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An Investigation of Thermal Comfort at High Humidities

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ABSTRACT

Climate chamber experiments were performed to investigate thermal comfort at high humidities. Subjective reports were recorded for a total of 411 subjects at frequent intervals during the three-hour experiments with 65 selected subjects equipped with instrumentation to record skin wettedness and skin temperature. The exposures ranged from 20°C (68°F)/60% RH to 26°C (78.8°F)/90% RH with two clothing levels, 0.5 and 0.9 clo, and three levels of metabolic activity, 1.2, 1.6, and 4 met. Clear differences in humidity response were not found for sedentary subjects; however, non-sedentary activities produced differences on several subjective scales. These differences, though, are dictated via heat balance and thermoregulation and cannot be separated from humidity-related effects. For metabolic rates 1.6 met and above, these data suggest that no practical limit on humidity will lower the percent dissatisfied below 25%.

INTRODUCTION

A significant fraction of building energy use goes toward maintaining indoor thermal environmental conditions. The definition of acceptable conditions plays an important role in determining both energy use in buildings and the design approaches that can be used to achieve those conditions. The thermal environmental conditions for human occupancy as specified in the recently revised *ANSI/ASHRAE Standard 55-1992* (ASHRAE 1992, 1995) affect both the design and operation of all HVAC systems, as well as whether certain energy-efficient cooling technologies are feasible. The upper limit on humidity has both these types of effects. First, it determines the amount of dehumidification needed in humid climates, influencing energy use, peak demand, and the design and operation of both building and equipment. Second, it determines the range of climatic conditions under which ventilative and direct evaporative cooling are viable alternatives to conventional cooling, especially in dry areas such as the western U.S. By reducing peak demand, these non-compressor-based cooling techniques provide substantial benefits to building operators and to electric utilities.

Table 1 summarizes the evolution of humidity standards in the U.S. since the turn of the century. Prior to 1915, documents of the American Society of Heating and Ventilating Engineers (ASHVE) focus almost exclusively on ventilation rates for different classes of buildings and rarely mention humidity. In 1915, the society introduced the Code of Minimum Requirements for ventilation in which an upper relative humidity limit of 50% is mentioned as desirable but not mandatory. In 1920, ASHVE adopted a "Synthetic Air Chart" (Palmer 1917) with a wet-bulb temperature limit of 64°F (18°C). Interestingly, this same limit (in part) is now included as an addendum to ASHRAE 55, ASHRAE 55a-1992 (ASHRAE 1995). In the 75 years since the Synthetic Air Chart, the ASHVE/ASHRAE upper humidity limit has gyrated between 60% and 100% (no limit) relative humidity—for temperatures spanning the comfort zone. This suggests that comfort considerations have not emerged as a clear delineator of humidity requirements in standard HVAC design practice.

The 1932 ASHVE ventilation standard extended the Synthetic Air Chart's humidity limit to 70% across all temperatures. In 1938 ASHVE released the "Code of Minimum Requirements for Air Conditioning" (ASHVE 1938), a code that was adopted by most city and state building codes over the following 20 years. The 1938 code specifies 75% relative humidity as an upper limit. ASHRAE's 1950-1965 comfort

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TABLE 1
Comfort Standards for Humidity

Year	Issuer	Maximum Humidity	Document
1915	ASHVE	50% relative humidity (recommended)	Code of Minimum Requirements for Ventilation
1920	ASHVE	64°F wet bulb (17.8°C)	Synthetic Air Chart
1932	ASHVE	70% relative humidity	ASHVE Ventilation Standard
1938	ASHVE	75% relative humidity	Code of Minimum Requirements for Comfort
1950-1965	ASHRAE	No explicit limit	ASHRAE Comfort Chart
1966	ASHRAE	60% relative humidity	Standard 55-66
1974	ASHRAE	14 mm Hg (12 g/KG humidity ratio)	Standard 55-74
1981	ASHRAE	12 g/Kg humidity ratio	Standard 55-81
1992	ASHRAE	60% relative humidity	Standard 55-92
1992a	ASHRAE	18°C (64.5°F) wet bulb, winter 20 °C (68 °F) wet bulb, summer	Addendum to Standard 55-92

chart references the Effective Temperature (ET) curves of Houghten and Yaglou (1923) and has no explicit humidity limit nor is any limit expressed in the accompanying text. With the 1966 introduction of ASHRAE Standard 55 (ASHRAE 1966), ASHRAE's relative humidity limit was lowered to 60%. "No air-conditioning system should be worthy of the name that does not control humidity within this range," that is, 20%-60%, claim McNall and Nevins in a 1968 *ASHRAE Journal* critique of Standard 55-66 (McNall and Nevins 1968).

