2.2 It is intended that all of the criteria in this standard be applied together since comfort in the indoor environment is complex and responds to the interaction of all of the factors that are addressed.

2.3 This standard specifies thermal environmental conditions acceptable for healthy adults at atmospheric pressure equivalent to altitudes up to 3000 m (10,000 ft) in indoor spaces designed for human occupancy for periods not less than 15 minutes.

2.4 This standard does not address such nonthermal environmental factors as air quality, acoustics, and illumination or other physical, chemical, or biological space contaminants that may affect comfort or health.

3. DEFINITIONS

adaptive model: a model that relates indoor design temperatures or acceptable temperature ranges to outdoor meteorological or climatological parameters.

air speed: the rate of air movement at a point, without regard to direction.

clo: a unit used to express the thermal insulation provided by garments and clothing ensembles, where 1 clo = 0.155 m^2·°C/W (0.88 ft^2·h·°F/Btu).

comfort, thermal: that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation.

draft: the unwanted local cooling of the body caused by air movement.

environment, thermal: the characteristics of the environment that affect a person's heat loss.

environment, acceptable thermal: an environment that a substantial majority of the occupants would find thermally acceptable.

garment: a single piece of clothing.

humidity ratio: the ratio of the mass of water vapor to the mass of dry air in a given volume.

humidity, relative (RH): the ratio of the partial pressure (or density) of the water vapor in the air to the saturation pressure (or density) of water vapor at the same temperature and the same total pressure.

insulation, clothing/ensemble (I_{cl}): the resistance to sensible heat transfer provided by a clothing ensemble. Expressed in clo units. ***Note:*** The definition of clothing insulation relates to heat transfer from the whole body and, thus, also includes the uncovered parts of the body, such as head and hands.

insulation, garment (I_{clu}): the increased resistance to sensible heat transfer obtained from adding an individual garment over the nude body. Expressed in clo units.

met: a unit used to describe the energy generated inside the body due to metabolic activity, defined as 58.2 W/m^2 (18.4 Btu/h·ft^2), which is equal to the energy produced per unit surface area of an average person seated at rest. The surface area of an average person is 1.8 m^2 (19 ft^2).

metabolic rate (M): the rate of transformation of chemical energy into heat and mechanical work by metabolic activities within an organism, usually expressed in terms of unit area of the total body surface. In this standard, metabolic rate is expressed in met units.

naturally conditioned spaces, occupant controlled: those spaces where the thermal conditions of the space are regulated primarily by the opening and closing of windows by the occupants.

neutrality, thermal: the indoor thermal index value corresponding with a mean vote of neutral on the thermal sensation scale.

percent dissatisfied (PD): percentage of people predicted to be dissatisfied due to local discomfort.

predicted mean vote (PMV): an index that predicts the mean value of the votes of a large group of persons on the seven-point thermal sensation scale.

predicted percentage of dissatisfied (PPD): an index that establishes a quantitative prediction of the percentage of thermally dissatisfied people determined from PMV.

radiant temperature asymmetry: the difference between the plane radiant temperature of the two opposite sides of a small plane element.

response time (90%): the time for a measuring sensor to reach 90% of the final value after a step change. For a measuring system that includes only one exponential time-constant function, the 90% response time equals 2.3 times the time constant.

sensation, thermal: a conscious feeling commonly graded using the categories *cold*, *cool*, *slightly cool*, *neutral*, *slightly warm*, *warm*, and *hot*; it requires subjective evaluation.

step change: an incremental change in a variable, either by design or as the result of an interval between measurement; typically, an incremental change in a control setpoint.

temperature, air (t_a): the temperature of the air surrounding the occupant.

temperature, dew point (t_{dp}): the temperature at which moist air becomes saturated (100% relative humidity) with water vapor ($p_{sdp} = p_a$) when cooled at constant pressure.

temperature, mean monthly outdoor air ($t_{a(out)}$): when used as input variable in Figure 5.3 for the adaptive model, this temperature is based on the arithmetic average of the mean daily minimum and mean daily maximum outdoor (dry-bulb) temperatures for the month in question.

temperature, mean radiant (t_r): the uniform surface temperature of an imaginary black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual nonuniform space; see Section 7.2 for information on measurement positions.

temperature, operative (t_o): 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 nonuniform environment; see Section 7.2 for information on body position within the imaginary enclosure.

