Moving air for comfort

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Abstract:
Moving air has long been used to provide comfort in warm environments. Provision for indoor air movement was one of the wellsprings of traditional architectural design in warm regions, affecting building form, components, and equipment over millennia. However, this design option has faded from practice since the advent of air-conditioning, in which the focus has been on controlling temperature and humidity. Despite the fact that air movement can be an energy efficient alternative to air cooling, it became viewed more as a possible source of undesirable draft, and comfort standards came to set room airspeed limits very low, even for temperatures as warm as 26ºC (79ºF). An exception was granted if the airspeed source was under personal individual control, such as a window in a private office, or a desk fan, but only above 26 ºC (79ºF).

Moving Air For Comfort

By **Edward Arens, Ph.D.,** Member ASHRAE; **Stephen Turner, P.E.,** Member ASHRAE; **Hui Zhang, Ph.D.;** And **Gwelen Paliaga,** Associate Member ASHRAE

Air movement can be an energy-efficient alternative to air cooling. However, in recent years it has been regarded more as a possible source of undesirable draft. Thermal comfort standards set room air speed limits low, even for temperatures as warm as 26°C (79°F). An exception was granted if the air speed source was under individual control, such as a window in a private office, or a desk fan, but only above 26°C (79°F).

Recent studies of occupied buildings provide consistent evidence that large percentages of occupants prefer more air movement than what they currently have, and small percentages prefer less. This is true in all conditions that occupants perceived as warm, thermally neutral, and even slightly cool. In terms of temperature, above 22.5°C (72.5°F) there is a small risk of draft and a strong preference for more air movement. This article describes these field study findings.

Responding to such findings, ANSI/ASHRAE Standard 55-2004, *Thermal Environmental Conditions for Human Occupancy,* is being updated with new provisions[1] that allow elevated air speed to broadly offset the need to cool the air in warm conditions,

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Thermal Sensation	Air Speed Range (m/s)	Percentage of Occupants Who Prefer			(N)	T_{op} (Standard Deviation) (°C)
		Less Air	No Change	More Air		
Cold (< −2.5)	0 to 0.2	33.33	46.85	19.82	111	22.66 (0.91)
	≥0.2	50.00	42.30	7.69	26	23.50 (1.45)
Cool (−2.5 to −1.5)	0 to 0.2	13.07	60.47	26.47	597	22.92 (1.08)
	≥0.2	11.55	72.51	15.94	251	24.28 (2.0)
Slightly Cool (−1.5 to −0.5)	0 to 0.2	10.75	53.08	36.17	1153	23.05 (1.23)
	≥0.2	11.35	62.23	26.42	458	24.59 (2.16)
Neutral (±0.5)	0 to 0.2	2.62	51.46	45.92	1407	23.30 (1.23)
	≥0.2	4.62	57.26	38.12	585	24.86 (2.03)
Slightly Warm (0.5 to 1.5)	0 to 0.2	2.31	27.73	69.95	822	23.65 (1.41)
	≥0.2	3.36	30.87	65.77	298	25.46 (1.85)
Warm (1.5 to 2.5)	0 to 0.2	4.24	18.37	77.39	283	23.75 (1.58)
	≥0.2	4.96	28.93	66.12	121	25.79 (2.08)
Hot (>2.5)	0 to 0.2	4.55	0	95.45	22	24.96 (1.28)
	≥0.2	7.14	14.29	78.57	14	26.23 (2.04)

***Table 1:** Air movement preferences by thermal sensation and for two ranges of air speed, n = 6,148.*

replacing provisions that originated primarily from climate chamber studies.

Building Occupants' Air Movement Preferences

Under ASHRAE sponsorship, field studies of occupant comfort in buildings worldwide have been assembled in a database.[2] Eleven studies in the database (comprising 53 buildings and 6,148 sets of data) included direct questions about the occupants' air movement preference. These studies (from Montreal and Honolulu, Sydney, Kalgoorlie, and Townsville in Australia) are used for the following analyses. The six Honolulu buildings are schools, and the others are office buildings. Except for two naturally ventilated schools and one mixed-mode office in Sydney, all the buildings are fully air conditioned.