In 1974 the revision to ASHRAE 55 (ASHRAE 1974) set the humidity limit at a humidity ratio of 14 mm Hg (12 g H_2O/Kg dry air), a limit that existed (ASHRAE 1981) until 1992. *ANSI/ASHRAE Standard 55-1992* (ASHRAE 1992) set the upper limit of relative humidity back down at 60%. Currently, the ASHRAE upper humidity limit is defined by two wet-bulb lines, one for winter clothing (18°C) and another for summer clothing (20°C) (ASHRAE 1995).

Summary of Previous Studies on Humidity and Comfort

Houghten and Yaglou (1923) developed the Effective Temperature (ET) scale, based on experiments with twin climate chambers. Subjects moved between the chambers and voted within 15 minutes of switching. The ET scale shows combinations of temperature and humidity that result in equal comfort. Glickman et al. (1950) concluded that the ET scale overemphasized the effect of humidity for long-term exposures. Koch et al. (1960) concluded that between 20°C (68°F) and 34°C (93.2°F) and 20% and 90% relative humidity, humidity had only a small effect on comfort. Nevins et al. (1966) determined that the temperature can be increased by 0.3°C (0.54°F) for each 10% reduction in relative humidity. McNall et al. (1967) tested several metabolic rates in a design similar to Nevins et al. (1966) and found little humidity effect at low metabolic rates and an increased humidity effect at higher metabolic rates. Andersen et al. (1973) found no effect on the perception of humidity with changes between 10% and 70% in relative humidity. Gwosdow (1986) found that the pleasantness of the sensation of fabric pulled across skin decreased with increasing humidity.

Tanabe et al. (1987) performed several climate chamber experiments in Japan examining the effect of relative humidity on thermal comfort. Sixty-four college-aged subjects were exposed for three hours to air temperatures at and beyond the upper boundary of the ASHRAE comfort zone. Relative humidities of 50% and 80% were tested as well as several air movement levels. Tanabe found that Predicted Mean Vote (PMV) (Fanger 1970) predicted thermal sensation votes for hot and humid conditions that were higher than the votes reported by their subjects. For low air movement, the difference is on the order of one-half of one category width, but it increases as air movement increases.

de Dear et al. (1989) studied the impact of humidity on thermal comfort during step changes between 20% and 80% relative humidity. While most previous experiments examined long-term steady-state responses, this experiment looked at a subject's instantaneous response to a change in humidity as well as how that response changed over the 90 minutes immediately following. Twin climate chambers were used, with the subjects spending an initial acclimation period in the first chamber and then moving to the second. de Dear et al. found that thermodynamics of moisture absorption and desorption in clothing fibers during humidity transients affected the heat balance and thermal sensation of the subject. The effect was most pronounced in the case of natural fibers, such as wool, but was also evident in the case of unclothed subjects due to the hygroscopic character of the skin surface. Jones and Ogawa (1992) developed a computer model to predict thermal response to such transients.

The J.B. Pierce Foundation completed a study of humidity effects on thermal comfort (Berglund 1989). Twenty subjects were exposed to temperatures of 21°C, 23.8°C, and 27.2°C and dew point levels of 1.7°C, 11.1°C, and 20°C. Three metabolic rates were tested, including sedentary, intermittent walking, standing, and continuous walking. Subjects felt cooler, drier, and more comfortable at the lower humidities and temperatures and judged the air to be fresher with a more acceptable air quality. Humidity played a role in the subjects' assessment of air quality, while temperature had effect an order of magnitude greater than humidity in determining thermal comfort. The subjects indicated that equal changes in humidity are more perceptible at higher humidities than at lower humidities.

In a more recent paper, Berglund (1995) further analyzed the results from the 1989 chamber study and concluded that the judgment of whether an environment is thermally acceptable or not depends on both thermal sensation and perceived skin moisture. This result accounts for the fact that at a given temperature, warm discomfort will increase with increasing humidity. By considering only the data for sedentary subjects wearing 0.56 clo at humidity conditions above the middle of the comfort zone, Berglund shows that the loci of points representing 80% thermal acceptability correlate fairly well with the newly prescribed upper humidity limit (constant wet-bulb temperature of 20°C (68°F) for summer conditions) of ASHRAE 55-1992 (ASHRAE 1995). Berglund suggests that the agreement with his data would be improved if the comfort zone were shifted to slightly cooler temperatures by 1.5°C (2.7°F).