temperature, plane radiant (t_{pr}): the uniform temperature of an enclosure in which the incident radiant flux on one side of a small plane element is the same as in the existing environment.

temperature, standard effective (SET): the temperature of an imaginary environment at 50% RH, <0.1 m/s air speed, and $t_r = t_a$, in which the total heat loss from the skin of an imaginary occupant with an activity level of 1.0 met and a clothing level of 0.6 clo is the same as that from a person in the actual environment, with actual clothing and activity level.

time constant: the time for a measuring sensor to reach 63% of the final value after a step change.

water vapor pressure (p_a): the pressure that the water vapor would exert if it alone occupied the volume occupied by the humid air at the same temperature.

water vapor pressure, saturated dewpoint (p_{sdp}): the water vapor pressure at the saturation temperature corresponding to the reference pressure and without any liquid phase.

velocity, mean (v_a): an average of the instantaneous air velocity over an interval of time.

zone, occupied: the region normally occupied by people within a space, generally considered to be between the floor and 1.8 m (6 ft) above the floor and more than 1.0 m (3.3 ft) from outside walls/windows or fixed heating, ventilating, or air-conditioning equipment and 0.3 m (1 ft) from internal walls.

4. GENERAL REQUIREMENTS

Use of this standard is specific to the space being considered and the occupants of that space. Any application of this standard must specify the space to which it applies or the locations within that space to which it applies, if not to the entire space. Any application of this standard must identify the occupants (who must have a residency of more than 15 minutes in the space) to which it applies.

The activity and clothing of the occupants must be considered in applying this standard. When there are substantial differences in physical activity and/or clothing for occupants of a space, these differences must be considered.

In some cases it will not be possible to achieve an acceptable thermal environment for all occupants of a space due to individual differences, including activity and/or clothing. If the requirements are not met for some known set of occupants, then these occupants must be identified.

The thermal environmental conditions required for comfort are determined according to Section 5.2 or Section 5.3 of this standard. Any application of this standard must clearly state which of these sections is used. Additionally, all requirements of the applicable section, 5.2 or 5.3, must be met.

5. CONDITIONS THAT PROVIDE THERMAL COMFORT

5.1 Introduction. Thermal comfort is that condition of mind that expresses satisfaction with the thermal environment. Because there are large variations, both physiologically and psychologically, from person to person, it is difficult to satisfy everyone in a space. The environmental conditions required for comfort are not the same for everyone. Extensive laboratory and field data have been collected that provide the necessary statistical data to define conditions that a specified percentage of occupants will find thermally comfortable. Section 5 of this standard is used to determine the thermal environmental conditions in a space that are necessary to achieve acceptance by a specified percentage of occupants of that space.

There are six primary factors that must be addressed when defining conditions for thermal comfort. A number of other, secondary factors affect comfort in some circumstances. The six primary factors are listed below. Complete descriptions of these factors are presented in Section 5.4 and Normative Appendices A and B.

1. Metabolic rate
2. Clothing insulation
3. Air temperature
4. Radiant temperature
5. Air speed
6. Humidity

It is possible for all six of these factors to vary with time. This standard only addresses thermal comfort in a steady state (with some limited specifications for temperature variations with time in Section 5.2.5). ***Note:*** As a result, people entering a space that meets the requirements of this standard may not immediately find the conditions comfortable if they have experienced different environmental conditions just prior to entering the space. The effect of prior exposure or activity may affect comfort perceptions for approximately one hour.

Nonuniformity is addressed in Section 5.2.4. ***Note:*** Factors 2 through 6 may be nonuniform over an occupant's body, and this nonuniformity may be an important consideration in determining thermal comfort.

The vast majority of the available thermal comfort data pertains to sedentary or near sedentary physical activity levels typical of office work. This standard is intended primarily for these conditions. However, it is acceptable to use the standard to determine appropriate environmental conditions for moderately elevated activity. It does not apply to sleeping or bed rest. The body of available data does not contain significant information regarding the comfort requirements of children, the disabled, or the infirm. It is acceptable to apply the information in this standard to these types of occupants if it is applied judiciously to groups of occupants, such as those found in classroom situations.

