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Air movement – good or bad?

Abstract Air movement – good or bad? The question can only be answered by those who are exposed when they are exposed. Human perception of air movement depends on environmental factors including air velocity, air velocity fluctuations, air temperature, and personal factors such as overall thermal sensation and activity level. Even for the same individual, sensitivity to air movement may change from day to day as a result of, e.g., different levels of fatigue. Based on existing literature, the current paper summarizes factors influencing the human perception of air movement and attempts to specify in general terms when air movement is desirable and when it is not. At temperatures up to 22–23°C, at sedentary activity and with occupants feeling neutral or cooler there is a risk of air movement being perceived as unacceptable, even at low velocities. In particular, a cool overall thermal sensation negatively influences the subjective perception of air movement. With occupants feeling warmer than neutral, at temperatures above 23°C or at raised activity levels, humans generally do not feel draught at air velocities typical for indoor environments (up to around 0.4 m/s). In the higher temperature range, very high air velocities up to around 1.6 m/s have been found to be acceptable at air temperatures around 30°C. However, at such high air velocities, the pressure on the skin and the general disturbance induced by the air movement may cause the air movement to be undesirable.

J. Toftum
International Centre for Indoor Environment and Energy, Technical University of Denmark, Lyngby, Denmark

Key words: Air movement; Air velocity; Draught; Temperature; Human perception

Dr Jørn Toftum
International Centre for Indoor Environment and Energy, Technical University of Denmark, Niels Koppels Allé, DTU, Building 402, 2800 Kongens Lyngby, Denmark
e-mail: jt@mek.dtu.dk
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Practical implications
Based on existing literature, the paper summarizes factors influencing the human perception of air movement and attempts to specify in general terms when air movement is desirable and when it is not.

Introduction

In ventilated and air-conditioned spaces, air movement considerably impacts occupants' thermal sensation and comfort, both locally and for the body as a whole. The effects of air movement on human comfort have had the attention of thermal comfort researchers for the past 60–70 years (e.g., Houghten et al., 1938). At the Technical University of Denmark, research on the human perception of air movement was initiated by Professor P.O. Fanger in the 1960s. Since then, numerous studies have been carried out on his initiative and under his supervision (e.g., Fanger et al., 1970; Fanger et al., 1974; Fanger & Pedersen, 1977; Fanger & Christensen, 1986; Fanger et al., 1988). Based on these studies, methods for the assessment of comfort effects of air movement were developed. These methods are now the basis for the design of air movement and indoor environments in general and have been included in national, European and international indoor environment standards and guidelines (DS 474, 1993; ASHRAE 55, 2004; CEN CR 1752, 1998; ISO 7730, 1994).

Thermal indices such as predicted mean vote (PMV), PPD, TSENS, DISC, and SET* all incorporate air movement in the calculation of thermal sensation and discomfort, based on overall heat balances for the human body (Fanger et al., 1970; Gagge et al., 1971; Gagge et al., 1986). Most HVAC systems are designed to provide a uniform environment within the occupied zone in order to attain an average overall thermal sensation for all occupants around neutral. At high heat loads, air movement can increase the cooling effect and maintain thermal comfort at elevated temperatures. This may result in reduced consumption of energy used to cool a building compared with general air conditioning, but requires individual control of the local air velocity by each occupant. In cool and moderate indoor environments, as for instance in Scandinavia or similar climatic regions, increased air velocity may result in local cooling of the skin, a cooler thermal sensation and higher discomfort.

To determine whether air movement is good or bad, subjective statements by humans are required. Both in buildings in practice and in laboratory studies, inter-individual differences cause some persons to perceive air movement as pleasant while others complain of draught at the same velocity and temperature. Thus, the perception of air movement depends not only on the air velocity and other thermal environment parameters, but also on personal factors such as activity level, overall thermal sensation and clothing. Based on the existing literature, this paper summarizes factors that influence human perception of air movement and attempts to specify in general terms when air movement is desirable and when it is not.

Moderate and cool environments

Under cool and moderate conditions draught is a frequent concern when designing indoor environments. Draught has been defined as an unwanted, local cooling of the skin caused by air movement. The convective cooling rate and thus the draught rating depend on the local air velocity and air temperature as demonstrated in numerous experimental studies (e.g., Houghten et al., 1938; Fanger & Pedersen, 1977; McIntyre, 1979; Fanger & Christensen, 1986; Fanger et al., 1988).