Hayakawa et al. (1989) investigated the physiological and psychological effects of air temperature and humidity on humans at three different metabolic rates during summer conditions. Climate chamber experiments were performed on four female subjects wearing 0.03 clo for a matrix of 36 conditions combining the following conditions: 30°C, 32.5°C, and 35°C (86°F, 90.5°F, and 95°F); 30%, 50%, 70%, and 90% relative humidity; and 1, 1.5, and 2 met. The results indicate that at 30°C (86°F) and 0.03 clo, there was no significant difference in thermal sensation vote for humidities up to 70%. The discomfort vote, however, appeared sensitive to changes above 50%. Both thermal sensation vote and discomfort vote increased noticeably for non-sedentary metabolic rates.

Ninety-eight college-age Singaporeans were tested in 10 climate chamber experiments (de Dear et al. 1991). The research design consisted of two humidities (35% and 70% relative humidity) and five temperatures around the upper temperature limit of the ISO 7730 (ISO 1984) and ASHRAE 55 (ASHRAE 1992) comfort zones. Subjects wore standard 0.6 clo uniforms and were sedentary throughout the three-hour experiments. Relative humidity was found by probit analysis to play only a relatively minor role in determining the position of the 20% thermal dissatisfaction temperatures (27.7°C [81.9°F] and 26.6°C [79.9°F] for conditions of low and high humidity, respectively).

In another study (Koseki et al. 1994; Imamura et al. 1994; Tanabe et al. 1995a, 1995b), a total of 72 subjects were exposed at air temperatures of 25°C, 28°C, and 30°C (77°F, 82.4°F, and 86°F) and 30%, 50%, and 70% relative humidity. Eight subjects were tested at a time in a chamber designed to look like a realistic office. Metabolic rate was 1.1 met with a 0.5 clo standard uniform. Standard Effective Temperature (SET*) had good correlation with thermal sensation vote. Japanese felt cooler than Americans around 25°C (77°F) SET*.

In another study (Tanabe 1994), 16 subjects were exposed under the combination of 26°C (78.8°F) SET* at 35% relative humidity, 55% relative humidity, 65% relative humidity, and 75% relative humidity and also 28°C (82.4°F) SET* for the four humidity levels. Each subject participated in eight experiments. Subjects wore a 0.6 clo standard uniform and were asked to exercise every ten minutes (step test, 1.2 met and 1.6 met). Thermal sensation and comfort votes were obtained, and humidity inside clothing was measured at two points. The thermal sensation vote was similar for all four humidities. Mean thermal sensation was around 0 at 26°C (78.8°F) SET* and 0.8 at 28°C (82.4°F) SET*. The comfort vote at 1.2 met was similar for 35%-75% after three hours' exposure. Feeling of skin moisture was similar for 35%-75% relative humidity.

In a laboratory study (Bauman et al. 1996), human subjects were exposed to thermal conditions representative of the warm upper boundary of the ASHRAE 55 specified summer comfort zone. Four test conditions were studied, consisting of relative humidities of 50%, 60%, 70%, and 80% along the constant ET* line of 26.1C (79°F). Ninety-two subjects were tested under steady-state conditions in a controlled environmental chamber configured to resemble a modern office with typical furniture and partitions. Wearing informal office attire (0.6 clo), the subjects repeated a series of step exercises to simulate three different activity levels (1.2 met, 1.6 met, and a short-term excursion up to about 4 met) during the three-hour experiment. Subjective responses to the test conditions were obtained from all subjects through written surveys, and 25 subjects were instrumented to measure local skin temperature and skin wettedness under the clothing.

The thermal sensation vote was similar for all four test conditions. At 1.2 met (sedentary office work), the thermal sensation vote was "slightly warm" and this feeling was acceptable to more than 85% of the subjects for a relative humidity of 50% and to 75% and 60% of the subjects was acceptable for relative humidities of 70% and 80%, respectively. Although the clothing, activity levels, and temperatures examined coincide exactly with those specified in ASHRAE 55, the warmth perception is uniformly higher than is supposed to be the case for the standard. This is because the conventional office chairs used in the experiment add to the subjects' clothing, raising the SET* above 26.1 (79°F)—Standard 55 as it is currently defined (ASHRAE 1992,1995) applies only to workers seated in chairs having zero additional clo insulation.