Section 5.2 contains the methodology that shall be used for most applications. The conditions required for thermal comfort in spaces that are naturally conditioned are not necessarily the same as those conditions required for other indoor spaces. Field experiments have shown that in naturally conditioned spaces, where occupants have control of operable windows, the subjective notion of comfort is different because of different thermal experiences, availability of control, and resulting shifts in occupant expectations. Section 5.3 specifies criteria required for a space to be considered naturally conditioned. The methods of Section 5.3 may, as an option, be applied to spaces that meet these criteria. The methods of Section 5.3 may not be applied to other spaces.

Section 5.4 describes in some detail variables that must be clearly understood in order to use the methods of Section 5 effectively.

5.2 Method for Determining Acceptable Thermal Conditions in Occupied Spaces. When Section 5.2 is used to determine the requirements for thermal comfort, the requirements of all subsections—5.2.1, 5.2.2, 5.2.3, 5.2.4, and 5.2.5—must be met. This standard recommends a specific percentage of occupants that constitutes acceptability and values of the thermal environment associated with this percentage.

5.2.1 Operative Temperature. For given values of humidity, air speed, metabolic rate, and clothing insulation, a comfort zone may be determined. The comfort zone is defined in terms of a range of operative temperatures that provide acceptable thermal environmental conditions or in terms of the combinations of air temperature and mean radiant temperature that people find thermally acceptable.

This section describes methods that are acceptable for use in determining temperature limits for the comfort zone. Section 5.2.1.1 uses a simplified Graphic Method for determining the comfort zone that is acceptable for use for many typical applications. Section 5.2.1.2 uses a computer program based on a heat balance model to determine the comfort zone for a wider range of applications. For a given set of conditions, the results from the two methods are consistent, and either method is acceptable for use as long as the criteria outlined in the respective section are met.

See Informative Appendix C and the 2009 *ASHRAE Handbook—Fundamentals*,[3] Chapter 9, for procedures to calculate operative temperature. It is permissible to use dry-bulb temperature as a proxy for operative temperature under certain conditions described in Appendix C.

5.2.1.1 Graphic Comfort Zone Method for Typical Indoor Environments. It is permissible to apply the method in this section to spaces where the occupants have activity levels that result in metabolic rates between 1.0 and 1.3 met and where clothing is worn that provides between 0.5 and 1.0 clo of thermal insulation. See Normative Appendix A for estimation of metabolic rates and Normative Appendix B for estimation of clothing insulation. Most office spaces fall within these limitations.

The range of operative temperatures presented in Figure 5.2.1.1 are for 80% occupant acceptability. This is based on a 10% dissatisfaction criterion for general (whole body) thermal comfort based on the PMV-PPD index, plus an additional 10% dissatisfaction that may occur on average from local (partial body) thermal discomfort. Normative Appendix D provides a list of inputs and outputs used in the PMV/PPD computer program to generate these graphs.

Figure 5.2.1.1 specifies the comfort zone for environments that meet the above criteria and where the air speeds are not greater than 0.20 m/s (40 ft/min). Two zones are shown—one for 0.5 clo of clothing insulation and one for 1.0 clo of insulation. These insulation levels are typical of clothing worn when the outdoor environment is warm and cool, respectively. It is permissible to determine the operative temperature range allowed for intermediate values of clothing insulation by linear interpolation between the limits for 0.5 and 1.0 clo, using the following relationships:

$$T_{min,\ Icl} = [(I_{cl} - 0.5\ \text{clo})\ T_{min,\ 1.0\ clo} + (1.0\ \text{clo} - I_{cl})\ T_{min,\ 0.5clo}] / 0.5\ \text{clo}$$

$$T_{max,\ Icl} = [(I_{cl} - 0.5\ \text{clo})\ T_{max,\ 1.0\ clo} + (1.0\ \text{clo} - I_{cl})\ T_{max,\ 0.5clo}] / 0.5\ \text{clo}$$

where

$T_{max,\ Icl}$ = upper operative temperature limit for clothing insulation I_{cl},

$T_{min,\ Icl}$ = lower operative temperature limit for clothing insulation I_{cl}, and

I_{cl} = thermal insulation of the clothing in question, clo.

It is acceptable to use elevated air speeds to increase the upper operative temperature limit for the comfort zone in certain circumstances. Section 5.2.3 describes these adjustments and specifies the criteria required for such adjustments.