Not only the mean air velocity, but also the air velocity fluctuations affect the dynamic response of the thermal sensors in the skin and the draught rating. Fanger and Pedersen (1977) showed that maximum discomfort was experienced when the air velocity fluctuated at a frequency between 0.3 and 0.5 Hz. This was confirmed by Zhou and Melikov, 2002; Zhou et al., 2002, who found an equivalent frequency in the range 0.2 Hz to 0.6 Hz to be the most uncomfortable. The equivalent frequency of a randomly fluctuating air velocity was defined as the frequency of sinusoidal velocity fluctuations with the same ratio of the standard deviation of acceleration to the standard deviation of air velocity as in the random velocity fluctuations. Measurements in mechanically and naturally ventilated offices showed that more than 60% of the measurements resulted in an equivalent frequency in the range 0.3–0.5 Hz (Zhou and Melikov, 2002; Zhou et al., 2002). Melikov et al. (1988) showed that both the mean air velocity and the turbulence intensity were lower in the occupied zone of naturally ventilated spaces than in mechanically ventilated spaces. The turbulence intensity in naturally ventilated spaces varied in the range 10% to 30% and in the range 20% to 40% in mechanically ventilated spaces. Also, the turbulence intensity was lower in spaces with displacement ventilation than in spaces with mixing ventilation or in heated rooms without mechanical ventilation (Melikov et al., 1990).

The effect of air velocity fluctuations on perceived discomfort may be explained by the discharge of impulses from the cold receptors in the skin. When exposed to air movement that causes a fluctuating, local cooling of the skin, the cutaneous cold receptors in exposed areas will respond with a high frequency of impulses due to the transient overshoot in receptor output at skin temperature fluctuations. An effect of turbulence intensity on draught discomfort was identified (Mayer, 1987; Fanger et al., 1988) and incorporated into a model that predicts the percentage of dissatisfied due to draught (DR) as a function of mean air velocity ($\bar{v}$), air temperature (t_a) and turbulence intensity (Tu) (Fanger et al., 1988):

$$DR = (34 - t_a) \cdot (\bar{v} - 0.05)^{0.62} \cdot (0.37 \cdot \bar{v} \cdot Tu + 3.14) \quad (\%)$$

The draught model is valid for sedentary, thermally neutral persons dressed in normal indoor clothing. Occupant responses recorded during field studies in different climatic regions have indicated that occupants were less sensitive to air movement than the model predicted and that a substantial number even preferred higher air velocities under warm conditions (Schiller et al., 1988; de Dear & Fountain, 1994; Donini et al., 1997; Cena & de Dear, 1999). As a consequence, ASHRAE in 1998 initiated research to evaluate the draught criteria in current indoor environment standards and guidelines (Toftum et al., 2002). The study found that several factors could have caused the discrepancy between occupant responses and the recommendations of the standards regarding air movement.

At higher activity levels, humans are less sensitive to air movement (Jones et al., 1986; Toftum & Nielsen, 1996a; Griefahn & Künemund, 2001). The average metabolic rate observed in the field studies was higher (1.2 met) than during the laboratory experiments (1 met). Persons engaged in sedentary activity such as office work typically have a metabolic rate around 1.2 met. An extension of Fanger's draught model has been suggested that addresses the effect of workload in the prediction of draught discomfort (Toftum, 1994a). The model specifies that the maximum recommendable air velocity increases considerably with the workload and that persons occupied at high activity levels can be exposed to rather high air velocities without feeling draught. The extension of the model was later adjusted by Griefahn et al. (2001) to account for effects of clothing and experimental procedure applied in the two studies.

Overall thermal sensation impacts the local draught sensation. The draught model applies to thermally neutral persons, but often building occupants feel slightly cool or slightly warm, which will shift their sensitivity to air movement to a higher or lower level, respectively. Toftum and Nielsen (1996b, 2003) found that a decrease in thermal sensation of 1 scale unit on the 7-pt scale from neutral resulted in 2–3 times higher

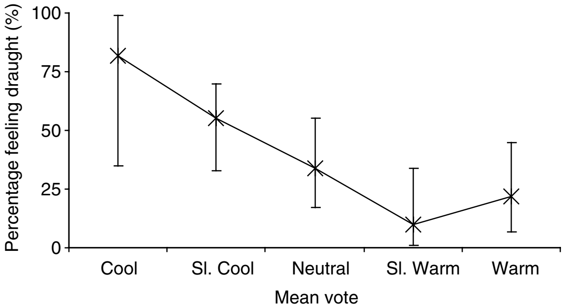

Fig. 1 Percentage of persons feeling draught as a function of their thermal mean vote. Error bars show 95% upper and lower confidence limits (from Toftum, 1994b).

percentage of draught dissatisfied. Although based on a limited number of occupant responses (100), Fig. 1 shows that persons feeling cool or slightly cool complained of draught more than those feeling neutral or warm (Toftum, 1994b). Occupant responses were recorded in nine industrial spaces including a printing house, large-scale kitchens, a fresh food storage facility, fish processing plants and an iron manufacturing plant.

