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Temperature and Humidity: Important Factors for Perception of Air Quality and for Ventilation Requirements

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ABSTRACT

A series of experiments was carried out to study the effect of temperature and humidity on the perception of indoor air quality. The study included both laboratory and controlled field experiments using an untrained sensory panel to judge the air quality at different levels of temperature and humidity. Facial and whole-body exposure for a short term (up to 20 minutes) was used in the laboratory study, and long-term whole-body exposure (up to 4.6 hours) was used in the field study. The study found a significant impact of temperature and humidity on the perception of indoor air quality. The air was perceived as less acceptable with increasing temperature and humidity, and the acceptability decreased linearly with increasing enthalpy of the air. Ventilation requirements for comfort can be significantly reduced by decreasing indoor air enthalpy.

INTRODUCTION

The temperature and humidity of indoor air have been widely recognized as factors that influence directly the thermal sensation of the human body (Fanger 1972). However, they were mainly considered to be indirect factors that influence perceived air quality due to their influence on indoor air pollution sources.

Many studies have been carried out to investigate the effect of humidity on human health and indoor air pollution, such as fungi, dust mites, particles, bacteria, viruses, pollutant emissions from building materials, respiratory and skin diseases, etc. So far, the direct impact of indoor air temperature and humidity on the perception of indoor air quality has not been emphasized, although it was pointed out by Yaglou et al. (1936) and indicated by several later studies (Kerka and Humphreys 1956; Andersson et al. 1975; Cain et al. 1983; Berglund and Cain 1989) that temperature and humidity may influence directly the perception of indoor air quality to a significant degree.

Recently, three experimental studies were carried out in Denmark. The studies investigated intensively the effect of temperature and humidity on the perception of air quality. The studies included a small-scale experiment with facial exposure in the laboratory, a full-scale experiment with short-term whole-body exposure in climate chambers, and a controlled longer-term field study in an office room. The results showed that both air temperature and humidity had a significant direct impact on the perception of air quality. The acceptability of air quality decreased linearly with increasing enthalpy of the assessed air. This effect may influence the ventilation requirements for comfort. This paper summarizes the three studies.

FACIAL EXPOSURE EXPERIMENT

Method

This experiment was carried out in a climate chamber using specially designed exposure equipment, consisting of 10 modified CLIMPAQs (chambers for laboratory investigations of materials, pollution, and air quality) (Gunnarsen et al. 1993; Fang et al. 1998a). The CLIMPAQ is a $1.005 \times 0.25 \times 0.22$ m^3 ($3.3 \times 0.82 \times 0.72$ ft^3) test box made of glass. Each of the modified CLIMPAQs had a diffuser to release the air for exposure to the subjects, and each of them was equipped with two independent air-conditioning systems, so that the temperature and humidity of the air inside the CLIMPAQs and released from the diffusers can be conditioned independently (see Figure 1).

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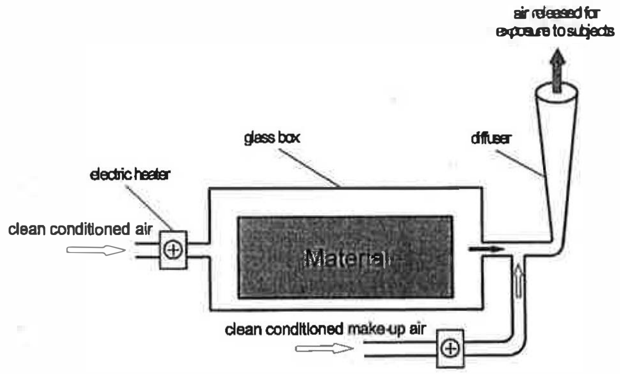