When activity level was increased above 1.2 met (1.6 met and short-term excursion to 4 met), the thermal sensation vote increased to about the same level for all four test conditions (50%-80% relative humidity). No significant differences were found in the comfort vote between any of the test conditions. Feeling of skin wettedness increased with increasing air humidity. Skin dampness acceptability was greater than 90% for 50% relative humidity but dropped to 70% for 90% relative humidity.

McIntyre (1980) cites several studies showing that for operative temperatures within the comfort zone, differences in relative humidity as disparate as 20% and 70% can be undetectable, let alone a source of discomfort. Tanabe et al. (1987) suggest that at high humidity levels (80% RH), the perception of thermal sensation does not act as a reliable predictor of thermal comfort and conclude that the use of thermal sensation to establish limits of thermal comfort is inappropriate at higher levels of humidity.

This summary of previous studies of humidity and comfort shows that conclusive results are not often found; fully half the studies found no perceptible relationship between humidity and comfort over a wide range of conditions. Other factors, temperature and clothing, for example, prove to be more reliable indicators. If any effects are found, they are at and beyond the upper temperature and humidity boundaries of the ASHRAE 55 comfort zone (ASHRAE 1995).

EXPERIMENTAL OBJECTIVES AND METHOD

The objective of the project was to use climate chamber experiments to evaluate thermal comfort at high humidities.

Tests on human subjects (Nevins et al. 1966; Fanger 1970; Tanabe et al. 1987; de Dear et al. 1991) and others described in Table 2 indicate that humidity has only a modest effect on thermal sensation at temperatures within the comfort zone. The physics of the effect of humidity on heat loss and thermal sensation is well developed, and indices such as ET* include the effects of humidity in scaling temperature and thermal sensation. Furthermore, water content in air above even 80% relative humidity can be comfortable in terms of thermal sensation. From the perspective of the body's thermal balance, there is no upper limit to humidity, since temperature adjustment is sufficient to achieve thermal neutrality at very

TABLE 2
Previous Studies of Humidity and Comfort

Year	First Author	Temperature Range Tested	Humidity Range Tested	Effects Noted
1923	Houghten	26.7-69.4°C (80°F-156.2°F)	22.8-45°C (73-113°F) wet bulb	In comfort zone, comfort depends equally on wet- and dry-bulb temperature.
1950	Glickman	Unspecified	30-80% RH	ET* overemphasizes RH for long exposures
1960	Koch	20-34°C (68-93.2°F)	20-90% RH	Small over entire range
1966	Nevins	18.9-27.8°C (66-82°F)	15-85% RH	Increase of 0.3°C temperature = decrease of 10% RH for sensation
1967	McNall	15.6-40.6°C (60-105°F)	20-90% RH	No effect at low met, some effect at higher met
1973	Anderson	23°C (73.4°F)	10-70% RH	None
1987	Tanabe	27.8-31.3°C (82-88.3°F)	50-80% RH	PMV predicts TS too high
1989	de Dear	23.3-28.8°C (73.4-83.8°F)	20-80% RH	Increase in thermal impact of humidity step-changes is caused by transient absorption and desorption of moisture in clothing
1989	Berglund	21-27.2°C. (69.8-81°F)	20-95% RH	Temperature order of magnitude more important for determining comfort
1989	Hayakawa	30-35°C (86-95°F)	30-90% RH	No effect on thermal sensation up to 70%—discomfort increased significantly with elevated metabolism
1994	Tanabe	25-30°C (77-86°F)	30-70% RH	SET* good relation with TS
1994	Tanabe	26-28°C (78.8-82.4°F)SET*	35-75% RH	TS vote at 1.2 met similar for all RH
1996	Bauman	26.1-26.6°C (79-79.9°F) 7ET*/26.2-28.1°C (79.2-82.6°F) SET*	50-80% RH	No change in thermal sensation, no difference in acceptability except under increased met
1995	Berglund	Reanalysis of 1989 data		Increased discomfort above 18°C (64.4°F) wet bulb

high humidity. Nevertheless, there may be comfort considerations apart from heat balance that suggest limits on humidity.