Table 1 lists occupants' stated air movement preference by the thermal sensation they reported at the same time. They are also arranged into two speed ranges: V<0.2 m/s (39 fpm; 0.44 mph) representing conditions below the draft limit in Standard 55-2004, and V ≥ 0.2 m/s (39 fpm), representing potentially drafty conditions (for the latter, the mean air speed was 0.32 m/s [63 fpm]). It is obvious that when people felt "neutral" or "warm" ("slightly warm," "warm," or "hot"), a small percentage of them (7% or less) wanted less air speed. This is true even for the higher speed range (V ≥ 0.2 m/s [39 fpm]) in which at least 93% of people accepted the higher air speed, or wanted even more. For both speed ranges, it is only under "cold" sensation that more people "want less" air speed than "want more." Even under "cool" and "slightly cool" sensations, substantially more people preferred more air speed than less.

The associated operative temperatures are also shown.* Under the same thermal sensation category, the operative temperature for the higher air speed is between 1.5 K to 2 K (3°F to 4°F) higher than the temperature for lower speed. This difference illustrates the trade-off between air speed and temperature in producing equivalent levels of comfort.

Air Movement for People Feeling Neutral to Slightly Warm

The following figures summarize air movement preferences in the thermal sensation range of –0.7 to 1.5. A sensation of –0.7 is a little cooler than the usual definition of neutral, but it matches the cool end of the Category III range (for acceptable existing buildings) in the European standard CEN 15251.[3] The figures exclude sensations above 1.5 because, although *Table 1* shows that air movement is clearly welcome when sensation is above 1.5, this sensation is too warm for normal office environments and ideally would not occur often. The –0.7 to 1.5 range should give a conservative estimate of air movement preference for neutral and slightly warm people.

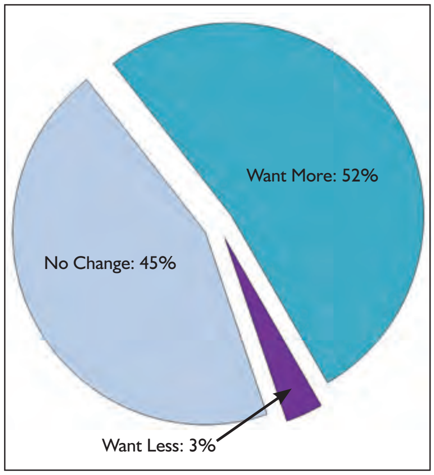
Figure 1 shows that under the sensation range (–0.7 to 1.5), far more people (52%) wanted more air movement than less air movement (3%). The percentage wanting more was greater than the percentage preferring "no change."

Figure 2 shows that when their air speed was at the higher range (≥0.2 m/s [39 fpm], *Figure 2*), a much higher percentage of people (47%) wanted more, or accepted the higher air speed (no change = 49%), than wanted less (4%).

Figure 3 shows that in the surveys, occupants also were asked whether the air movement was "acceptable." Twenty-nine percent of all occupants said it was not. Looking at these

* The operative temperature is a measure combining the air temperature (affecting the body by convection) and the surface temperatures of the surroundings (affecting the body by radiant exchange). It 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 nonuniform environment.

respondent's preference votes, one can see that the unacceptable air movement is due to too little air movement, not too much. 84% wanted more, 7% wanted less (*Figure 3*).



