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THE EFFECT OF AIR VELOCITY ON THERMAL COMFORT AT MODERATE ACTIVITY LEVELS

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ABSTRACT

The primary purpose of this study was to determine if the thermal comfort of subjects working at a moderate level of activity (2.3 MET) was improved or adversely affected by air motion. A second purpose of the study was to compare experimental results with the predicted responses given by the Fanger thermal comfort model and the Azer thermal response model. Tests were conducted with subjects wearing 0.65 clo and 1.09 clo of clothing insulation and with relative air velocities of approximately 40 fpm (0.20 m/s) and 240 fpm (1.2 m/s). The air temperature was varied over a range selected to include the optimum comfort level. The results indicate that comfort is as good, if not better, with the higher air velocity. The experimental results showed a higher sensitivity to temperature than predicted by either model.

INTRODUCTION

Previous studies (Konz et al. 1983; McIntyre 1978; Rohles et al. 1974, 1982, 1983; Rosen and Konz 1982) have shown that the use of fans has no adverse effect on the level of comfort that can be attained, and they may actually enhance comfort in some situations. These studies were all conducted with sedentary subjects. However, many people spend a good deal of time at moderate activity (1.5 MET to 2.5 MET), which is certainly more typical of industrial workplaces and probably many office and home environments also. It was felt that moderate activity levels actually represent a better application for fans than sedentary activity levels for at least two reasons. First, these higher activity levels require fairly low dry-bulb temperatures to maintain thermal neutrality with no air motion, particularly if much clothing must be worn. It may not be practical, or economical, to provide these conditions in many circumstances. Second, moderate activity implies an active person. The adverse sensations produced by air motion are probably less noticed by the active person. Moderate activity levels, therefore, should allow tolerance of higher air velocities than will be accepted by sedentary subjects.

The primary purpose of this study was to determine if air motion affected comfort when subjects were working at a moderate activity level. A second objective was to compare the experimental data collected to the thermal models of Fanger (1970) and Azer (1977).

EXPERIMENTAL DESIGN AND PROCEDURES

This project had only a limited budget and thus was commensurately limited in scope. It was exploratory in nature and was not intended to yield definitive mathematical relationships for comfort. A considerable amount of additional data will be required to develop such relationships. One activity level (2.3 MET) was used for all tests. Two clothing insulation values (0.65 clo and 1.09 clo) and two air motion conditions for each value of clothing insulation were used. Dry-bulb temperature was varied for each clothing-air motion combination to provide conditions that ranged from cooler than to hotter than conditions required for thermal neutrality.

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Activity

The activity consisted of walking over two 9 in (230 mm) steps as shown in Figure 1. The subjects walked over the steps (up and down) once every 15 seconds and stood quietly between walk cycles. There was a 5-minute rest period every 30 minutes, during which the subjects sat down and filled out comfort ballots. This activity was estimated to average 2.3 MET using the method developed by Konz (1979). Significant deviations from this average value will exist since the actual activity level depends upon the height and weight of a subject.

Air Velocity

The average relative air velocities were 42 fpm (0.21 m/s) and 264 fpm (1.32 m/s) with the cooler clothing and 42 fpm (0.21 m/s) and 218 fpm (1.09 m/s) with the warmer clothing. The lower velocity was due mostly to subject motion. During this conditions, no fan was used and the air motion due to the chamber's environmental control system was less than 20 fpm (0.1 m/s). The higher air velocities were created with a large fan in the chamber as shown in Figure 2. The resulting velocity field was not uniform, and subjects experienced large variations in velocity as they performed the prescribed activity. The relative velocities for each work location were measured, both with and without the fan in operation, by moving two omnidirectional anemometers through the same time-motion pattern that the subjects performed. One anemometer was at head level and one at waist level. Measurements were taken continuously for five minutes, and this procedure was repeated four times at each location. The average velocities for each work location are given in Table 1. The standard deviation for a given work location, as determined using the above measurement scheme, was approximately 46 fpm (0.23 m/s) with the fan in operation and 16 fpm (0.08 m/s) with no fan.