Figure 1 *Principle of the modified CLIMPAQ.*

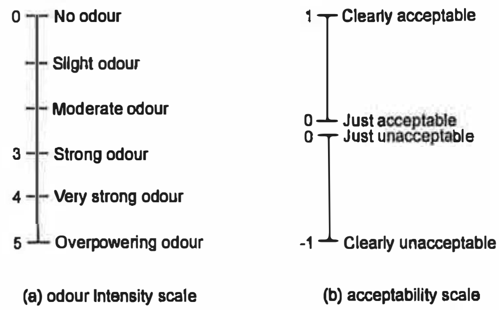


Figure 2 *Odor intensity and acceptability scales used by the sensory panel during the experiment.*

Five building materials were placed in the CLIMPAQs sequentially as pollution sources. They were PVC flooring, waterborne acrylic floor varnish, loomed polyamide carpet, waterborne acrylic wall paint, and acrylic sealant. The experiment tested the perception of air polluted by each building material at different levels of temperature and humidity. Each time, an equal amount of the same material was placed in each CLIMPAQ and was ventilated by an equal flow of clean outdoor air with the same temperature and humidity (23°C [73.4°F] and 50%RH); however, the air released from the diffuser for exposure was reconditioned at nine different combinations of three levels of temperature (18°C, 23°C, 28°C [64.4°F, 73.4°F, 82.4°F]) and three levels of humidity (30%, 50%, and 70% RH). Therefore, the assessed air had the same composition but a different temperature and humidity. The perception of odor intensity and acceptability of the polluted air released from the diffusers were judged by a group of 40 untrained subjects using the scales shown in Figure 2. The experimental procedure has been described in more detail by Fang et al. (1998a).

Results

Figures 3 and 4 show the sensory response surfaces fitted to the mean odor intensity and acceptability votes at the nine tested levels of temperature and humidity. The average standard deviation of the means (ASDM) is also given on each figure. The experiment found no significant impact of temperature and humidity on the perception of odor intensity of the air, as shown in Figure 3. However, it was found that temperature and humidity significantly influenced the acceptability of the air. The results obtained are presented in Figure 4. The response surfaces in Figure 4 show that the air was perceived as less acceptable with increasing temperature and humidity

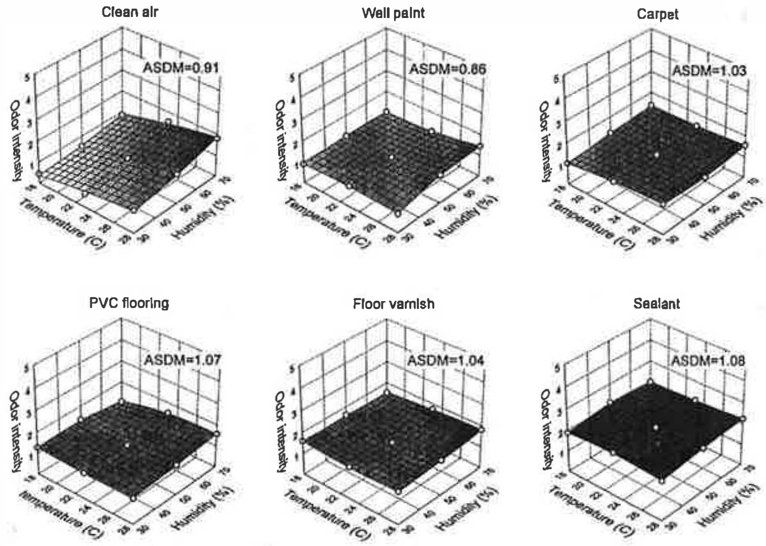


Figure 3 *Odor intensity of clean air and air polluted by the five building materials observed from facial exposure at different temperatures and humidities.*

