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Standards for design and evaluation of the indoor thermal environment

ASHRAE and ISO thermal comfort standards should be used in the design and operation of building HVAC systems

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The main purpose of most HVAC systems is to provide a healthy and comfortable indoor climate for the building's occupants. In recent years, there have been many buildings that do not provide comfortable and healthy conditions for their occupants—sick buildings.[1,2]

In most reported cases of buildings with indoor environmental problems, the thermal environment contributed significantly to the number of occupants being dissatisfied.[3] These problems could probably have been avoided because the knowledge we have today on how the thermal environment influences people, and the requirements needed to provide an acceptable thermal environment, is very extensive.

Many people believe that the quality of the thermal environment can be evaluated simply by measuring the air temperature (the dry-bulb temperature). However, this is far from accurate.

The thermal environment is actually a combination of air temperature, mean radiant temperature, air velocity, humidity and two personal factors (clothing insulation and activity level) that will influence a person's perception of warmth or coolness. Often, two or more of these parameters are combined in a thermal index.

A few examples will illustrate that the air temperature alone is not sufficient to evaluate the thermal environment. The operative temperature, a thermal index used in both *ASHRAE Standard 55* and *ISO Standard 7730*,[4,5] is the average of the air temperature and mean radiant temperature weighted by the convective and radiation heat transfer coefficient respectively. In typical indoor environments with low air velocities, a simple average is an acceptable approximation of the operative temperature.

In a typical winter situation, people sitting close to a large window feel cooler than people in the interior zone. The air temperature is the same in both places. However, people at the window are exposed to a lower mean radiant temperature. This is caused by the low window surface temperature, which can be quantified by a lower operative temperature.

As in winter, where outside air temperature and air velocity are combined to create the "wind chill" temperature, it is also necessary for the indoor environment to combine air temperature, mean radiant temperature and air velocity.

For example, consider a summer situation where the air velocity is increased by

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a ceiling fan. The air temperature and even the operative temperature may stay the same, but people feel cooler because of the higher air velocity, which cannot be quantified by the operative temperature.

These examples illustrate that the air temperature alone and, in some cases, the operative temperature are not sufficient to evaluate the thermal environment.

Based on many years of research, national and international standards such as *ASHRAE Standard 55* and *ISO Standard 7730* have been established. Both standards have recently been revised and are currently available.

When evaluating a given thermal environment to see whether it fulfills the requirements recommended in the standards, it will be necessary to measure the different thermal parameters. The requirements for instrumentation and methods to perform these measurements are also specified in *ASHRAE Standard 55* and in *ISO Standard 7726.*[6]

This article describes the methods and requirements included in the above standards. The differences between the ASHRAE and ISO standards will also be discussed.

Acceptable thermal environments

An acceptable thermal environment is defined in both *ASHRAE Standard 55* and *ISO Standard 7730* as an environment that at least 80% of the occupants would find thermally acceptable. Acceptance of the thermal environment and the perception of comfort and temperature are related to metabolic heat production, its transfer to the environment, and the resulting physiological adjustments of body temperatures and sweating.

Dissatisfaction may be caused by warm or cool discomfort for the body as a whole. This is called general thermal discomfort (thermal neutrality). The recommended limits for general thermal discomfort expressed in operative temperature or by the PMV index are based on a 10% dissatisfaction criterion.

Thermal dissatisfaction may also be caused by an undesirable heating or cooling of one particular part of the body. This is called local thermal discomfort. The recommended limits for local thermal discomfort are based on a 5% to 15% dissatisfaction criterion.

Because of individual differences, it is impossible to specify a thermal environment that will satisfy everyone. The people who feel general thermal discomfort may also feel local thermal discomfort. Therefore, the percentage of dissatisfied people is not additive. It is assumed that, in total, less than 20% will be dissatisfied when the recommendations in the standards are followed.

General thermal comfort

A first requirement for an acceptable thermal environment is that a person feels thermally neutral for the body as a whole. For example, a person does not know whether they would prefer a higher or lower ambient temperature level.