The mechanism by which humidity affects comfort is not known. One hypothesis is that hygroscopic absorption of atmospheric moisture by the skin's stratum corneum, or by salt on the skin's surface, increases skin wettedness. Skin wettedness is known to be closely connected to human perception of comfort/discomfort under warm conditions (Gagge et al. 1972). Discomfort, then, may result from a clinging sensation of clothing on the wet skin, caused by a softening of the stratum corneum over which clothing fibers pass, and possibly due to changes in the clothing fibers themselves.

Another hypothesis for discomfort is related to periodic variation in metabolic levels. People at light metabolic level (less than or equal to 1.2 met) may in their daily activities temporarily elevate their met levels by climbing stairs, carrying things, etc. During the elevated activity, a higher heat loss is required for thermal balance. If the humidity is high, the heat dissipation ability of the body is reduced, and the sweat rate will increase over that of a body in a dry environment. The resulting skin wettedness may persist after the activity rate has subsided and the skin cooled off. Discomfort could then result from increased skin temperature during the intermittent exercise or residual skin wettedness left over after the exercise.

Finally, there is the possibility that the humidity is perceived in the respiratory system or some other site.

This study specifically examined effects related to skin wettedness, skin temperature, metabolic variation, winter and summer clothing differences, and many subjective responses that may be affected by variations in humidity.

Each subject completed a questionnaire covering demographics and ratings of general office environment characteristics and current feelings of warmth/dampness every 30 minutes for the two-and-a-half-hour exposure period. Experiments were performed at several discrete relative humidities along ISO-ET* lines on a psychrometric chart. The values of ET* tested were 20°C, 21.5°C, 23°C, 24.5°C, and 26°C (68°F, 70.7°F, 73.4°F, 76.1°F, and 78.8°F). ET* was calculated using a computer model (Fountain and Huizenga 1997). At 60% RH, ET* of 21.5°C, 23°C, 24.5°C, and 26°C (70.7°F, 73.4°F, 76.1°F, and 78.8°F) were tested. At 70% RH, ET* of 20°C, 21.5°C, 23°C, 24.5°C, and 26°C (68°F, 70.7°F, 73.4°F, 76.1°F, and 78.8°F) were tested, and so forth. The matrix of experiments is presented in Table 3. In each cell of the matrix, 16 subjects were tested, preserving an even mix of gender. The subjects wore standard clothing, 0.5 clo for the summer conditions and 0.9 clo for the winter conditions. For selected points, both clo values were tested. Subjective reports were recorded for a total of 411 subjects at frequent intervals during the three-hour experiments, with 65 selected subjects equipped, in addition, with instrumentation to record skin wettedness and skin temperature. Table 3 and Figure 1 show the points tested.

Our experimental protocol follows closely the protocol used by Bauman et al. (1996), who conducted their experiment using the same controlled environment chamber and instrumentation used in the current study. Very similar protocols have been used by Nevins et al. (1966), Fanger (1970), Tanabe et al. (1987), and de Dear et al. (1991). From four to six subjects are scheduled for each two-and-a-half-hour test. The chamber is activated and fine-tuned to the desired test condition during a three-and-a-half- hour stabilization period before the test. Two of the subjects wear a harness with skin temperature and skin humidity sensors placed on the chest, back, arm,

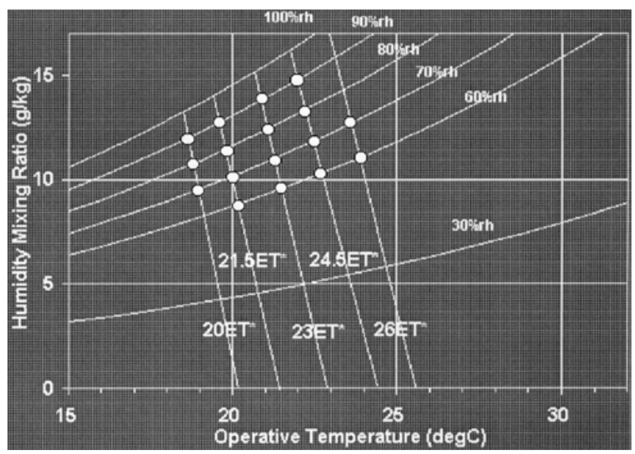

Figure 1 *Psychrometric chart representation of experimental matrix.*

TABLE 3
Matrix of Experiments*

	20°C, 68°F ET†	21.5°C, 70.7°F ET†	23°C, 73.4°F ET†	24.5°C, 76.1°F ET†	26°C, 78.8°F ET†
60%		16†	16	16	16
70%	16	16	16	16	16
80%	16	16	16	16	
90%	16	16	16	16	

* White cells = 0.5 clo, light-shaded cells = 0.5 and 0.9 clo, dark cells = 0.9 clo, with 16 subjects in each cell.
† Cell values indicate the number of subjects tested at each condition.

and leg. The instrumented subjects change to standard uniform clothing in a dressing area within the chamber while the subjects without instruments change outside the chamber (due to space and privacy constraints) and enter the chamber when finished. A background survey given during an initial acclimation period asks demographic questions such as age, height, weight, and gender.