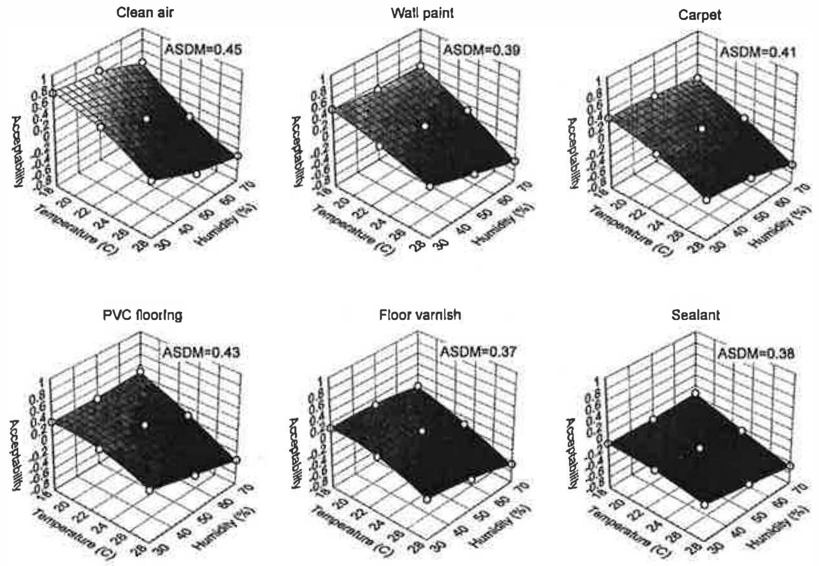


Figure 4 *Acceptability of clean air and air polluted by the five building materials observed from facial exposure at different temperatures and humidities.*

and that this impact was more pronounced with a decreasing level of air pollution (indicated by increased acceptability). Analysis of variance showed that the impact of both temperature and humidity on acceptability of the air is highly significant ($p < 0.002$) at all the pollution levels tested. Furthermore, the interaction of temperature and humidity is also significant at a level of $p < 0.05$. This interaction can be observed in Figure 4 as well. Within the temperature and humidity range tested, the effect of relative humidity on acceptability increased with increasing air temperature and vice versa.

WHOLE-BODY EXPOSURE EXPERIMENT

Method

The whole-body exposure experiment was designed to verify whether the impact of temperature and humidity on the perception of air quality, observed by facial exposure, was still valid when people adapted to the air to which they were exposed with their whole body. The experiments were conducted in two identical adjacent climate chambers designed for air quality studies (Albrechtsen 1988). The climate chambers were made of stainless steel with a volume of $3.6 \times 2.5 \times 2.55$ m^3 ($11.8 \times 8.2 \times 8.4$ ft^3) for each. To obtain good air quality, the air change rate for each chamber can reach 60 h^{-1} of outdoor air. The air in each of the twin chambers can be conditioned independently, and two different levels of air temperature and humidity in the two chambers can thus be established simultaneously.

The investigation comprised two experimental series. During the first experimental series, the two chambers were kept at different temperatures and humidities with the same ventilation rate of 420 L/s (890 cfm or 57 h^{-1}) clean outdoor air. The temperature and humidity in the two chambers were changed alternately every 20 minutes. The subjects were instructed to stay in one chamber for 20 minutes and were then asked to move to the other chamber. Each time the subjects moved from one chamber to the other, they experienced a step-change of temperature and/or humidity of the air. Their immediate assessment of the acceptability of the air and their assessments after 2.5, 5, 10, 15, and 20 minutes were made using the same scale as used in the facial exposure experiment. When the subjects stayed in one chamber, the temperature and humidity in that chamber were kept constant. Meanwhile, the temperature and humidity in the other unoccupied chamber was adjusted to prepare for the next 20-minute exposure; therefore, each 20-minute exposure was also a 20-minute prior exposure for the next 20-minute exposure.

In the second experimental series, the same procedure was used except that air pollution sources were introduced into one chamber to establish a higher pollution level. The ventilation rate in that chamber was decreased to 200 L/s (424 cfm or 27 h^{-1}) of clean outdoor air. PVC and acrylic sealant were used together as pollution sources. The emission of these two materials was found to be influenced less by air temperature and humidity (Fang et al. 1999b).