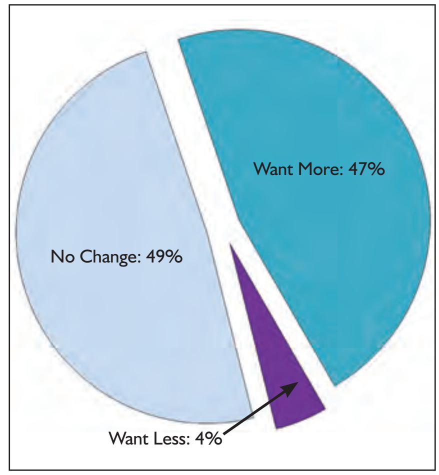


Figure 1 (left): Air movement preference (sensation –0.7 to 1.5), all air speeds (n = 3,230).
Figure 2 (right): Air movement preference (sensation –0.7 to 1.5), air speed ≥ 0.2 m/s (n = 924).

When people felt the air speed was not acceptable, *and* when they were experiencing the higher range (≥0.2 m/s [39 fpm]), did they feel the speed was too much and, therefore, not acceptable? *Figure 4* shows that for the higher speed range, when people said that they felt the speed was not acceptable, the unacceptability was still due to insufficient air movement. The percentage wanting more (73%) is still far more than the percentage wanting less (17%). The difference is now smaller, but it is still clear that the majority found the speed unacceptable because there wasn't enough, even with the speed in the higher range.

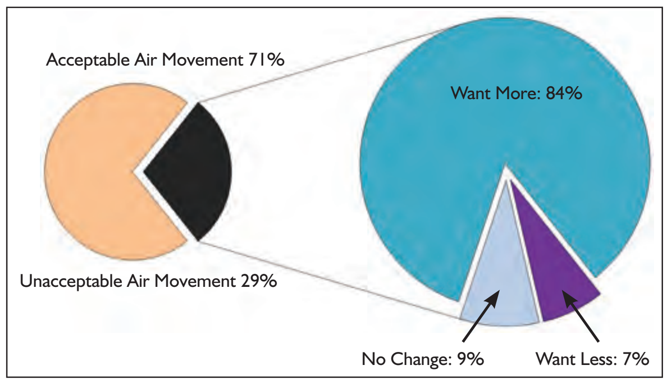


Figure 3: Air movement preference for people (sensation –0.7 to 1.5) who said the air speed was unacceptable. (n = 2,091).

One may also calculate the draft risk percentage (DR) for all the database's occupants based on the equations provided in the previous ASHRAE standard, using air speed, temperature, and turbulence intensity as inputs. Looking at the air movement preference for those people when their DR exceeded 20% (thermal sensation again within –0.7 and 1.5, n=172), the percentage wanting less air speed was 8%; 59% wanted no change, and 33% wanted more. The result is that 92% of a population predicted to be at an unacceptable risk of draft accepted their air speed or actually wanted it higher.

Summarizing these ASHRAE field study results, it is clear that for sensations –0.7 to 1.5, air movement should be encouraged. The air movement should not be made so great that it leaves people feeling cold, but a certain amount of it does answer a basic need found in the surveys, and can offset an increase in temperature in the space. Similar results have been found for a building in which occupants have personal or group control over window ventilation.[4]

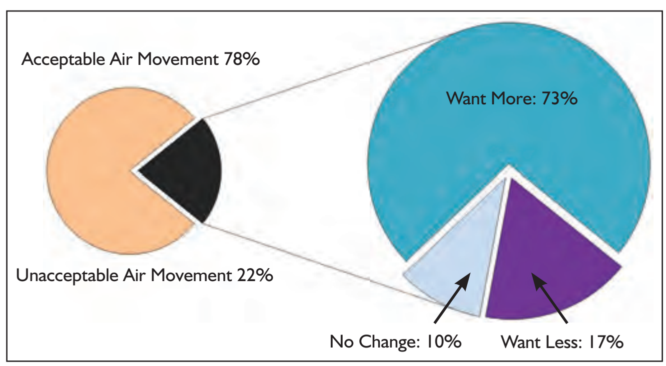


Figure 4: Air movement preference for people (sensation –0.7 to 1.5) who said the air speed was unacceptable, V≥ 0.2 m/s (n = 324).