Subjects arrived at the climate chamber ready to change into a standard uniform. The uniform consisted of 100% cotton short-sleeved shirts, thin trousers, underwear, and socks (0.5 clo) for summer conditions (Figure 2) with the addition of a thick cotton sweatshirt (0.9 clo total) for winter conditions (Figure 3). The moisture permeability index of these ensembles is likely to be between 0.43 and 0.45 (i_m) (McCullough et al. 1989).

During the test, subjects were either sedentary, reading or writing at a desk, or performing an exercise routine designed to produce a specific rate of metabolic activity. A periodic exercise protocol verified by laboratory testing of respiratory oxygen consumption (Arens et al. 1993) was used. The exercise protocol involves rising from a seated position once every ten minutes, moving to a nearby eight-inch step (refer to Figure 2), and stepping up and stepping down 12 times. The subject then returns to his/her seat. Three different activity levels can then defined as follows: (1) 12 steps/10 minutes (1.2 met), (2) 20 steps/5 minutes (1.6 met), and (3) 40 steps at once, representing a short-term exertion of approximately 4 met.

For the first 90 minutes, the subjects repeat the periodic light exercise described above to maintain 1.2 met. Every 30 minutes throughout the experiment, the subjects filled out a new subjective survey. After 90 minutes of 1.2 met, the subjects increased their metabolic activity (by increasing the frequency of stepping on the stool) to 1.6 for 20 minutes. After 20 minutes of 1.6 met, the subjects again increased their metabolic activity to 4 met for 3 minutes and then are sedentary for the remaining 30 minutes of the experiment.

RESULTS

Current ASHRAE comfort zone boundaries are drawn on the premise of acceptability (ASHRAE 1992,1995). Using data from climate chamber experiments, 10% of subjects are presumed to vote "unacceptable" at the boundary due to purely heat-balance factors (with an additional 10% voting unacceptable for non-heat-balance reasons including thermal asymmetry, drafts, local discomfort, etc.) Several different proxies have been used for acceptability in past experiments. For example, a thermal sensation vote between –0.5 and +0.5 (or –1.5 and +1.5) can be binned as "acceptable" and anything outside that range considered "unacceptable." For preference votes, a vote of "no change" is often binned as "acceptable" and votes of "want warmer" or "want cooler" binned as "unacceptable." In this experiment, we queried the subjects directly for an assessment of acceptability.

Table 4 shows acceptability responses in each matrix cell. Note that two specific differences exist between Table 3 (the

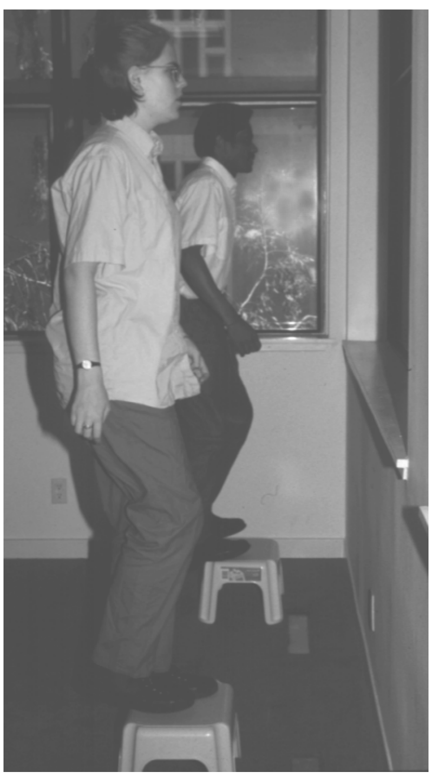

Figure 2 *Summer clothing.*

Figure 3 *Winter clothing.*

TABLE 4
Acceptability by Experimental Matrix Cells*

	20°C, 68°F ET†	21.5°C, 70.7°F ET†	23°C, 73.4°F ET†	24.5°C, 76.1°F ET†	26°C, 78.8°F ET†
60%		16, 0/16, 0	17, 4/16, 1	14, 2/12, 4	13, 3
70%	20, 2/21, 1	18, 0/12, 0	16, 0/16, 0	15, 1	13, 4
80%	3, 2	16, 0/15, 1	17, 2/18, 0	15, 1	
90%	0, 0	4, 2	16, 2/17, 0	14, 2	