5.2.1.2 Computer Model Method for General Indoor Application. It is permissible to apply the method in this section to spaces where the occupants have activity levels that result in average metabolic rates between 1.0 and 2.0 met and where clothing is worn that provides 1.5 clo or less of thermal insulation. See Normative Appendix A for estimation of metabolic rates and Normative Appendix B for estimation of clothing insulation.

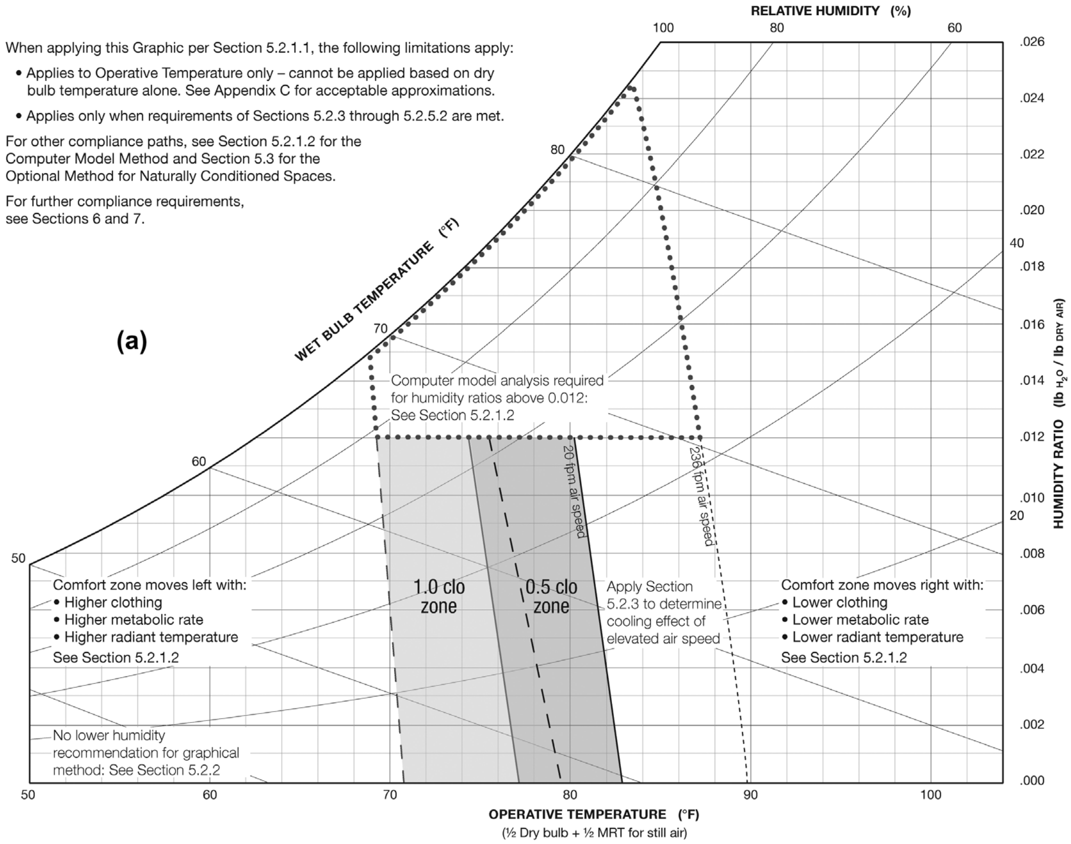
The ASHRAE thermal sensation scale, which was developed for use in quantifying people's thermal sensation, is defined as follows:

+3 hot
+2 warm
+1 slightly warm
0 neutral
–1 slightly cool
–2 cool
–3 cold

The predicted mean vote (PMV) model uses heat balance principles to relate the six key factors for thermal comfort listed in Section 5.1 to the average response of people on the above scale. The PPD (predicted percentage of dissatisfied) index is related to the PMV as defined in Figure 5.2.1.2. It is based on the assumption that people voting +2, +3, –2, or –3 on the thermal sensation scale are dissatisfied and on the simplification that PPD is symmetric around a neutral PMV.

Table 5.2.1.2 defines the recommended PPD and PMV range for typical applications. This is the basis for the Graphical Method in Section 5.2.1.1.