A total of 36 untrained subjects participated in the experiments. The subjects entered the chamber in groups of six and stayed for ten 20-minute exposure periods. After the subjects entered one chamber, they were encouraged to adjust their clothing whenever necessary so that their thermal neutrality was maintained. The experiment was performed in the same range of temperature and humidity as in the facial exposure experiment. More detailed experimental procedure is described by Fang et al. (1998b).

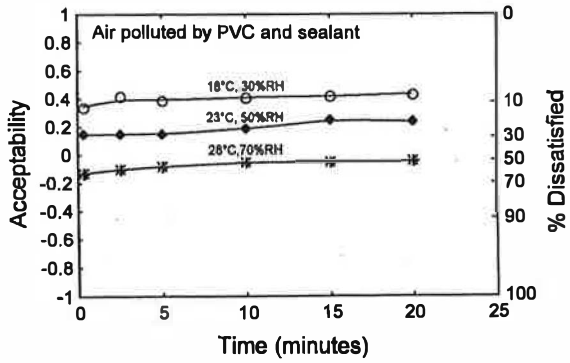


Figure 5 *Time course acceptability of air observed from the whole-body exposure chamber study at three levels of temperature and humidity.*

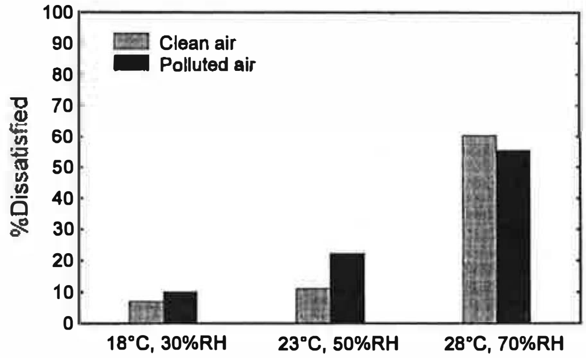


Figure 6 *Comparison of PD between clean and polluted air at three different combinations of temperature and humidity.*

Results

The whole-body exposure experiment also found a significant impact of temperature and humidity on the perception of air quality. Figure 5 shows the acceptability of the air during a 20-minute exposure. The air was polluted by PVC flooring and sealant at three levels of temperature and humidity. The figure shows a constant acceptability of air at each level of temperature and humidity during a 20-minute exposure, and the acceptability consistently decreased with increasing air temperature and humidity. Figure 6 shows the percentage of dissatisfied (PD) for both clean and polluted air at the three levels of temperature and humidity. The PD was elevated with increasing temperature and humidity, and the perceived air quality was mainly determined by air temperature and humidity when the air was warm and humid. The experiment also found that the odor intensity of the air polluted by the building materials was independent of the air temperature and humidity.

FIELD STUDY

Method

The observed impact of temperature and humidity on perceived air quality in laboratory studies was validated in a field study. The field study was carried out in a 36 m^2 (388 ft^2) office room that was equipped with a ventilating and air-conditioning system that can maintain constant temperature, humidity, and ventilation rate with a stability of ±0.3°C (±0.54°F), ±3%RH, and ±5%, respectively. To establish a moderate level of indoor air pollution, tufted bouclé carpet was used as the main pollution source. The carpet had been in use for 20 years and was taken from an office building with a history of occupant complaints.

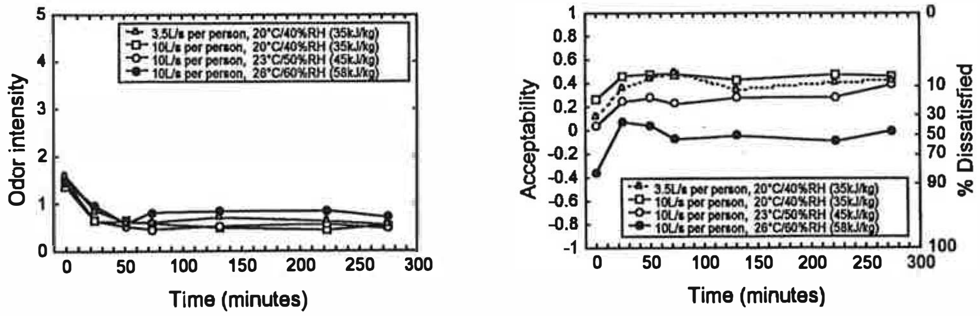
The experiment was conducted under four environmental conditions: three levels of indoor air enthalpy—35 kJ/kg (15 Btu/lb) at 20°C/40% RH, 45 kJ/kg (19 Btu/lb) at 23°C/50% RH, and 58 kJ/kg (25 Btu/lb) at 26°C/60% RH at a ventilation rate of 10 L/s (21.2 cfm) per person—and one extra condition at a low ventilation rate of 3.5 L/s (7.4 cfm) per person and a low indoor air enthalpy of 35 kJ/kg (15 Btu/lb) at 20°C/40% RH.