Man's thermal sensation is influenced by the following parameters:

- Personal parameters:
  Activity level, M (met, W/m^2, Btu/h per ft^2)
  Thermal insulation of clothing, I_{cl} (clo, $m^2\,°C/W$, $ft^2\,°Fh/Btu$)
- Environmental parameters:
  Air temperature, t_a (°C, °F)
  Mean radiant temperature, $\bar{t}_r$ (°C, °F)
  Air velocity, v_a (m/s, fpm)
  Air humidity (water vapor pressure), p_a (Pa, mm Hg)

These parameters can be combined in many ways and provide an acceptable thermal environment. *ASHRAE Standard 55* does not include an analytical method to combine these parameters. However, it provides diagrams that take these parameters into account.

Both *ISO Standard 7730* and the *ASHRAE Handbook—Fundamentals*[7] describe analytical methods to estimate the combined influence. *ISO Standard 7730* standardizes a method using the PMV-PPD index.[8] This method is also described in the *Handbook—Fundamentals.*

Based on studies with more than 1,300 subjects, an equation was established that predicts the average thermal sensation of a large group of people (PMV value) on a seven-point thermal sensation scale: (+3 hot, +2 warm, +1 slightly warm, 0 neutral, −1 slightly cool, −2 cool, −3 cold). A PMV value equal to 0 is equivalent to thermal neutrality.

The quality of the thermal environment may also be expressed as the predicted percentage of dissatisfied, PPD index, which is related to the PMV value. In *ISO Standard 7730*, the recommended limits for an acceptable thermal environment are:

$$-0.5 < PMV < 0.5$$
$$PPD < 10\%$$

The use of recommended limits is illustrated in *Figure 1.* The recommended operative temperature interval can be found for combinations of clothing insulation and activity level.

For a typical winter situation (heating period, clothing insulation is 1.0 clo) where the occupants have light, mainly sedentary work (1.2 met; office, school), the recommended operative temperature range is 20° to 24°C (68° to 75°F).

In summer (clothing insulation is 0.5 clo), the corresponding interval is 23° to 26°C (73° to 79°F).

The same requirements as in *ISO Standard 7730* for the winter situation

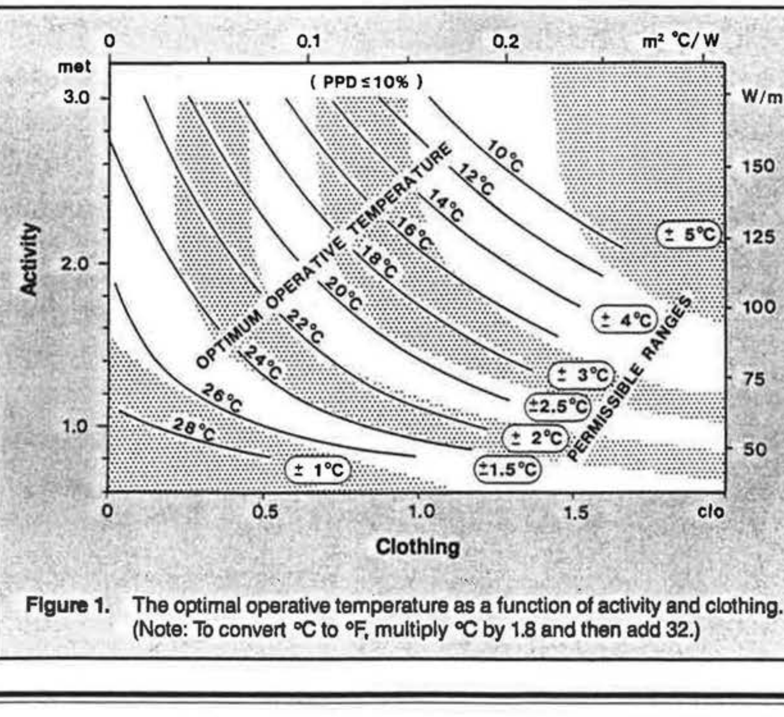

Figure 1. The optimal operative temperature as a function of activity and clothing. (Note: To convert °C to °F, multiply °C by 1.8 and then add 32.)