* White cells = 0.5 clo, light-shaded cells = 0.5 and 0.9 clo, dark cells = 0.9 clo.
† Cell values indicate the number of subjects voting (acceptable, unacceptable) at the 90th minute. Where two sets of values are listed, the first set of values represents 0.5 clo, the second set represents 0.9 clo.

experimental design) and Table 4 (the experiment as completed)—the number of cells in which two levels of clothing were tested increased and some cells have less than 16 responses. In the first case, we wanted to collect additional data where possible to boost the sample size, and in the second case, we discovered that certain conditions (i.e., 20°C (68°F) ET* and 80% or 90% RH) could not be stabilized for the duration of the experiment in our climate chamber. Table 4 clearly shows that there is not a clear trend showing increases in unacceptability while subjects are sedentary.

Figure 4 shows the results of a probit analysis on "direct"assessment of acceptability. Probit regression allows the fitting of dose-response data to a sigmoid function. The "dose" in this case is humidity ratio and the response is "direct" acceptability.

Note that the probit curve lies below 10% dissatisfied for humidity ratios up to 15 g/Kg for a metabolic rate of 1.2 met. This result is calculated across all matrix cells (Figure 1) so all temperature and clothing levels are included. Ideally, different temperatures and clothing levels would be examined independently, but our data are neither fine-grained enough nor consistent enough to allow that level of disaggregation. At 1.6 met, the percent dissatisfied is between 25% and 40% for all humidities within the comfort zone. The number of samples in each cell is either 16 or 32 (for those tested with the two different clo levels). Fiducial limits on these curves could not be established However, inasmuch as it represents trends in our data, Figure 4 allows us to make two relevant assertions: (1) the humidity limit for determining acceptability of persons at metabolic rates of 1.2 met or below may be quite high, and (2) no practical limit on humidity will likely lower the percent dissatisfied below 25% for persons at 1.6 met.

Figure 5 shows the percent dissatisfied for all cells as a function of humidity ratio (HR) for all subjects aggregated.

The interesting feature in this figure is the effect of metabolic excursions on acceptability. At the 60th minute, the humidity response is slight. After 90 minutes, immediately before the subjects shift to 1.6 met, we begin to see an effect. At the 110th minute, the subjects are at the end of the 1.6 met level with a slight increase in discomfort. At the 115th minute, the subjects have just completed the 4 met excursion. Acceptability is rated lowest at this point, but the recovery period is rapid—after just five minutes of rest, acceptability is above the steady-state 1.6 met level.

Figure 6 shows two measures of acceptability (direct acceptability and air humidity acceptability) at the 90th minute as a function of wet-bulb temperature. Curves are

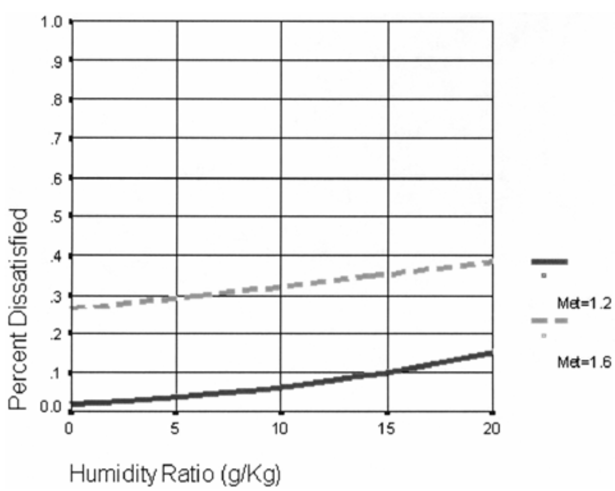

Figure 4 *Probit analysis of direct acceptability on humidity ratio (all temperatures combined).*