Thirty female subjects participated in the experiment. They were divided into five groups of six subjects. Each group participated in the experiment on the same weekday. On each experimental day, one group of subjects was exposed to one of the four indoor environmental conditions for 4.6 hours. The order of the environmental conditions inside the office in which the subjects were exposed was randomized.

During the experiment, the subjects were assigned to perform simulated office work and were asked to assess the air quality, thermal comfort, and irritation sensations in their eyes, nose, and throat, etc., upon entering the office and after 24, 51, 73, 132, 223, and 274 minutes of occupation. After the subjects had entered the office and assessed their first impression of the indoor environment, they were encouraged to adjust their clothing in order to maintain thermal neutrality throughout the whole period of occupation. The same scale as shown in Figure 2 was also used in this study to rate the perceived air quality. See Fang et al. (1999a) for more detailed experimental procedures.

Results

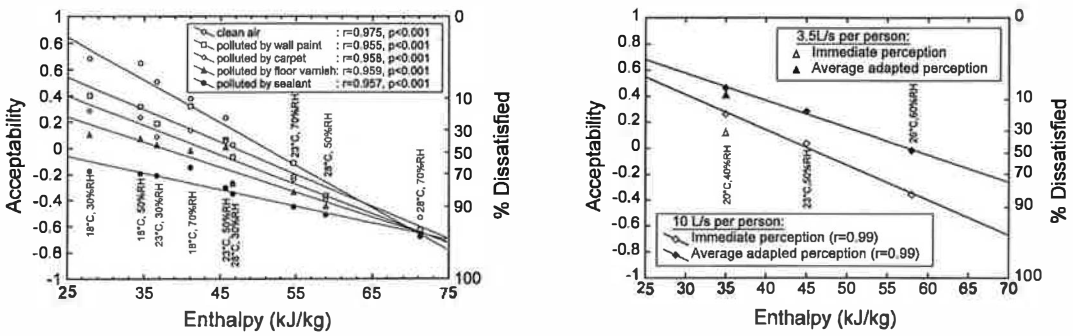
Figure 7 shows the time course perception of odor intensity and acceptability of the air quality at the three levels of indoor air temperature and humidity and two ventilation rates. The results show that air temperature and humidity do not affect significantly the perception of odor intensity and confirm the effect of temperature and humidity on the acceptability of air quality, as observed in the climate chamber studies. Figure 7b also shows that the perceived air quality improved after 30 minutes' exposure under all four different indoor environmental conditions. This improvement may be due to adaptation. However, by comparing the two figures in



(a) odor intensity perception

(b) acceptability perception

Figure 7 *Time course of odor intensity perception and acceptability of air observed from the whole-body exposure field study under different environmental conditions.*



(a) Facial exposure

(b) whole-body exposure

Figure 8 *Linear correlations between acceptability and enthalpy of the air observed from the facial exposure climate chamber study and the whole-body exposure field study.*

Figure 7, it seems that the adaptation of acceptability perception was due to the adaptation of odor intensity perception. The effect of air temperature and humidity on perception of acceptability of air quality did not diminish after adaptation, since both the acceptability of the first impression and the acceptability after adaptation showed a similar gradient with decreasing indoor air temperature and humidity.