Provisions for Elevated Air Speed in Standard 55

Standard 55-2004 will soon provide a two-step procedure for setting a comfort zone for temperature, radiation, humidity, and air movement. Both steps of this process can be carried out using the ASHRAE Thermal Comfort Tool,[5] or can be interpolated from figures in the standard. The first step, unchanged from the previous standard, combines air temperature and radiant temperature in the index "operative temperature" as defined earlier, which is then combined with humidity to produce comfort zones for still-air conditions displayed on a psychrometric chart. This step uses the predicted mean vote (PMV) human heat balance model, combining these environmental variables with the occupant's clothing level (expressed in the insulation unit, clo) and activity level (expressed in the metabolic rate unit, met).[6,7]

The second step evaluates elevated air speeds. It uses a different model that better accounts for convective cooling of the body. The standard effective temperature (SET) thermo-physiological model is based on long-standing ASHRAE research and practice.[6,8] Equal heat balance and skin-wettedness for different air speeds can be plotted in

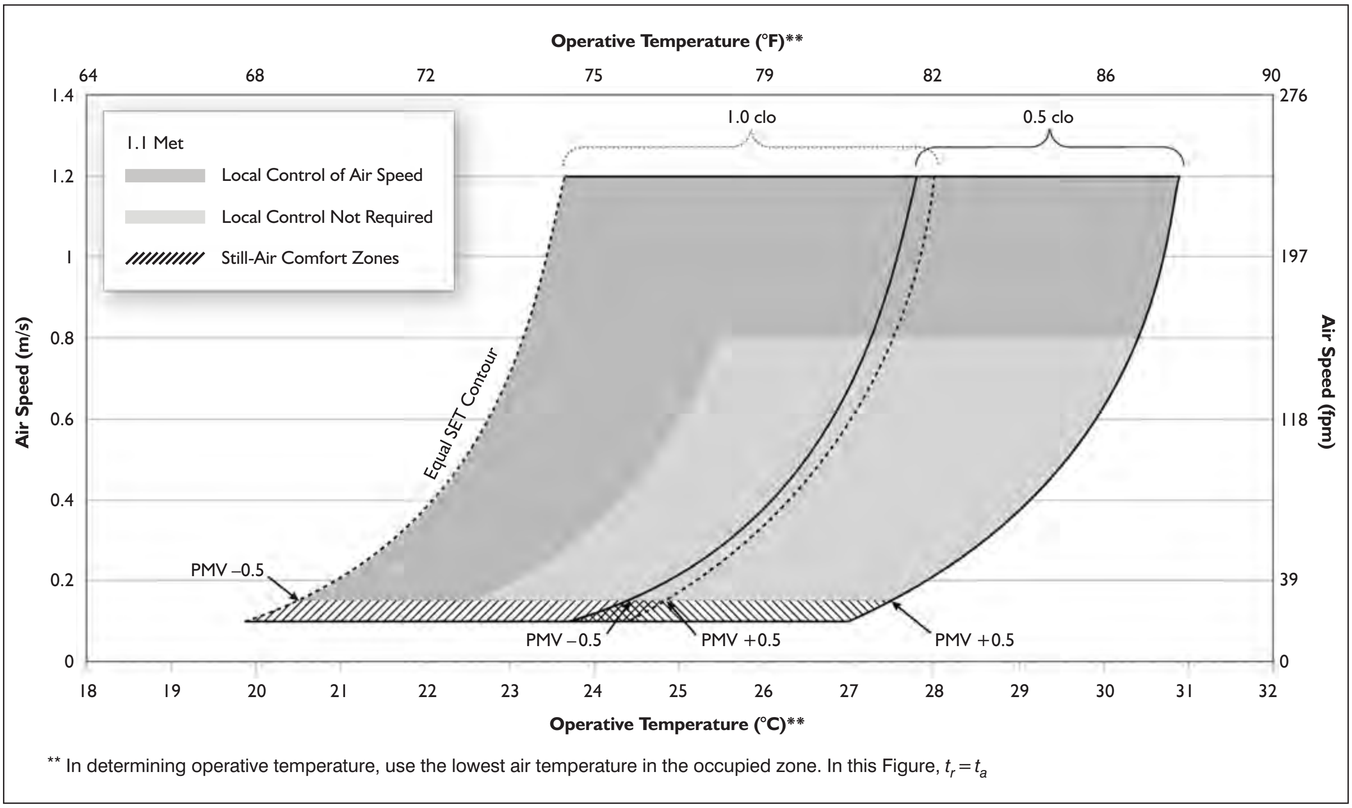


Figure 5: Elevated air speed for warm air temperatures.