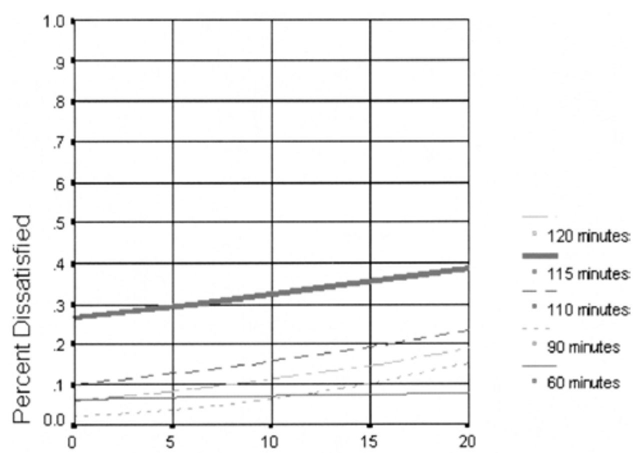

Figure 5 *Probit analysis of direct acceptability on humidity ratio (all surveys and all temperatures).*

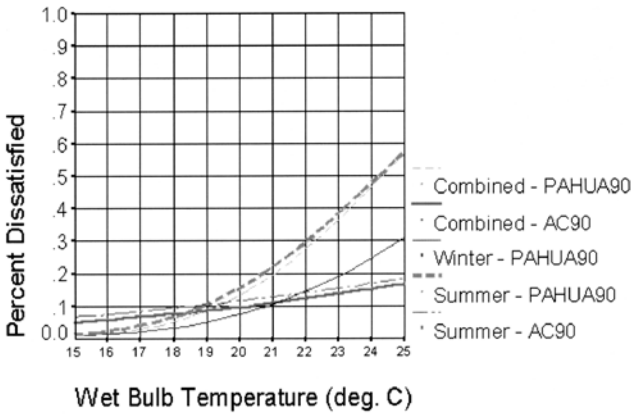

Figure 6 *Probit analysis of acceptability on wet bulb (all temperatures).*

shown for winter and summer conditions and both combined. At 18°C wet, less than 10% of subjects wearing winter clothing voted unacceptable. At 20°C wet bulb, just over 10% of subjects wearing summer clothing voted unacceptable and just over 15% voted that they were specifically dissatisfied with the air humidity.

CONCLUSIONS

The objective of the project was to evaluate thermal acceptability near the upper humidity levels for comfort. This paper presented a short summary of previous studies on the influence of humidity on thermal comfort, described the methods used to investigate the upper boundary in the current study, and presented our results and conclusions.

We found few differences in human response to humidity exposures between 60% RH and 90% RH (9-15 g/Kg HR (humidity ratio)) for the temperature range 20-26 ET*) while sedentary. This study does not indicate that no effect exists, but we were unable to clearly distinguish effects, if any, in our data. Non-sedentary activities produced differences in overall acceptability, thermal sensation, skin dampness feeling, and air humidity acceptability. We suspect that these differences are a result of the onset of sweating and increase in skin temperature that occur when metabolism is increased. However, these effects are dictated via heat balance and thermoregulation, and, therefore, they cannot be separated from effects due to humidity. We can say generally, though not with statistical support, that (a) the 90% RH condition was typically the least favorably rated, (b) the 80% RH condition was not apparently worse than the 60% or 70% condition, and (c) the 70% condition was frequently more favorably rated than the 60% condition. In addition, our data are consistent with ASHRAE 55a-1995 (ASHRAE 1995). Finally, for metabolic rates 1.6 met and above, we conclude that no practical limit on humidity will likely lower the percentage dissatisfied below 25%.

NOMENCLATURE

Symbol	Description	Units (if applicable)
AC	"Direct" acceptability	Yes/No
PAHUA	Air humidity acceptability	Yes/No
Clo	Clothing insulation	clo ($m^2 \cdot °C$ /W)
ET*	New effective temperature	°C
It	Total clothing insulation	clo
Met or M	Metabolic rate	W/m^2
MRT	Mean radiant temperature	°C
Pa	Water vapor pressure (ambient)	torr
Pm	Water vapor pressure (at skin)	torr
Pssk	Water vapor pressure (saturation)	torr
PMV	Predicted mean vote	Thermal sensation scale units
PPD	Predicted percent dissatisfied	%
RH	Relative humidity	%
SET*	New standard effective temperature	°C
Ta	Air temperature in workstation	°C
Top	Operative temperature	°C
TS	Thermal sensation	Scale units
Tsens	Predicted thermal sensation	Scale units
Tsk	Skin surface temperature	°C
Vel	Air velocity	m/s
W	Skin wettedness	Fraction

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