Also the direction of the airflow impacts the draught sensation. Zhou (1999) and Mayer and Schwab (1988) showed that at equal air velocity airflow from below resulted in the highest percentage of subjects dissatisfied due to draught, whereas airflow from above resulted in the least percentage of dissatisfied subjects. Toftum et al. (1997) noted that the effect of the airflow direction depended on the air temperature. At the lower temperatures used in this experimental study (20°C and 23°C) most subjects perceived discomfort when exposed to air movement from below, whereas at 26°C most subjects perceived discomfort with air movement from above. At 26°C the rising natural convection flow caused by the temperature difference between the subjects' surface and the air was weaker than at lower air temperatures.

Warmer environments

Numerous laboratory studies have investigated overall thermal sensation and comfort when air movement was used to compensate for high air temperatures, both at low and high turbulence intensities. At air temperatures up to 28°C, thermal comfort could be created or discomfort reduced at air velocities around 0.8 m/s (Fanger et al., 1974; McIntyre, 1978). Above this temperature, the air velocities required to reduce warm discomfort produced too much disturbance. Nevertheless, Rohles et al. (1983) and Scheatzle et al. (1989) demonstrated that if the air movement was created by a ceiling fan, the acceptable air velocities could be extended to an effective temperature of 29°C at 1 m/s with comfort remaining the same as at lower temperatures and still air. However, none of these studies explicitly addressed air movement acceptability, but focused mostly on overall thermal sensation and comfort.

Even higher air velocities, up to 1.6 m/s at a modified temperature of 31°C, were preferred by Japanese subjects when exposed to a range of hot environments (Tanabe et al., 1987). Modified temperature was defined as the ambient temperature connected to the equivalent condition at 50% rh and 0.1 m/s air velocity, according to the PMV-model, that would be felt equally warm by a subject wearing 0.6 clo. With air velocities fluctuating according to different fluctuation patterns (sine wave, constant, random, pulse), Kimura et al. (1993) showed that fluctuating air movement of a sine wave nature made the subjects feel cooler than did other fluctuation patterns. Kimura and Tanabe (1993) presented a relationship between air velocity and operative temperature that takes into account the effect of air movement on clothing insulation and skin wettedness. The relationship shows that increasing the relative humidity at high temperatures suppresses evaporative cooling; higher air velocities are thus required to maintain the thermal sensation.

With results collected from a range of field studies on thermal comfort conducted in all parts of the world, a database with matched pairs of thermal environment measurements and occupant responses has been developed (de Dear, 1998). Data from each study was classified according to measurement reliability, and the four ASHRAE field studies (Schiller et al., 1988; de Dear & Fountain, 1994; Donini et al., 1997; Cena & de Dear, 1999) belong to the highest category, where laboratory grade instrumentation was used to measure temperature, air velocity and turbulence at several heights at each occupant's workstation. Unfortunately, the distribution of air velocities measured during these field studies was skewed towards rather low values. Thus, out of a total number of 5653 observations, only 8% resulted in air velocities higher than 0.2 m/s, 3% higher than 0.25 m/s and 2% higher than 0.3 m/s. This alone may explain why occupants under warm conditions frequently expressed a desire for more air movement rather than complained of draught.

Table 1 presents air movement preference as observed in the four ASHRAE field studies. Only metabolic rates in the range 1.1 met to 1.4 met and temperatures in the range 22.5°C to 23.5°C were included in the analysis. At higher temperatures too few responses were recorded to provide a meaningful analysis. Data were grouped according to air velocities measured at 1.1 m above the floor in the ranges: 0–0.15 m/s and 0.15–0.25 m/s. At higher air velocities all data were excluded since each bin contained fewer than 20 observations. Finally, data were binned also according to observed thermal sensation.