(heating period) and summer situation (cooling period) are specified in *ASHRAE Standard 55* (see *Figure 2*). It is important to notice that the specifications are given as operative temperature, which is an average value between the air and mean radiant temperatures. The boundaries of the comfort envelope in *Figure 2* are based on ET* lines.[9]

ASHRAE Standard 55 specifies a humidity range between a lower limit of 2°C dewpoint and an upper limit of 60% relative humidity (RH). The humidity only has a minor influence on the recommended comfort zones for winter and summer conditions at low activity levels.

In winter, the influence on the lower operative temperature limit is from 19.8°C (67.6°F) at 60% RH to 20.2°C (68.4°F) at 2°C dewpoint or 30% RH. In summer, the influence on the upper operative temperature limit is from 25.6°C (78.1°F) at 60% RH to 27°C (80.6°F) at 2°C dewpoint or 20% RH.

For people with mainly sedentary activity, an increase in humidity of 10% RH can be offset by a decrease in temperature of only 0.3°C (0.5°F).

The humidity limits specified in *ASHRAE Standard 55* are not for thermal comfort reasons, but for the impact the relative humidity may have on the indoor air quality. The upper humidity level of 60% RH is being re-evaluated and an addendum to the standard is planned. In *ISO Standard 7730*, it is recommended to control the humidity between 30% and 70% RH.

In *ISO Standard 7730*, there is no limitation for temperature cycling, temperature drifts or ramps. The PMV index just has to stay within the recommended range. This means that the operative temperature must stay in the acceptable range both for all locations in the occupied zone and at all times.

For example, for the winter (heating) period, if the operative temperature difference between the coldest location in the occupied zone (near a window) and the warmest location (interior wall) is 3°C (5°F), then the temperature must be controlled by a thermostat within a 1°C (2°F) range to stay within the recommended operative temperature range of 4°C (7°F). On the other hand, if the building HVAC system provides a very uniform environment, a large control range is accepted.

For temperature cycling, *ASHRAE Standard 55* has no restrictions on the rate of change if peak-to-peak value of the operative temperature is 1.1°C (2°F) or less. If the peak-to-peak value is higher, the rate must not exceed 2.2°C/h (4°F/h).

The maximum allowable drift or ramp is an operative temperature rate of 0.5°C/h (1°F/h). This must not exceed the comfort zone guidelines by more than 0.5°C (1°F) for longer than one hour.

Local thermal discomfort

Thermal neutrality described by the PMV-PPD indices or the operative temperature is not the only condition for thermal comfort. A person may feel thermally neutral for the body as a whole, but may not be comfortable if one part of the body is warm and another cold. Therefore, it is a further requirement for thermal comfort that no local warm or cold discomfort exists at any part of the human body.

Such local discomfort may be caused by excessive levels of asymmetric radiant field, local convective cooling (draft), contact with a warm or cold floor, or a vertical air temperature difference.

In *ISO Standard 7730* and *ASHRAE Standard 55*, the recommended limits for local discomfort for people occupied with light, mainly sedentary work (1.2 met) are as follows:

- The radiant temperature asymmetry (Δt_{pr}) from windows or other cold vertical surfaces shall be less than 10°C (18°F), in relation to a small vertical plane 0.6 m (24 in.) above the floor.
- The radiant temperature asymmetry (Δt_{pr}) from a heated ceiling must be less than 5°C (9°F), in relation to a small horizontal plane 0.6 m (24 in.) above the floor.
- Vertical air temperature difference between head and ankle level shall be less than 3°C (5°F). In *Standard 55*, it is specified as the difference between the air temperature at the 0.1 m (4 in.) and 1.7 m (68 in.) levels.
- Surface temperature of the floor shall normally be between 19° and 26°C (66° to 79°F), but floor heating systems can be designed for 29°C (84°F). In *Standard 55*, a general range of 18° to 29°C (64° to 84°F) is specified.

One of the most critical factors is draft. Many people are very sensitive to air velocities, so draft is a very common complaint in ventilated and air-conditioned spaces.

Research has shown that fluctuations of the air velocity have a significant influence on a person's sensation of draft.[10] The fluctuations may either be expressed by the standard deviation of the air velocity or by the turbulence intensity Tu, which is equal to standard deviation SDv_a divided by the mean air velocity SDv_a (SDv_a/v_a).