terms of SET† contours. If one starts with the underlying PMV comfort zone, these SET contours form the boundaries of an air-movement comfort zone in which air speed is plotted against operative temperature.

These steps are shown in *Figure 5*, taken from the new standard. *Figure 5* shows two example comfort zones, for the clothing insulation levels: 0.5 clo (e.g., summer short-sleeved shirt and slacks) and 1.0 clo (winter heavy business suit), and the sedentary activity level of 1.1 met. These clo and met levels have been traditionally used in the standard's first figure, which plots PMV-based still-air comfort zones on a psychrometric chart. In *Figure 5*, those zones are transposed to the bottom of the y-axis, in the region defined as "still air" (0.1 to 0.15 m/s [20 fpm to 30 fpm]), for 50% relative humidity. The comfort zones each extend from –0.5 PMV (the thermal sensation midway between "neutral" and "slightly cool") and +0.5 (between "neutral" and "slightly warm"). One can see some temperature dependence on air speed within this still-air region, as predicted by the PMV model.

Comfort envelope. Starting with these still-air zones, 0.5 and 1.0 clo comfort envelopes for air speeds above 0.15 m/s (30 fpm) are generated using the SET model. SET contours of equal heat-loss relate a range of air speeds and temperatures to the equivalent PMV value in the still-air zones. These two comfort envelopes can be interpolated to roughly account for other clothing levels, but in practice, envelopes for any clothing, activity, and humidity level would be determined more accurately using the ASHRAE Thermal Comfort Tool.

Limits to air speed. *Figure 5* provides additional limits not based on SET. These are divided into two categories, with and without local control.

With local control. The full equal heat-loss envelope for a given clothing level in *Figure 5* applies when control of local air speed is provided to occupants. For control over their local air speed, control directly accessible to occupants must be provided for every six occupants (or less) or for every 84 m^2 (900 ft^2) (or less). The range of control shall encompass air speeds suitable to maintain comfort for sedentary occupants. The air speed should be adjustable continuously or in maximum steps of 0.25 m/s (50 fpm) as measured at the occupant's location.

Without local control. Within the equal heat-loss envelope, if occupants do not have control over the local air speed in their space, limits apply as shown by the light gray area in *Figure 5*. They apply for light, primarily sedentary office activities. For other types of activities or occupancies, such as retail or warehousing, these limits may differ or not be necessary. There is little quantitative information available for other types of occupancies.

For operative temperatures *above 25.5°C* (77.9°F), the upper limit to air speed is 0.8 m/s (160 fpm).

† **temperature, standard effective (SET):** the temperature of an imaginary environment at 50% RH, <0.1 m/s air speed, and with *mean radiant temperature equal to air temperature*, 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.[1,6,8]

Below 22.5°C (72.5°F), the limit is 0.15 m/s (30 fpm) to avoid cold discomfort due to draft. 0.15 m/s (30 fpm) is the upper limit of the still-air zone, and is coincidentally equal to the air speed self-generated by an office worker at 1.2 met.