Clothing

The clothing insulation values (Icl) were 0.65 clo and 1.09 clo as measured on a stationary thermal manikin. The 0.65 clo ensemble was the KSU standard uniform, which consisted of a long-sleeved shirt and trousers worn over the subject's own briefs, socks, and shoes. The 1.09 clo ensemble included the same clothing with a T-shirt, sweater, and hard hat added. All of the tests with the 0.65 clo ensemble were conducted in February and March of 1985. All of the tests with the 1.09 clo ensemble were conducted in July of 1985. Also, the high velocity condition was not exactly the same for the two clothing conditions. For these reasons, care must be used in drawing any conclusions about the effect of clothing from these data.

Temperatures

Dry-bulb temperatures were initially selected to result in mean thermal sensations ranging from slightly cool (-1) to slightly warm (+1) based on mean votes predicted with the Fanger (1970) thermal comfort model. However, the responses of the subjects in these tests proved to be more sensitive to temperature than the model predicted and in some cases the temperature range was modified to accommodate this difference. The mean radiant temperature was equal to the dry-bulb temperature for all tests and the relative humidity was between 50% and 60%.

Subjects

Subjects were obtained by advertising in the university newspaper. Four subjects were tested at each condition, two males, and two females. All tests were conducted in the KSU-ASHRAE environmental chamber. Subjects reported to the pre-test room where their oral temperatures and heart rates were measured. They were not allowed to participate if their oral temperatures was above 99.1 F (37.3°C) or if their heart rate was above 90 beats per minute. After this screening, the subjects left the pre-test room to change into the required ensemble and returned. Their height and weight were recorded at that time and they were given an orientation describing the test and the ballots to be used in the voting. The subjects were in the pre-test room approximately 30 minutes before entering the environmental chamber at the beginning of the formal test. The pre-test room dry-bulb temperature 75 F (23.9°C).

Ballots

Three separate ballots were used to evaluate the thermal response of the subjects. The first was the nine-point thermal sensation ballot with responses ranging from very cold (1) to very hot (9) as shown in Table 2. The second ballot was the thermal comfort ballot developed by Rohles and Milliken (1981). The same weighting scheme as employed by Rohles and Milliken was used. The thermal comfort ballot allowed subjects to indicate their responses using adjective pairs as shown in Table 3. The third ballot was the thermal satisfaction-dissatisfaction ballot developed by Rohles and Laviana (1985). With this ballot subjects indicate how well a given term describes their attitudes. The terms are shown in Table 4 with each one given a rating from 1 (very inaccurate) to 7 (very accurate). The same weighting scheme as employed by Rohles and Laviana was used in the present study. Subjects voted before entering the chamber and every half-hour during a test. Tests were concluded after the two-hour vote. Details of all of the test conditions, other measurements, and calculations are given by Hsieh (1985).

RESULTS AND DISCUSSION

Mean thermal sensation and thermal comfort responses are shown in Figures 3 and 4, respectively. The thermal satisfaction and dissatisfaction responses generally were consistent with the thermal comfort responses and are shown in Figures 5 and 6. All data shown are for the two-hour vote. There is a fair amount of data scatter due to the small sample size. However, one trend is clear in Figure 4; maximum comfort levels attainable with the higher air velocities are at least equal to and probably greater than those that can be obtained at the lower air velocity. The thermal satisfaction results lead to the same conclusions. The thermal dissatisfaction results are less conclusive but suggest no real differences in the lowest level of dissatisfaction attainable with and without the fan. This result is rather significant, since maximum comfort levels with the higher air velocities occur at approximately a 10 F (5.6°C) higher temperature than with no motion. These results indicate that supplementing cooling with air motion may not only be economical but also desirable from a comfort point of view.

There appear to be no clear trends when comparing the maximum comfort of the two different clothing insulation values. The maximum values appear to be about the same in both cases. Any differences that do exist may not be solely due to clothing, however, as the 1.09 clo tests were run in the summer while the 0.65 tests were run in the winter; and the air velocity was not exactly the same. Therefore, some of the differences could be attributed to seasonal and velocity effects.

For thermal sensation votes, the male and female responses can be compared statistically. These results are shown in Figures 7 and 8. The values of R^2 for the regression equations are given in Table 5. In all cases the female subjects appear to be more sensitive than the male subjects to temperature changes. Only in the case of 0.65 clo and the low air velocity is this difference statistically significant. The lack of statistical significance for the other cases is most likely due to small sample size. The consistency and the size of the difference in sensitivity indicates that this result is not due just to random chance. These results are also consistent with the findings on an earlier study with sedentary subjects (Nevins et al. 1966).

