5929

ASHRAE Research

Using laboratory-based models to predict comfort in office buildings

Current practices for maintaining comfortable thermal environments should be re-examined

By Gail S. Brager, Ph.D.
Member ASHRAE

The office environment presents numerous challenges for the engineer trying to maintain acceptable indoor thermal conditions. Trends in open-plan office design combined with centrally controlled HVAC systems may hinder the ability to serve the wide-ranging individual needs of the workers.

Rather than catering to each individual, HVAC systems are typically designed to provide thermal conditions that are relatively uniform over space and constant over time. The goal is to satisfy the majority of occupants by following standards such as ASHRAE *Standard 55-1981*[1] and ISO *Standard 7730-1984*.[2]

These standards are based on extensive research in laboratory facilities and are subjected to years of rigorous review. While these experiments have provided a great deal of vital information, it is not known to what extent these results can be applied to real work settings.

One major shortcoming of laboratory experiments is the artificial conditions under which the data are collected. Laboratory subjects are not in familiar surroundings nor engaged in their usual work activities during testing. As a result, they may perceive and accept the thermal environment atypically, influencing the study's results.

In contrast, a field study avoids these potential problems by investigating people's thermal responses in their normal working conditions. As such, it is important that laboratory data be supplemented by and compared to field data to fully understand the reliability of its application to the workplace.

In ASHRAE-sponsored research project RP-462, procedures were developed for assessing thermal environments and occupant comfort in existing office buildings. A field study using these procedures was then conducted in 10 San Francisco-area office buildings during the winter and summer seasons of 1987.

This article compares the data collected in these office buildings to comfort predictions based on two models cited in the literature.[3,4] Also discussed is the extent to which theoretical and laboratory-based equations accurately predict workers' responses in real office buildings.

Methodology

A total of 2,342 visits were made to 304 workers in the 10 buildings during the two seasons. At each visit, the worker completed a thermal assessment survey including 53 data fields addressing thermal sensation, thermal preference, comfort, mood, clothing and activity.

We used a continuous form of the ASHRAE Thermal Sensation Scale showing both numbers and their associated adjectives. Besides the commonly used Thermal Sensation Scale, the survey also collected direct comfort judgments using a six-point General Comfort Scale (1,2,3 = very, moderately, and slightly uncomfortable; and 4,5,6 = slightly, moderately, and very comfortable, respectively).[5]

After completing the survey, the worker stepped away from the desk and a mobile instrumentation cart was placed directly at the workstation, measuring air temperature, dewpoint temperature, globe temperature, air velocity, radiant temperature asymmetry, and illuminance. Mean radiant temperature was calculated for each visit based on these measurements. (Detailed descriptions of the data collection methods, surveys and instrumentation are presented by Schiller[5,6] and Benton.[7])

The thermal sensation predictions used are based on two models cited in the literature. These models are formulated to predict the average response of a large group of people, rather than a single response from an individual. Schiller[8] provides greater details on how the models were used for these analyses.

Continued on page 46

About the author

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Laboratory-based models

Continued from page 44

The most commonly used predictive indices of thermal sensation and acceptability are Predicted Mean Vote (PMV) and Predicted Percent Dissatisfied (PPD), developed by Fanger.[3]

PMV is an index that predicts the mean vote (thermal sensation) of a large group of people exposed to the same thermal conditions. The vote is based on the seven-point ASHRAE Thermal Sensation Scale.

PPD is the predicted percentage of people expressing dissatisfaction with a given thermal environment, based on the assumption that thermal sensation votes of "warm" or "hot" (vote = 2, 3) or "cool" or "cold" (vote = −2, −3) imply dissatisfaction.

A modified version of PMV was recently cited by Gagge,[4] and is called PMV_g in this article. Although PMV_g uses the same algebraic form as Fanger's original PMV, the major difference is that dry heat transfer from the skin is calculated using skin temperature (T_{sk}) as calculated from Gagge's two-node model, instead of Fanger's empirical equation for T_{sk} corresponding to neutral thermal sensation at the given activity level. PPD_g is then calculated as a function of PMV_g using the same equation developed by Fanger.[3]