Analysis of variance of the acceptability data at different levels of temperature and humidity showed that the effect of temperature and humidity on acceptability of air (both the first and the adapted perception) was statistically significant ($p < 0.05$). Figure 7b also shows that reducing the ventilation rate decreased acceptability for the first impression of the air ($p < 0.2$) at 20°C (68°F) and 40% RH but only slightly decreased acceptability after adaptation. However, even at the low ventilation rate of 3.5 L/s (7.4 cfm) per person, the air with a low temperature and humidity of 20°C (68°F) and 40% RH was still perceived as more acceptable compared to the air with higher levels of temperature and humidity at the higher ventilation rate of 10 L/s (21.2 cfm) per person.

All three experiments found that the acceptability of the air decreased linearly with increasing enthalpy of the air. The highly significant linear correlations between enthalpy and acceptability of the air, obtained from the facial experimental study and the field study, are shown in Figure 8. It can be observed from Figure 8 that the impact of enthalpy on perceived air quality became stronger when the air was less polluted. Adaptation may improve the perception of air quality, but the impact of enthalpy seems equally strong for perception of the air quality both before and after adaptation.

DISCUSSION

The present studies showed that the decrease in perceived air quality (acceptability of the air) due to increasing air temperature and humidity was not caused by increased odor intensity of the air. A cooling effect in the respiratory tract may help to explain the reason. It is well known that chemical pollutants influence perception of the air by acting directly on the olfactory and chemical sense and lead to the perception of odor or irritation. Temperature and humidity, however, change the energy content of the inspired air and provide a changed cooling of the respiratory tract. In general, the effect of the thermal exchanges on inhalation is to cool the mucosa if the temperature of the inhaled air is below the mucosal temperature, which is normally at a level of 30°C (86°F) to 32°C (89.6°F). This cooling process includes both sensible and latent heat transfer. Therefore, the total heat transfer was determined by enthalpy of the inhaled air. With a high indoor air enthalpy, an insufficient cooling may be interpreted as a local warm discomfort in the respiratory tract and lead to the inhaled air being perceived as unacceptable.

Recently, Toftum et al. (1998) studied jointly the respiratory thermal sensation and the perceived comfort due to respiratory cooling. The experiment led to almost the same results as those of the present study. A similar linear correlation between air freshness and enthalpy was observed by Berglund and Cain (1989). The present study further indicated that when the respiratory cooling effect decreases to a certain level, the air will be perceived as very poor whether it is clean or polluted, and increasing the ventilation rate would be a waste of energy without a significant improvement in perceived air quality. In this case, decreasing air temperature and humidity would succeed whereas increasing the ventilation rate could fail to achieve acceptable air quality.

Ventilation is required in order to obtain a comfortable and healthy indoor environment. For nonindustrial buildings, comfort usually determines the required ventilation rate. The ventilation rates prescribed in existing ventilation standards (e.g., CEN 1998 and ASHRAE 1999) do not include the impact of air temperature and humidity. In ASHRAE Standard 62 (ASHRAE 1999), the ventilation requirement for office spaces is determined as 10 L/s (21.2 cfm) per person. The European Design Criteria (CEN 1998) suggest a minimum ventilation requirement of 4 L/s (8.5 cfm) per person to obtain a perceived air quality of 2.5 dp (30% PD). However, results presented in Figure 7b show that with a ventilation rate of 10 L/s (21.2 cfm) per person, the air was perceived as unacceptable on first impression, with 40% and 85% dissatisfied (PD) at 23°C/50% RH (73.4°F/50% RH) and 26°C/60% RH (78.8°F/60% RH), respectively. After adaptation, about 50% of the occupants still found the air unacceptable at 26°C/60% RH (78.8°F/60% RH). At 20°C/40% RH (68°F/40% RH), however, both immediate and adapted perception of the air quality was improved to 19% and 8% PD, which fits quite well with the European Design Criteria (CEN 1998).