More occupants feeling slightly warm preferred more air movement than occupants feeling slightly cool, and

Table 1 Air movement preference as observed in the four ASHRAE field studies (Schiller et al., 1988; de Dear & Fountain, 1994; Donini et al., 1997; Cena and de Dear, 1999)

Thermal sensation	Air velocity range (m/s)	Percent of occupants preferring			
Less	No change	More	N_{obs}		
Slightly cool	0–0.15	13.6	46.3	40.1	147
	0.15–0.25	16.7	41.7	41.6	48
Neutral	0–0.15	2	46	52	150
	0.15–0.25	2	68.6	29.4	51
Slightly warm	0–0.15	2.7	21.9	75.4	73
	0.15–0.25	8.4	33.3	58.3	24

Only data in the temperature range 22.5°C to 23.5°C were included in the table. Field data downloaded from the ASHRAE RP-884 "The adaptive thermal comfort model" database (de Dear, 1998).

in general only a modest percentage of the persons feeling neutral or slightly warm preferred less air movement. However, rather many occupants feeling slightly cool preferred more air movement despite the fact that more air movement would make them feel even cooler. The responses in Table 1 were obtained under moderate temperature conditions, where complaints of draught and a preference of less air movement were expected. Yet only few occupants complained of draught at these low air velocities.

Based on their experiments with occupant controlled air movement, Fountain et al. (1994).

Defined an index of Predicted Percent Satisfied (PS) as the fraction of a sample of persons that prefer a certain level of air velocity or lower at a particular air velocity and operative temperature. PS was expressed as:

$$PS = 1.13 \cdot t_o^{0.5} - 0.24 \cdot t_o + 2.7 \cdot \bar{v}^{0.5} - 0.99 \cdot \bar{v} \quad \text{(fraction)}$$

where t_o and $\bar{v}$ are operative temperature (°C) and mean air velocity (m/s), respectively.

The PS model can be used to predict the percent of satisfied persons in an office environment when locally controlled air movement is available. The model was developed based on experiments carried out in the upper temperature range of the comfort zone and above (25.5°C –28.5°C). A comparison of predictions made with the DR and the PS model is not valid because of the different assumptions concerning temperature and control of air movement.

In order to study whether thermal comfort attained at high air temperature and velocity was subjectively preferable to thermal comfort at low air velocity and moderate temperature, Toftum et al. (2002) in two adjacent climate chambers exposed subjects to such different thermal environments. Subjects had to state their preference for an environment at 26°C, 0.2 m/s and elevated temperature conditions at 28°C, 0.6 m/s or 29.5°C, 1.4 m/s in a second experiment. In both experiments, the subjects stated their preference twice: when they went from the moderate to the elevated temperature conditions and when they returned.

The moderate environment was preferred by the subjects rather than the environment with high temperature and velocity, but when subjects were delegated individual control of the air velocity, the comfort and thermal sensation votes in the elevated environment did not differ from the votes cast in the moderate environment. These results confirm the importance of individual control of the air velocity. However, the range of air velocities preferred by the subjects was very wide (0.35 m/s to 1.35 m/s at 28°C and 0.55 m/s to 1.85 m/s at 29.5°C).

Discussion

Under many different conditions, the effects of air movement on comfort have been investigated. If air movement is good or bad depends not only on the thermal environment, but also on personal factors such as activity level and overall thermal sensation. Furthermore, the answer may be complicated by other factors such as sex and the clothing habits related to sex as well as the degree of fatigue. Griefahn and Künemund (2001) found that women felt cooler and were more sensitive to draught than men and that draught discomfort was higher in tired than in alert persons. However, other studies did not identify an effect of sex on draught (e.g., Fanger et al., 1988; Toftum et al., 2002). In the following an attempt is made to characterize human perception of air movement based on the referenced studies.

At temperatures up to 22–23°C, at sedentary activity and with occupants feeling neutral or cooler there is a risk of air movement being perceived as unacceptable, even at low velocities. In particular, a cool overall thermal sensation negatively influences the subjective perception of air movement. With occupants feeling warmer than neutral, at temperatures above 23°C or at raised activity levels, humans generally do not feel draught at air velocities most typical for indoor environments (up to around 0.4 m/s). In the higher temperature range, very high air velocities up to around 1.6 m/s have been found to be acceptable at air temperatures around 30°C. However, at such high air velocities, the pressure on the skin and the general disturbance induced by the air movement may cause discomfort in itself. It is also important when local air movement is used to offset elevated temperatures that it is under the control of each exposed occupant. Even though it has been proven possible to maintain thermal comfort and sensation by high air velocity at elevated temperatures, subjects' dominant preference was for lower air velocity and a temperature in the comfort range.

In buildings in practice, numerous factors will influence whether occupants find air movement good or bad. To accommodate all occupants, general air movement should be designed for low velocities. To provide comfort for occupants who prefer higher air velocities, local air movement under individual control can easily be created, e.g. by a desk fan.

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