Probably most interesting of the results is the comparison of the thermal sensations measured in this experiment with those predicted by the Fanger model and the Azer model as shown in Figures 9 and 10. The results for the Fanger model were expanded linearly from its seven-point scale (-3 to +3) to the nine-point scale (1 to 9). The validity of this transformation has not been established. However, it was felt that comparing a seven-point scale for the model with a none-point scale for the experiment would not be fair. The experimental results show a higher degree of sensitivity to temperature than do the model predictions, particularly those tests with 1.09 clo of clothing insulation. For all but the 0.65 clo, no fan test, the main difference between the experiment and the models is one of sensitivity, as neutral responses (thermal sensation of 5) for the experiment and models are not greatly different. For the 0.65 clo, no fan condition, there also appears to be an offset (difference at the neutral condition) between the experiment and the models. This offset is interesting since the maximum thermal comfort for the 0.65 clo, no fan condition occurs at approximately 62.5 F (17°C) in Figure 4, the same temperature for which the models predict a near neutral mean thermal sensation. The differences in sensitivity are not readily explained. It could be due to measuring techniques employed in the study or it could reflect difficulties in applying the models to the activity and environmental conditions used in this study.

CONCLUSION

This study indicates that the levels of comfort that can be attained when exerting at 2.3 MET activity levels are as high if not higher at elevated air velocity than they are with relatively still air. The study also indicates that females are more sensitive to temperature than are males at this activity level. Finally, the study raises some questions about how well thermal responses can be predicted for these activity levels and shows a need for a more complete data base for moderate activity so that existing models and relationships can be verified and refined if necessary.

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The authors would like to thank Dr. N. Z. Azer for his assistance and cooperation in providing the predictions using his model.

TABLE 1
Results of Air Velocity Measurements

	Location*			
	1	2	3	4
Test	fpm (m/s)	fpm (m/s)	fpm (m/s)	fpm (m/s)
0.65 clo, fan	228 (1.14)	232 (1.16)	261 (1.31)	332 (1.66)
0.65 clo, no fan	42 (0.21)	42 (0.21)	42 (0.21)	42 (0.21)
1.09 clo, fan	186 (0.93)	196 (0.98)	224 (1.12)	266 (1.33)
1.09 clo, no fan	42 (0.21)	42 (0.21)	42 (0.21)	42 (0.21)

*Refer to Figure 2 for locations.

TABLE 2
Responses on Thermal Sensation Ballot

(9) Very Hot
(8) Hot
(7) Warm
(6) Slightly Warm
(5) Neutral
(4) Slightly Cool
(3) Cool
(2) Cold
(1) Very Cold

TABLE 3
Adjective Pairs for Thermal Comfort Ballot

Comfortable	Uncomfortable
Bad Temperature	Good Temperature
Pleasant	Unpleasant
Warm	Cool
Unacceptable	Acceptable
Satisfied	Dissatisfied
Uncomfortable Temperature	Comfortable Temperature

TABLE 4
Terms Used in Thermal Satisfaction-Dissatisfaction Ballot

1. uncomfortable
2. content with
3. agreeable
4. tolerable
5. unpleasant
6. inadequate
7. annoying
8. undesirable
9. satisfactory
10. miserable
11. satisfied with
12. good
13. unacceptable
14. enjoyable
15. great
16. distressful
17. bad
18. acceptable
19. discontent with
20. pleasant
21. dissatisfied with
22. comfortable
23. intolerable
24. disagreeable
25. adequate
26. desirable
27. unsatisfactory
28. gratifying
29. pleasing
30. poor
31. appealing
32. delightful

TABLE 5
R^2 Values for Linear Regression Equations

Figure	Clo	Fan	Sex	R^2
3	0.65	on	both	0.86
3	0.65	off	both	0.93
3	1.09	on	both	0.65
3	1.09	off	both	0.94
7	0.65	on	male	0.85
7	0.65	on	female	0.88
7	0.65	off	male	0.94
7	0.86	off	female	0.88
8	1.09	on	male	0.23
8	1.09	on	female	0.83
8	1.09	off	male	0.79
8	1.09	off	female	0.92