In the revised *ISO Standard 7730* and *ASHRAE Standard 55*, the requirements are based on a 15% dissatisfaction criteria. The recommended limits are shown in *Figure 3*.

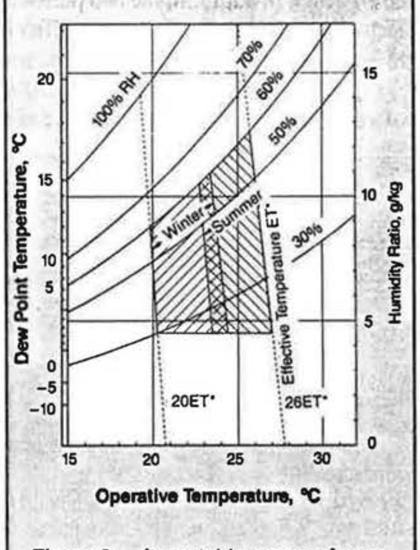

Figure 2. Acceptable ranges of operative temperature and humidity for people in typical summer and winter clothing during light, primarily sedentary activity. (Note: To convert °C to °F, multiply °C by 1.8 and then add 32.)

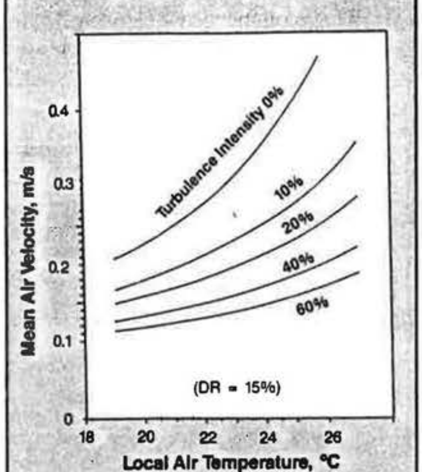

Figure 3. Combination of mean air velocity, air temperature and turbulence intensity that will result in less than 15% dissatisfaction. (Note: To convert °C to °F, multiply °C by 1.8 and then add 32. To convert m/s to fpm, divide m/s by 0.00508.)

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It may be beneficial to offset the influence of the elevated temperature above 26°C (79°F) by an increased air velocity above the limits in *Figure 3*. In *ISO Standard 7730*, this relation between increased temperature and increased air velocity can be estimated by using the PMV equation up to a mean air velocity of 1 m/s (200 fpm).

In *ASHRAE Standard 55*, there is a similar method where a graph shows how much the air velocity should be increased to offset the temperature increase. The maximum allowable air velocity is 0.8 m/s (160 fpm) for sedentary occupancy.

This will offset for a temperature increase of 2.5°C (4.5°F); from 26°C (79°F) to 28.5°C (83.5°F). However, it is required that the occupant must have individual control of the local air velocity.

Measuring the thermal environment

To verify that the above criteria are met either in a dispute over the indoor climate or during commissioning, it is important to be able to measure the thermal environmental parameters. Fortunately, there are instruments available to do that with the necessary accuracy.

Both *ASHRAE Standard 55-1993* and *ISO Standard 7726* specify measuring range, accuracy and response time for instruments. In *Table 1*, the *ISO Standard 7726* requirements for measuring moderate thermal environments are shown. Similar requirements are listed in *ASHRAE Standard 55*.

The recommended measuring heights are also specified. The general rule is to measure at levels that represent the head, middle and ankle levels of a person.

The PMV-PPD index, operative temperature, radiant temperature asymmetry, humidity and mean air velocity are measured at middle level. This is 0.6 m (24 in.) for sedentary and 1.1 m (44 in.) for standing.

Draft (air temperature, mean air velocity and standard deviation) and air temperature difference are measured at ankle (0.1 m; 4 in.) and head level (1.1 m; 44 in.) for sedentary, and at 1.7 m (68 in.) for standing. The measurement locations must reflect the position of the occupants. Common sense must also be used so that the instruments are not "shaded" from the exposure of the environment.

Field studies

Field studies of the thermal environment in offices have been reported in the literature.[11-13] These studies indicate that the number of dissatisfied is higher and the preferred operative temperatures are lower than predicted by the existing standards (*ISO Standard 7730* and *ASHRAE Standard 55*).