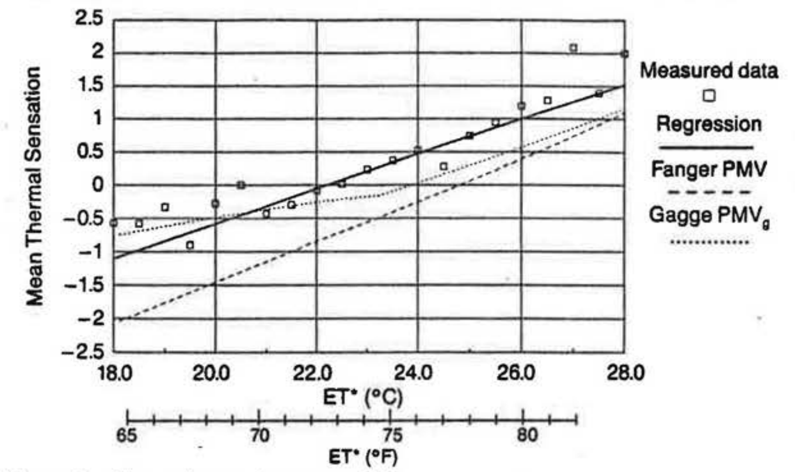

Figure 1. Thermal sensation versus ET*

Results

Predicted comfort indices are often used to determine how changes in the thermal environment will affect the average thermal sensation felt by a large group of people. Our analysis takes this further to determine how the measured changes in workers' responses compared with the predicted trends.

Figure 1 shows the regression line from the measured data, as well as the results of the PMV and PMV_g calculations. The best agreement between our measured data and the prediction index PMV_g was found between 66.2° and 71.6°F (19° and 22°C), the region near and slightly below the measured neutral temperatures.

As conditions moved away from optimum, PMV_g predictions were more conservative and office workers were voting at more extremes than predicted, particularly in the warm regime. Fanger's PMV consistently underpredicted thermal sensation by 0.5 to 1.0 units, with the difference being strongest at the cooler temperatures.

Our results suggest that, for buildings where occupants' clothing and activity levels are similar to those studied here, and for thermal conditions that fall within the range found in these office buildings, workers may typically feel warmer than predicted by the Fanger and Gagge comfort models.

The comfort zones specified in the ASHRAE and ISO standards center around the neutral temperature, T_n. Quantitatively, T_n is the temperature at which the mean thermal sensation of a large group of people is neutral (mean TS = 0).

For a given range of thermal conditions, can one expect that a group will experience a mean sensation of neutral at the same temperature in both a laboratory and real-world setting? If the real-world setting is familiar, such as an office environment, does acclimatization influence workers' responses?

Both PMV and PMV_g overpredicted neutral temperatures. PMV predictions were higher than the measured T_n by 4.3°F (2.4°C) in both seasons, while PMV_g predictions were higher by 2.5° to 2.9°F (1.4° to 1.6°C).

Table 1 shows that the measured neutral temperatures were closer to predictions based on the findings of 50 years of field surveys,[9,10] as compared to predictions from both the PMV and PMV_g models. A similar result was found by deDear and Auliciems[11] in examining data from six Australian office buildings.

These results are important because they suggest that the prevailing thermal environments in the buildings might affect workers' expectations and preferences and influence their degree of discomfort as

Continued on page 48

Table 1. Neutral Temperature (Measured and Predicted)

Neutral temperatures, T_n (ET*)	Winter	Summer
Measured	22.0°C 71.6°F	22.6°C 72.7°F
PMV-predicted	24.4°C 75.9°F	25.0°C 77.0°F
PMV_g-predicted	23.6°C 74.5°F	24.0°C 75.2°F
Acclimatization predicted	22.1°C 71.8°F	22.4°C 72.3°F
Measured averages used for predictions		
Air temperature	22.8°C 73.0°F	23.3°C 73.9°F
Mean radiant temperature	23.0°C 73.4°F	23.6°C 74.5°F
Velocity	0.06 m/s 0.20 f/s	0.10 m/s 0.33 f/s
Clothing	0.58 clo	0.52 clo
Activity	1.12 met	1.14 met
Values required to match PMV_g-predicted and measured T_n		
Clothing	0.80 clo	0.72 clo
Activity	1.75 met	1.75 met

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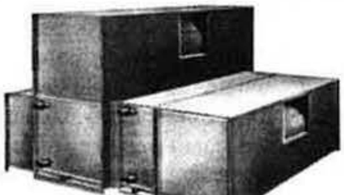

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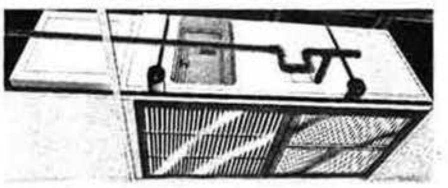

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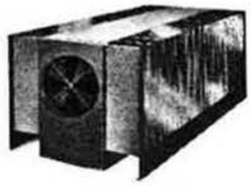

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Laboratory-based models

Continued from page 46

conditions deviate from these preferred conditions.