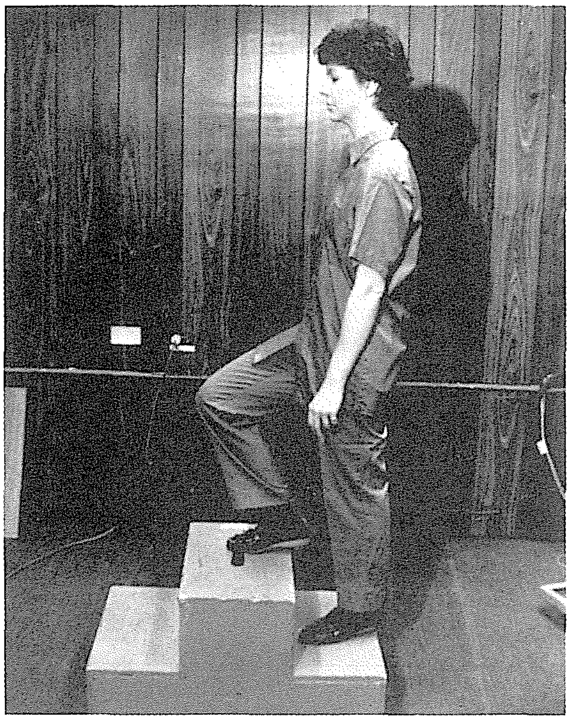

Figure 1. Activity performed by subjects

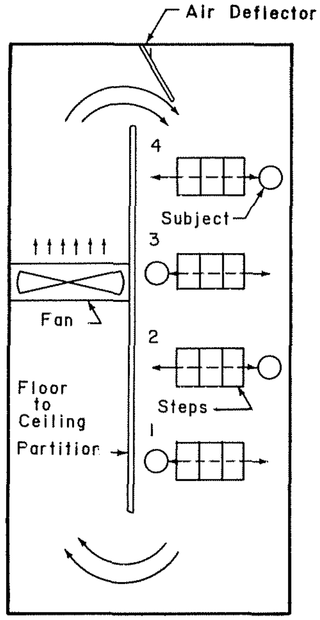

Figure 2. Test chamber layout (top view)