The comfort zone is defined by the combinations of the six key factors for thermal comfort for which the PMV is within the recommended limits specified in Table 5.2.1.2. The PMV model is calculated with the air temperature and mean



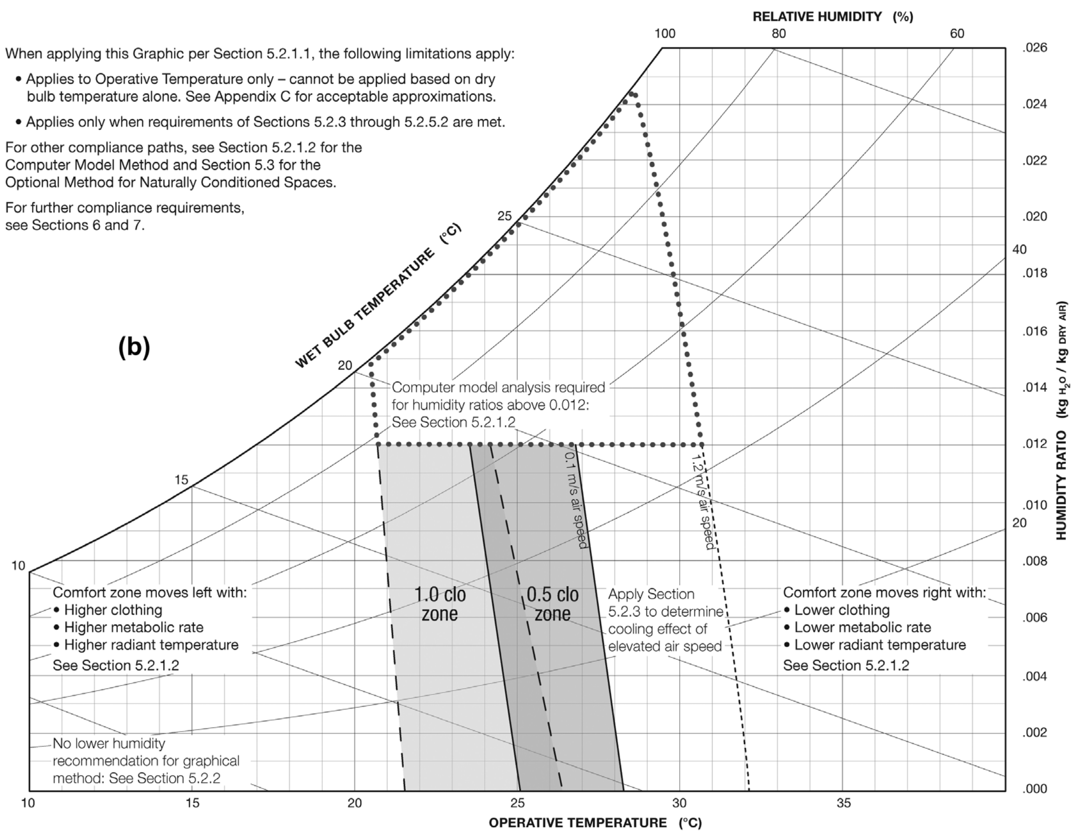


Figure 5.2.1.1 Graphic Comfort Zone Method: Acceptable range of operative temperature and humidity for spaces that meet the criteria specified in Section 5.2.1.1 (1.1 met; 0.5 and 1.0 clo)—(a) I-P and (b) SI.

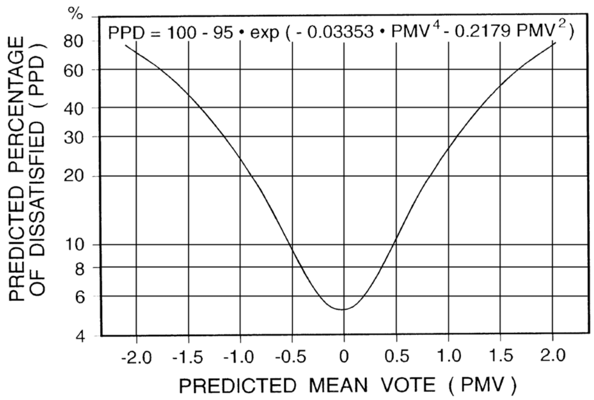


Figure 5.2.1.2 Predicted percentage dissatisfied (PPD) as a function of predicted mean vote (PMV).

TABLE 5.2.1.2
Acceptable Thermal Environment for General Comfort

PPD	PMV Range
<10	–0.5 < PMV < +0.5

radiant temperature in question along with the applicable metabolic rate, clothing insulation, air speed, and humidity. If the resulting PMV value generated by the model is within the recommended range, the conditions are within the comfort zone.