Workers' preferences for cooler temperatures than predicted could be partially explained if their effective clothing insulation had been underestimated. For example, perhaps the insulating value of a typical office chair could account for part of this discrepancy. Specifically, laboratory subjects sit in string chairs with negligible insulation, while a real office chair could insulate 20% to 25% of the body surface area.

As conditions deviate from the neutral temperature, it is useful to know how the range of thermal responses varies, as well as the mean. Engineers and facility managers endeavor to minimize the number of people likely to register complaints by providing thermal conditions acceptable to the greatest number of people.

Acceptability is often expressed in terms of the percentage of people dissatisfied. How do the minimum rates of dissatisfaction obtained in the laboratory compare with those found in the workplace? And how rapidly does acceptability of the environment deteriorate as conditions move away from optimum?

For the combined winter and summer measured data, *Figure 2* shows the percentage of people dissatisfied as a function of thermal conditions. The *minimum* level of measured dissatisfaction in the office buildings is approximately 12%. This is substantially higher than the optimum of 5% predicted by PPD and PPD_g.

Because our measurements indicated there was negligible radiant asymmetry and, on average, very low air velocities in the office buildings, it is unlikely that draft or radiant effects can account for the difference in measured and predicted acceptability. However, the PPD and PPD_g curves are based on a single clo value corresponding to the average clothing worn.

The group of workers wore a relatively wide range of clothing in comparison to the standard uniforms in the laboratory experiments. This range of conditions might explain the higher minimum rate of dissatisfaction found in office buildings.

Looking at acceptability beyond the optimum, predictions from both models consistently underestimate the measured number of people dissatisfied at temperatures above 74.3°F (23.5°C). Measured data shows that 10% to 50% of the people are dissatisfied *beyond* the amount predicted by either PPD or PPD_g. At temperatures below the measured optimum of 72.5°F (22.5°C), measured thermal acceptability falls between the two predictions made by PPD and PPD_g. Fanger's PPD *overestimates* dissatisfaction by up to approximately 20% dissatisfied, while Gagge's PPD_g *underestimates* it by up to 30% dissatisfied.

Another observation apparent from *Figure 2* concerns the difference between measured and predicted optimum temperature. Measured optimum temperature was approximately 4.1°F (2.3°C) cooler than that determined by Fanger's PPD and 2.5°F (1.4°C) cooler than predicted by PPD_g. These findings are similar to those found for neutral temperature.

Figure 2 also illustrates that the office workers' sensitivity to temperature changes were relatively flat, or at least broadly curved, over a 3° to 5°F (2° to 3°C) range near the optimum. This is compared to a stronger peak shown in Fanger's PPD curve, where people's responses changed fairly rapidly as conditions deviated from neutral.

In contrast, the shape of Gagge's PMV_g is quite similar to the shape found from the measured data and is even broader than the curve fitted to the data points. The dissatisfaction rate changes quite slowly near neutral, with the slopes increasing at a similar rate at the more extreme temperatures.

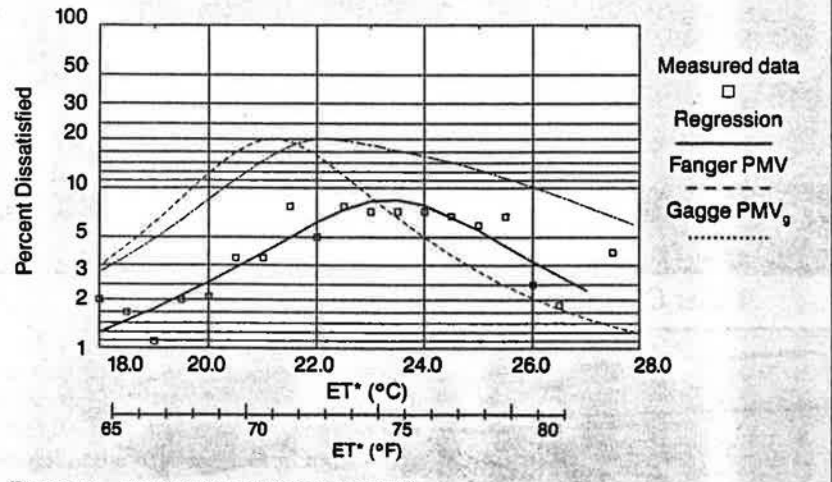

Figure 2. Percent dissatisfied versus ET.*

Conclusions

The range of thermal environments that existed in the office buildings during the measurement periods was fairly narrow, although the thermal sensation votes covered the full range of the seven-point ASHRAE Thermal Sensation scale. Workers were voting at more extremes than predicted, especially for the warmer temperatures.