Between 22.5°C and 25.5°C (72.5°F and 77.9°F), the allowable speed follows an equal SET curve dividing the light and dark gray areas. This local-control boundary between 22.5°C and 25.5°C (72.5°F and 77.9°F) is not linked to any PMV comfort zone, but is based on temperatures that have been observed in office field studies to cause virtually no risk of draft.[9]

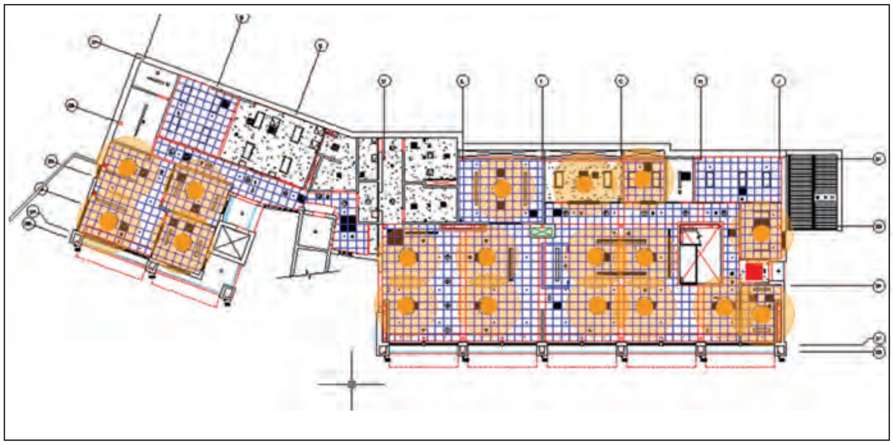


Figure 6: Orinda City Hall plan view. Orange circles are the ceiling fans, and the light orange circles are the areas in which 0.75 m/s (150 ft/min) air velocity is supplied in the occupied zone.

Using a temperature-based local-control boundary provides a substantial practical advantage in environmental control: decentralized air movement sources (such as ceiling fans) can be manufactured or retrofitted with temperature-based speed controllers for automatic control of common spaces.

The 1 clo zone in *Figure 5* represents a higher level of clothing than is typical for situations in which air-movement cooling is used. For more typical summer clothing levels such as 0.5 and 0.6 clo, the limits to air speed and temperature will be determined by the cool-side SET boundary of the comfort zone, not by this occupant-control boundary.

Air speed measurement. Above 22.5°C (72.5°F), the overall heat balance of the body determines comfort. For this, the standard uses the average air speed of the three measurement heights that represent the seated occupied zone—0.1, 0.6, and 1.1 m (4, 24, and 43 in.). Measurements should be taken in the occupants' estimated vicinity. To prevent anyone from attempting to use the standard to justify cold-air dumping from poorly designed HVAC supply air outlets, the coldest temperature in the occupied zone must be used to represent the entire zone. This also renders it improbable that cold air-distribution systems can be used as the source of elevated air movement because they are likely to produce cold air jets, as opposed to using fans, stack effect, or window ventilation as a means to elevate air speed.

Below 22.5°C (72.5°F), the problem is avoiding thermal discomfort on a local, usually unclothed, part of the body. The SET and PMV models do not distinguish between clothed and unclothed portions of the body, so the following conservative approach is adopted: the *maximum* mean air speed of the three measurement heights, and the *lowest* air temperature is used for the SET calculations, thereby over-predicting the whole-body cooling to a level that more closely approximates the cooling of the most affected local part.

There is no longer a requirement to measure turbulence intensity for determining draft risk.

Validation. In lab studies where air speed has been imposed on people, conditions on the cool side of the without-local-control (light gray zone) boundary have been found to be comfortable, even recommended as optimal.[10,11,12] Imposed air movement does not appear to be a problem at these temperatures. This is also supported in the ASHRAE field database described previously. For air speeds above 0.4 m/s (79 fpm) and air temperatures between 22.5 and 25.5°C (73°F and 78°F), 32% wanted more air movement, 59% wanted no change, and only 9% wanted less.

On the warm side of 25.5°C (77.9°F), ceiling fan studies (with no occupant control) have found 1 m/s (197 fpm, 2.2 mph) acceptable to 77% of subjects[13] and above (95%,[14] 80% to 100%[15]). A frontal desktop breeze of 0.8 m/s (157 fpm) air speed produced an acceptability level of 80%.[12] Subjects in preferred air speed studies[16,17,18] often chose air speeds well above 1 m/s (197 fpm). Fountain[19] summarized many of these studies, from which one can see that the SET-based curves in Standard 55 represent the laboratory results well.