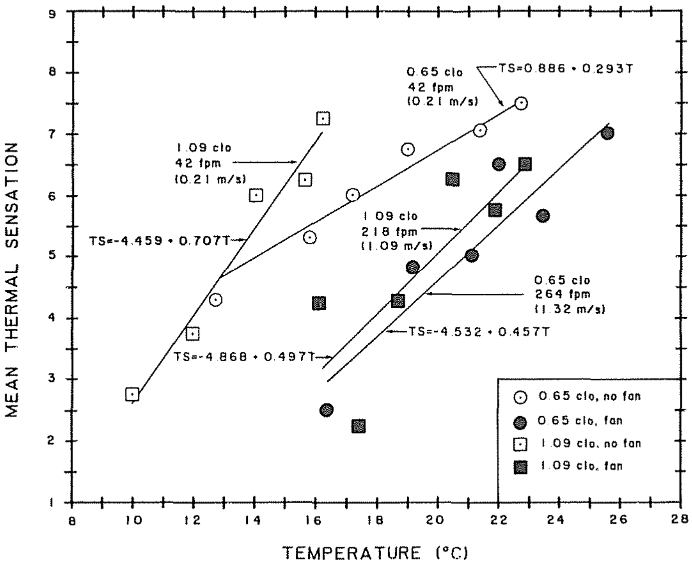

Figure 3. Mean thermal sensation responses

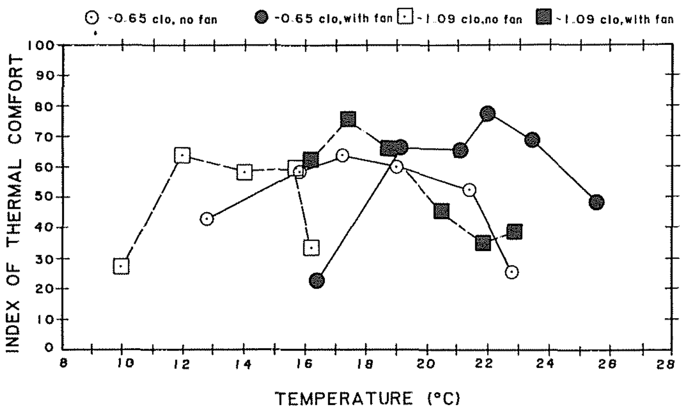

Figure 4. Mean thermal comfort responses

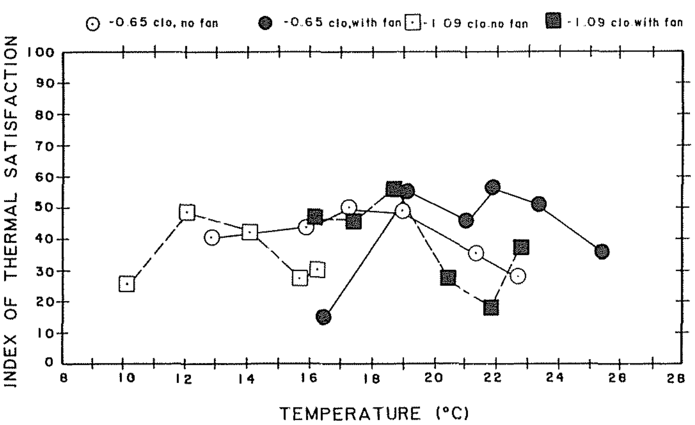

Figure 5. Mean thermal satisfaction responses

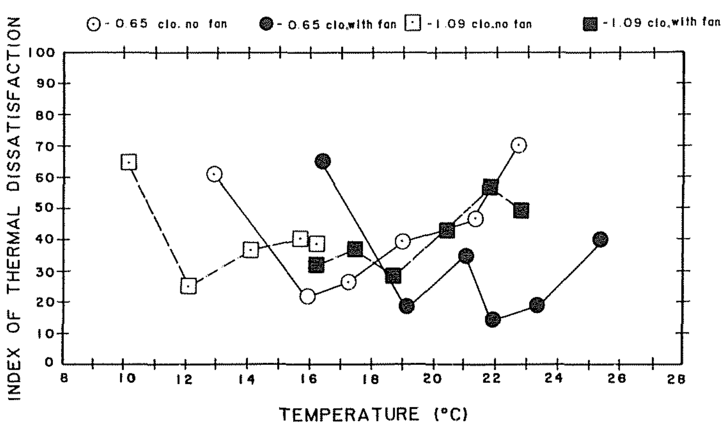

Figure 6. Mean thermal dissatisfaction responses

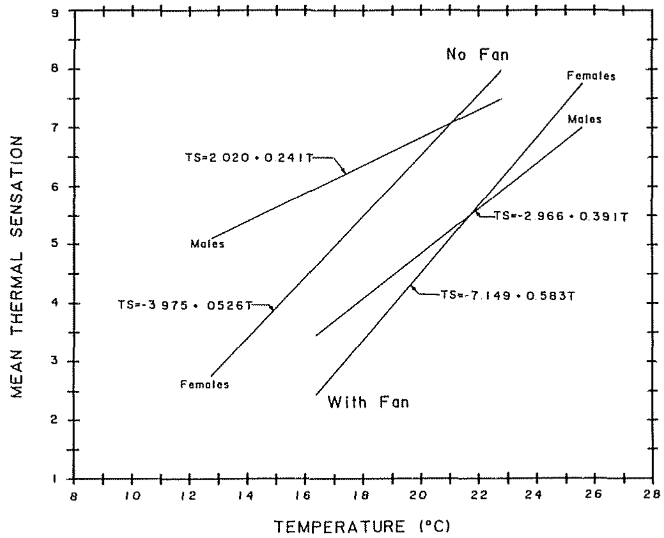

Figure 7. Regression equation for male and female responses for 0.65 clo tests

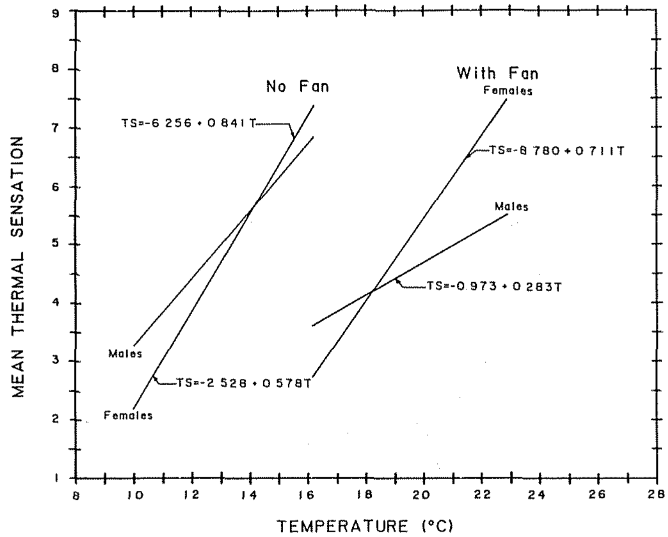

Figure 8. Regression equations for male and female responses for 1.09 clo tests

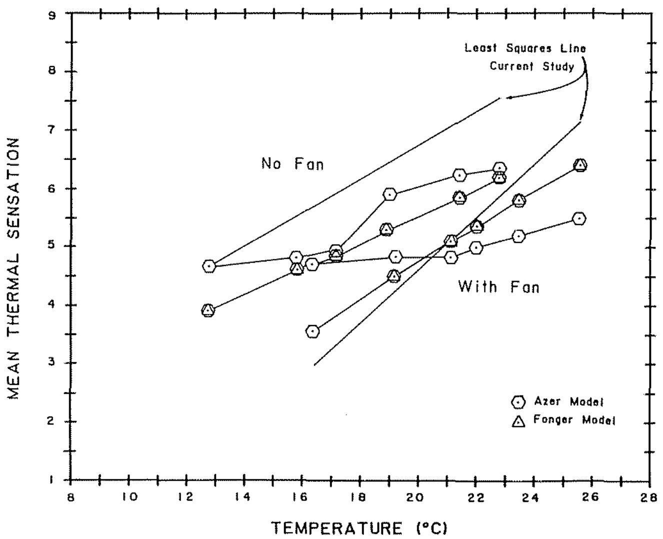

Figure 9. Comparison of experimental results with model predictions for 0.65 clo

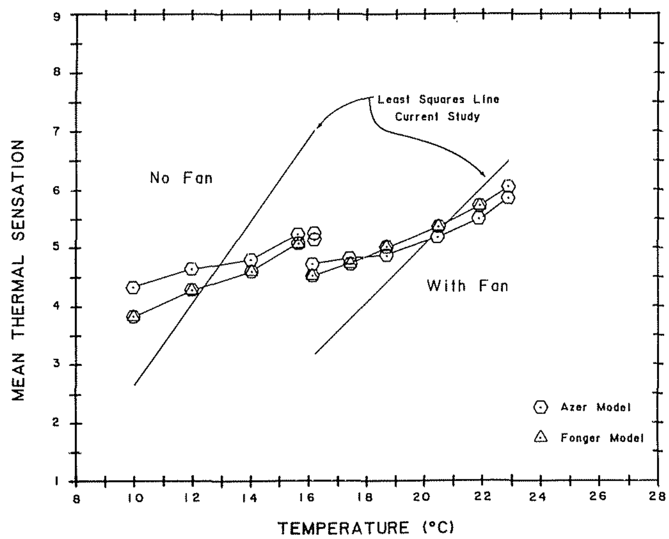

Figure 10. Comparison of experimental results with model predictions for 1.09 clo

Discussion

O.J. NUSSBAUM, P.E., Consulting Engineer, Newton, PA: In today's electronic office, a great deal of worker discomfort is caused by radiation of heat from electronic equipment such as word processors, personal computers, CRTs, etc. Is any information available from the research reported at this symposium that will be helpful in designing HVAC for people in such an environment?

B.W. Jones: I do not believe any of the papers at this symposium addressed this particular problem. Chapter 8 of ASHRAE Fundamentals and the book Thermal Comfort by P.O. Fanger describe how to deal with radiant heat sources. I am not aware of any information specifically describing heat radiation characteristics of these types of devices. Such information would be useful.