated by determining a value that satisfies the two equations for those environmental conditions. Computer software to perform the calculations includes the ASHRAE Thermal Comfort Tool.

In the SET model, clothing insulation is linked to metabolic rate and skin wettedness is linked to mean body temperature. The standard MET rate is taken as 1.1MET and linked to a clothing insulation of 0.6CLO. However, a SET value can be calculated for any combination of the six thermal comfort factors: air temperature (DBT/WBT), humidity levels (per cent RH), mean radiant temperature (MRT), air velocity (Air V), activity level (MET) and clothing (CLO).

ET and SET are very similar for "normal conditions" in air conditioned buildings, typically around 22°C to 24°C when relative humidity is around 50 per cent. However, if operative temperature rises above approximately 30°C, the effect of relative humidity in SET is greater than in ET.

SET focuses on "skin wettedness" in the calculation of evaporative cooling from sweating and is a more suitable index to use than ET when assessing thermal comfort in humid environments.

Comfort variables and SET analysis

The ASHRAE 55 preferred way to determine how much dry-bulb air temperature can be offset by elevating air speed is to enter the relevant DBT, MRT, RH, MET and CLO conditions for the occupants and the space, along with the proposed elevated air speed into computer software analysis tools such as the ASHRAE Thermal Comfort Tool or the CBE Berkeley Comfort Tool.

These comfort tools will compute a range of outputs including SET. The SET is the equivalent air temperature of an isothermal environment at 50 per cent RH in which a subject, wearing clothing standardised for the activity concerned, has the same heat stress (skin temperature) and thermoregulatory strain (skin wetness) as in the actual environment.

Input the comfort factor values, note the value of SET calculated and then reduce the air speed value. A new SET will be computed. The difference between the original SET and the latter SET is the dry-bulb temperature offset achievable from the elevated air speed. The SET index is used for hot humid tropical climates because it is the only index included in the tool that takes account of skin wetness, an important factor in human body heat exchange in warm conditions.

Comfort variables and PMV analysis

Originally developed through field experimentation, the predicted mean vote (PMV) analysis refers to a thermal scale that runs from cold (-3) to hot (+3). A mathematical model of the relationship between all environmental and physiological comfort factors (or variables) was derived and adopted into ISO 7730 and ASHRAE 55.

The PMV equation for thermal comfort is a steady-state empirical equation for calculating (predicting) the average vote of a large number of people on a seven-point scale (-3 to +3) of thermal comfort. It only applies to humans exposed for a long period to constant conditions at a constant metabolic rate.

The equation uses the steady state heat balance of the human body and develops a link between the thermal comfort vote and the degree of stress or load on the body caused by any deviation from perfect balance. The greater the load, the more the comfort vote will deviate from zero. The partial derivative of the load function was estimated by exposing a number of people to enough different conditions sufficient to fit a curve. PMV is a widely used thermal comfort index and ISO 7730 uses limits on PMV as an explicit definition of the comfort zone.

From the PMV, the predicted percentage of dissatisfied people (PPD) can be determined. As PMV moves away from neutral (PMV = 0) in either direction, PPD increases, i.e., more people are dissatisfied. The maximum number of people that can be dissatisfied with their comfort conditions is 100 per cent and the minimum number is 5 per cent. A 20 per cent PPD figure (80 per cent satisfied) is generally considered acceptable. ■

Next month: Controls and HVAC