Use of the PMV model in this standard is limited to air speeds below 0.20 m/s (40 fpm). It is acceptable to use air speeds greater than this to increase the upper temperature limits of the comfort zone in certain circumstances. Section 5.2.3 describes the method and criteria required for such adjustments.

There are several computer codes available that predict PMV-PPD. The computer code in Normative Appendix D is to be used with this standard.[4] If any other version is used, it is the user's responsibility to verify and document that the version used yields the same results as the code in Appendix D for the conditions for which it is applied.

5.2.2 Humidity Limits. When the Graphic Comfort Zone Method in Section 5.2.1.1 is used, systems shall be able to maintain a humidity ratio at or below 0.012, which corresponds to a water vapor pressure of 1.910 kPa (0.277 psi) at standard pressure or a dew-point temperature of 16.8°C (62.2°F).

There are no established lower humidity limits for thermal comfort; consequently, this standard does not specify a minimum humidity level. ***Note:*** Nonthermal comfort factors, such as skin drying, irritation of mucus membranes, dryness of the eyes, and static electricity generation, may place limits on the acceptability of very low humidity environments.

5.2.3 Elevated Air Speed. This standard allows elevated air speed to be used to increase the maximum operative temperature for acceptability under certain conditions. Limits are imposed depending on environmental and personal factors and whether the occupants have local control of air speed.

5.2.3.1 Graphical Elevated Air Speed Method. The amount that the temperature may be increased is shown in Figure 5.2.3.1. The combinations of air speed and temperature defined by the lines in this figure result in equal levels of heat loss from the skin. The reference point for these curves is the upper air-speed limit of the PMV-defined comfort zone, 0.20 m/s (40 fpm), as described in Section 5.2.1.2. The figure applies to a lightly clothed person (with clothing insulation between 0.5 clo and 0.7 clo) who is engaged in near sedentary physical activity (with metabolic rates between 1.0 met and 1.3 met). The curves are generated by the SET thermophysiological model described in Section 5.2.3.2.

The indicated increase in temperature pertains to both the mean radiant temperature and the air temperature. That is, both temperatures increase by the same amount with respect to the starting point. When the mean radiant temperature is low and the air temperature is high, elevated air speed is less effective at increasing heat loss. Conversely, elevated air speed is more effective at increasing heat loss when the mean radiant temperature is high and the air temperature is low. Thus, the curve in Figure 5.2.3.1 that corresponds to the relative difference between air temperature and mean radiant temperature must be used. It is acceptable to interpolate between curves for intermediate differences.

Under the Graphical Elevated Air Speed Method, the required air speed for light, primarily sedentary activities may not be higher than 0.8 m/s (160 ft/min)—although higher air speeds are acceptable when using the SET Method in Section 5.2.3.2. Any benefits gained by increasing air speed depend on clothing and activity. Due to increases in skin wettedness, the effect of increased air speed is greater with elevated activity than with sedentary activity. Due to increased amounts of exposed skin, the effect of increased air speed is greater with lighter clothing. Thus, Figure 5.2.3.1 is conservative for activity levels above 1.3 met and/or for clothing insulation less than 0.5 clo and may be applied in these circumstances.

Due to increased body coverage, the effect of increased air speed is less with higher levels of clothing insulation. Thus, Figure 5.2.3.1 will underestimate the required air speed for clothing insulation greater than 0.7 clo and shall not be applied in these circumstances.

5.2.3.2 SET Method. Figure 5.2.3.2 represents a particular case of equal skin heat loss contours created by the Standard Effective Temperature (SET) model. The model, however, is not restricted to this particular case and it is acceptable to use it to determine the comfort zone for a broad range of applications.

The SET model uses a thermophysiological simulation of the human body to reduce any combination of real environmental and personal variables into the temperature of an imaginary standard environment in which the occupant's skin heat loss is equal to that of the person in the actual environment. This model enables air velocity effects on thermal comfort to be related across a wide range of air temperatures, radiant temperatures, and humidity ratios.

Figure 5.2.3.2 uses SET to extend the Figure 5.2.1.1 comfort zones across a range of air speeds for the example humidity ratio of 0.010. Figure 5.2.1.1 is based on PMV calculated for 0.1 m/s air speed (20 fpm). The extension in