Figure 7b shows further that decreasing the ventilation rate from 10 to 3.5 L/s (21.2 to 7.4 cfm) per person can be compensated for by decreasing indoor air enthalpy from 45 kJ/kg (19 Btu/lb) at 23°C/50% RH to 35 kJ/kg (15 Btu/lb) at 20°C/40% RH so as to avoid deteriorating perceived air quality. The present field study also found that decreasing the ventilation rate from 10 to 3.5 L/s (21.2 to 7.4 cfm) per person at 20°C/40% RH (68°F/40% RH) did not increase irritation symptoms. The questionnaire survey for different SBS symptoms showed that after working for 4.6 hours, headache and fatigue symptoms became more severe at the high levels of room air temperature and humidity compared to the symptoms reported at the lower levels of air temperature and humidity, even though thermal comfort was maintained. More severe headache and fatigue symptoms were reported at 23°C/50% RH (73.4°F/50% RH) and 26°C/60% RH (78.8°F/60% RH) with a high ventilation rate of 10 L/s (21.2cfm) per person than at 20°C/40% RH (68°F/40% RH) with a low ventilation rate of 3.5 L/s (7.4 cfm) per person.

These results indicate the importance of the indoor air temperature and humidity in determining the ventilation requirement and the great potential that exists for reducing the ventilation rate by decreasing the indoor air temperature and humidity. Recently, a case study by Liu et al. (1999) provided data from the field in practice. They found that decreasing peak room relative humidity in an office building from 70% to 55% and simultaneously reducing the total outside airflow by 86% significantly improved comfort conditions for the office workers and saved 27% of the building's energy consumption.

A decrease in air humidity will increase moisture loss from the skin and mucous membranes; therefore, it is usually believed that low air humidity will lead to a sensation of dryness, which is one of the most common SBS symptoms. However, it has been documented (Andersen et al. 1974; Andersson et al. 1975; Sundell and Lindvall 1993) that a sensation of dryness may be related not only to air humidity but also to the air temperature and indoor air pollutants. The present experimental results appear to agree with these previous findings, indicating that indoor air pollutants may contribute to certain symptoms that are similar to a dry sensation.

Figure 9 shows the assessment of the air humidity at two levels of ventilation rate with the same enthalpy and at two levels of enthalpy with the same ventilation rate. For the first impression, the air with lower humidity and temperature was felt to be drier than the air with higher temperature and humidity, but the air with the same temperature and humidity was

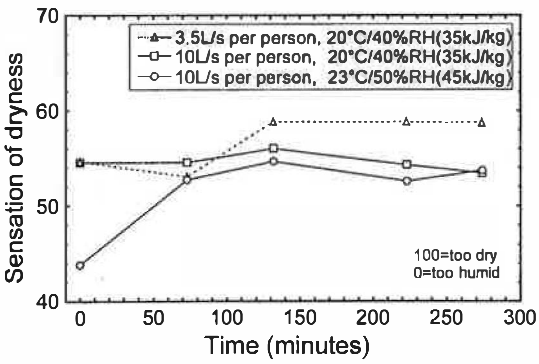


Figure 9 *Time course of dry sensation of air observed from the whole-body exposure field study at different levels of temperature, humidity, and ventilation rate.*

perceived to have the same humidity at the two levels of ventilation rate. However, after two hours' exposure, the subjects could not distinguish the different humidities at the same ventilation rate, and the air was perceived to be drier at the low ventilation rate than at the high ventilation rate, even though the physical humidity and temperature were the same.

These results showed that decreasing the ventilation rate may increase the sensation of dryness. In contrast, decreasing the humidity did not increase the sensation of dryness after a longer exposure. However, the lowest humidity level (40% RH at 20°C [68°F]) tested in the present experiment is still a moderate level. For exposure to an even lower level of humidity, the study by Andersen et al. (1974) showed that there was no significant impact of low humidity on physiological impairment of the human body and subjective sensations of discomfort after 78 hours' exposure to clean dry air at 9% RH. The low limit of humidity for human exposure may be affected by air pollution and vary with people from different climatic areas. Such a limit is still unclear and needs to be further investigated.