Neutral temperatures in the buildings were lower than predicted from the laboratory-based comfort models by 2.5° to 4.3°F (1.4° to 2.4°C), and predictive indices underestimated thermal sensations by up to 1.0 units in the warm regime.

The predictions were based on an insulating value calculated from clothing alone. Further analysis suggested that the insulating value of the worker's chair may account for part, if not all, of the discrepancy because laboratory subjects sat in string chairs with negligible insulating value. Results may also reflect workers' preferences for cooler conditions in the workplace as compared to the laboratory setting.

Optimum acceptability in the office environments was 12% dissatisfied, compared to a predicted minimum of 5% based on laboratory experiments. This could be explained by either the wider range of clothing worn by office workers at any given effective temperature, compared to the standard uniforms in the laboratory experiments or by the range of people's thermal expectations and preferences.

The low levels of acceptability, and the range of workers' comfort requirements due to clothing, activity or thermal preference, suggest that centralized, autonomous environmental control systems have inherent limitations to their effectiveness.

Additional analyses reported in a more complete paper[8] examined the extent to which thermal comfort was associated with thermal neutrality, by comparing results from both the Thermal Sensation and General Comfort scales. This comparison indicated that the majority of people who were decidedly uncomfortable associated their feeling with an extreme sense of warmth, rather than coolness.

The results also suggest that the concept of comfort covered a broader range of thermal sensations than commonly assumed, and that people voting within the extreme sensations were not necessarily dissatisfied.

Utilizing more direct assessments of thermal comfort and satisfaction in future surveys (in both the laboratory and the field) would allow a more thorough investigation of the relationship between thermal sensation and acceptability.

These results suggest that current standards and practices for maintaining comfortable thermal environments in office buildings need to be re-examined, supplementing laboratory data with information obtained in field studies.

Based on our findings, recommendations for future research include repeating field studies in more extreme climatic zones, conducting laboratory experiments in more realistic and familiar settings, utilizing direct assessments of comfort and satisfaction, and investigating the effectiveness of demand-controlled environmental control systems for increasing worker satisfaction.

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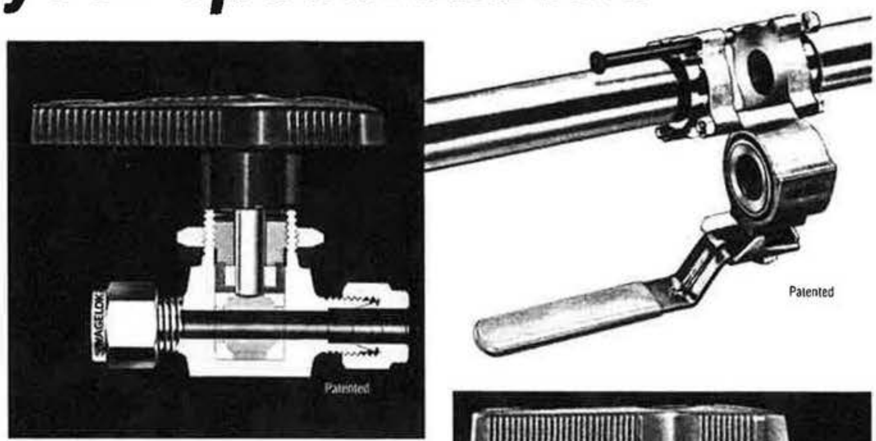

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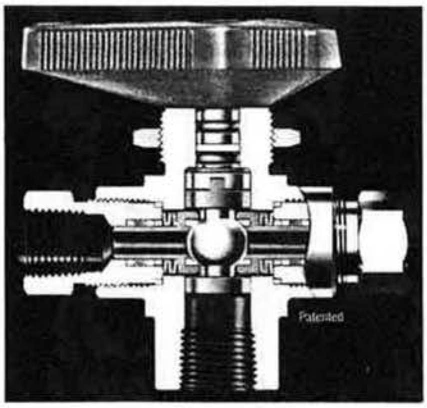

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