The differences in percent dissatisfied is not surprising. In laboratory studies (which are normally uniform thermal environments), the dissatisfaction level is directly related to the temperature level because this is the only influencing factor.

However, in field studies, several other factors may influence the evaluation of a person's dissatisfaction (air quality, light, noise, draft, temperature changes, etc.). Therefore, higher percent dissatisfied can be expected. In addition, the two personal factors (clothing and activity) are difficult to estimate accurately in field studies.

The thermal insulation of clothing is often estimated from tables where the values are based on measurement with a standing thermal mannikin.[4,14] These values do not include the added insulation a chair may have. Because the chair only covers a portion of the body surface (< 20%), the added insulation is limited and is probably in the range of 0.1 to 0.2 clo.

For a summer situation when people are assumed to wear 0.5 clo, the added insulation of a chair assumed to be 0.15 clo will have the same impact as a 1.5°C (2.5°F) increase of the operative temperature. More information is needed on the thermal insulation of chairs to verify these values.

The field studies report activity levels around 1.1 met. Normally it is assumed that sedentary office work with papers or computers will give an activity level of 1.2 met. In addition, people normally are not sitting at their desks the whole time, but are often increasing their activity level by performing other tasks (standing up, filing, walking around, etc.).

For the thermal comfort aspects related to the thermal sensation, the evaluation of the activity level must be based on an average of the previous one hour. It is likely that actual metabolic rates (activity levels) are higher than estimated from survey responses. This contributes in part to the discrepancy.

Another factor that influences the activity level is the mental performances of the subjects. Laboratory studies have shown that mental performance may increase the sedentary activity up to around 1.3 met.[15]

At lower activity levels (sedentary) and normal indoor clothing, an increase of the activity level with 0.1 met will have the same impact as a 0.7°C (1.3°F) increase in the

Table 1. Measuring Range and Precision for Measuring Individual Parameters in a Moderate Thermal Environment

Parameter	Unit	Measuring Range	Precision Specified	Precision Desirable	Response Time (90%)	Comments
Air temperature, t_a	°C °F	10-30 50-86	±0.5 ±7	±0.2 ±0.4	Response time shortest possible	Precision shall be valid for $\lvert t_a - \bar{t}_r \rvert \leq$ 10°C (18°F)
Mean radiant temperature, $\bar{t}_r$	°C °F	10-40 50-104	±2 ±3.6	±0.2 ±0.4	Response time shortest possible	This precision may be difficult to obtain by a globe thermometer
Radiant temperature asymmetry, Δt_{pr}	°C °F	0-20 0-36	±1 ±2	±0.5 ±1	Response time shortest possible	
Air velocity, v_a	m/s ft/min	0.05-1 10-200	$\pm\lvert 0.05+0.05\,v_a \rvert$ $\pm\lvert 10+0.05\,v_a \rvert$	$\pm\lvert 0.02+0.07\,v_a \rvert$ $\pm\lvert 4+0{,}07\,v_a \rvert$	Specified 1 s Desirable 0.5 s	Precision shall be fulfilled with a solid angle 3 Π sr. Mean value for 3 min. is desirable. Fluctuations are described by the standard deviation
Humidity, P_a	P_a	500-2500	±150	±150	Response time shortest possible	Prescision shall be valid for $\lvert t_a - \bar{t}_r \rvert \leq$10°C (18°F)
Surface temperature	°C °F	0-50 32-122	±1 ±2	±0.5 ±1	Response time shortest possible	

operative temperature. Together with the added insulation of chairs, this may explain the differences found between field and laboratory studies. More information is needed on the actual activity levels in offices and how to estimate these values.

Conclusion

The thermal environment is an important factor for the quality of the indoor environment and has a large impact on the energy consumption in a building.

The knowledge about the thermal environment is much more advanced than the knowledge on indoor air pollutants.

The effect of the thermal parameters on the occupants can often be predicted.

The thermal parameters can be measured by commercially available instruments.

National and international standards for achieving a comfortable thermal environment do not differ significantly. It is highly recommended in the design and operation of building and systems to use the established standards reported in this article. ■

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