Air speed requirements for industrial occupancies. Standard 55 has also added an informative appendix (Addendum *f*, forthcoming) to address more strenuous indoor activities than office work, such as industrial work. For such work in hot environments, sweating may be acceptable to the occupants. Elevated air speeds provide high rates of cooling by sweat evaporation. Using SET as described above, hot conditions with high air speeds may be equated to their temperature equivalents at lower air speeds. There is no specified limit to air speed in this range.

Impact in Practice

The new provisions allow designers to use fans, stack effect, or window ventilation to offset mechanical cooling, or in some climates to supplant it entirely. The following two examples are of offices using ceiling fans.

City Hall, Orinda, Calif., (*Figure 6*). Ceiling fans are used to enable a mixed-mode system that combines passive cooling through operable windows and a stack vent with indirect-direct evaporative cooling, instead of compressor-based cooling. The building is 1300 m^2 (14,000 ft^2) with 40 full-time occupants along with a community meeting room and conference rooms.

Figure 7: Orinda City Hall with ceiling fans. The left photo shows open space, and the right photo shows cubicles and hallway.

The building management system controls clerestory window opening based on indoor-outdoor temperature differential and illuminates signs that instruct occupants to open/close their windows. A total of 36 fans with 1321 mm (52 in.) blade diameter are provided in office, conference, and circulation spaces. *Figure 7* shows two spaces, one with four fans arrayed in a 100 m^2 (1,076 ft^2) open space (left image), another with 10 fans arrayed for 273 m^2 (2,938 ft^2) of cubicles and hallways (right image). Fans are controlled individually or in groups of two or three from wall-mounted switches and have three speed levels. The fans use approximately 30 to 70 W per fan. In the design, they were assumed to allow the air temperature

Advertisement formerly in this space.

to increase 2.6 K (4.7°F) at 0.75 m/s (148 fpm). Simulations of indoor temperature and comfort predict that the fans are critical to maintain comfort for 100 to 200 hours per year when the evaporative cooler has limited capacity and space temperatures rise.

The building has been occupied for a year and a half, and the users are happy with the fans.

Loisos+Ubbelohde Office, Alameda, Calif., (*Figure 8*). This 223 m^2 (2,400 ft^2) design office is cooled only by a system of operable windows, automated shading, and ceiling and desk fans. The occupancy is 18, for an occupant density of 12 m^2 (133 ft^2) per person. Ceiling fans are individually controllable from one control panel in the entry area. They are controlled in groups of one or two. Fans have high-efficiency twisted airfoil blades designed by Florida Solar Energy Center/AeroVironment, generating approximately 40% higher cfm/W than paddle-blade fans, drawing between 9 W to 50 W from low to full speed (0.4 to 1.6 m/s [79 fpm to 315 fpm]).[20]

The system has been in place through one summer in its present configuration, with owner and occupants expressing satisfaction. The owner feels that the fan density shown could be increased for more even coverage. He suggests that air motion sectional diagrams, similar to photometric curves, be published to facilitate the design layout of fans in accordance with work stations.

Conclusions

Forthcoming addenda to Standard 55-2004 include new provisions for using air movement to offset warm air temperatures. They are based on field studies that consistently demonstrate that in neutral and warm environments, people want more air speed. The SET model is used to generate comfort zones in which elevated air speed offsets warm air temperature. New criteria for group local control are specified, making it possible to use air movement in open-plan offices as shown in the two examples. The new air movement provisions should assist the design of both passive and mechanical systems such as natural ventilation, thermal mass cooling, evaporative cooling, and mixed-mode HVAC.

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Figure 8: Design office in Alameda, Calif. Left photo shows ceiling fans in open office space, and the right photo shows ceiling fans.

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