CONCLUSIONS

- Air temperature and humidity have a significant impact on both the immediate and the adapted perception of indoor air quality.
- Decreasing the indoor air temperature and humidity improved the perceived air quality significantly; the acceptability of air increased linearly with decreasing enthalpy of air.
- Ventilation required for comfort may be significantly reduced when decreasing indoor air enthalpy.

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REFERENCES

Albrechtsen, O. 1988. Twin climatic chambers to study sick and healthy buildings. *Proceedings of Healthy Buildings '88, Stockholm*, vol. 3, pp. 25-30.

Andersen, I., G.R. Lundqvist, P.L. Jensen, and D.F. Proctor. 1974. Human response to 78 hour exposure to dry air. *Arch. Environ. Health* 29: 319-324.

Andersson, L.O., P. Frisk, B. Lofstedt, and D.P. Wyon. 1975. *Human response to dry, humidified and intermittently humidified air in large office buildings.* Swedish Building Research, LiberTryck Stockholm.

ASHRAE. 1999. *ANSI/ASHRAE Standard 62-1999, Ventilation for acceptable indoor air quality.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Berglund, L., and W.S. Cain. 1989. Perceived air quality and the thermal environment. *Proceedings of IAQ '89, The Human Equation: Health and Comfort*, pp. 93-99. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Cain, W.S., B.P. Leaderer, R. Isseroff, L.G. Berglund, R.J. Huey, E.D. Lipsitt, and D. Perlman. 1983. Ventilation requirements in buildings. I. Control of occupancy odour and tobacco smoke odour. *Atmospheric Environment* 17: 1183-1197.

CEN. 1998. *Ventilation for buildings—Design criteria for the indoor environment.* European Committee for Standardization, CR 1752.

Fang, L., G. Clausen, and P.O. Fanger. 1998a. Impact of temperature and humidity on the perception of indoor air quality. *Indoor Air* 8 (2): 80-90.

Fang, L., G. Clausen, and P.O. Fanger. 1998b. Impact of temperature and humidity on perception of indoor air quality during immediate and longer whole-body exposures. *Indoor Air* 8 (4): 276-284.

Fang, L., P. Wargocki, T. Witterseh, G. Clausen, and P.O. Fanger. 1999. Field study on the impact of temperature, humidity and ventilation on perceived air quality. *Proceedings of Indoor Air '99, Edinburgh*, vol. 2, pp.107-112.

Fang, L., G. Clausen, G. and P.O. Fanger. 1999. Impact of temperature and humidity on chemical and sensory emissions from building materials. *Indoor Air* 9 (3): 193-201.

Fanger, P.O. 1972. *Thermal comfort.* New York: McGraw-Hill.

Gunnarsen, L., P.A. Nielsen, and P. Wolkoff. 1993. Design and characterisation of the CLIMPAQ, chamber for laboratory investigations of materials, pollution and air quality. *Proceedings of Indoor Air '93, Helsinki*, vol. 2, pp. 507-512.

Kerka, W.F., and C.M. Humphreys. 1956. Temperature and humidity effect on odour perception. *ASHRAE Transactions* 62: 531-552.

Liu, M, Y. Zhu, B.Y. Park, et al. 1999. Airflow reduction to improve building comfort and reduce building energy consumption—A case study. *ASHRAE Transactions* 105 (1): 384-390.

Sundell, J., and T. Lindvall. 1993. Indoor air humidity and sensation of dryness as risk indicators of SBS. *Indoor Air* 3: 382-390.

Toftum, J., A.S. Jørgensen, and P.O. Fanger. 1998. Effect of humidity and temperature of inspired air on perceived comfort. *Energy and Buildings* 28 (1): 15-23.

Yaglou, C.P., E.C. Riley, and D.I. Coggins. 1936. Ventilation requirements. *ASHVE Transactions* 42: 133-162.