Building and Environment 96 (2016) 228–236

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Sensation of draft at uncovered ankles for women exposed to displacement ventilation and underfloor air distribution systems

Stefano Schiavon [a,*], Donghyun Rim [b,c], Wilmer Pasut [a], William W Nazaroff [b]

[a] Center for the Built Environment, University of California Berkeley, CA, USA
[b] Department of Civil and Environmental Engineering, University of California Berkeley, CA, USA
[c] Architectural Engineering Department, Pennsylvania State University, University Park, PA 16802, USA

A R T I C L E I N F O

Article history:
Received 2 September 2015
Received in revised form
27 October 2015
Accepted 10 November 2015
Available online 17 November 2015

Keywords:
Thermal comfort
Air movement
Draught (draft)
Displacement ventilation
Underfloor air distribution (UFAD)

A B S T R A C T

Draft is defined as unwanted local convective cooling. Existing draft risk models, developed in the 1970s, focus on air movement at the neck. The purpose of the present study is to experimentally evaluate ankle draft risk for women with uncovered ankles because of current widespread use of displacement ventilation and underfloor air distribution systems and changes in dress customs. Thirty female university students participated in nine double-blind randomized tests. The subjects wore sandals with lower legs, ankles and feet uncovered. Exposures occurred in an environmental chamber resembling an office environment. The operative temperature at 1.1 m above the floor was maintained at 24.1 °C. The measured air speeds at the ankle varied between 0.16 and 0.59 m/s and the air temperature at the ankle varied between 18.0 and 21.7 °C. Subjective responses were obtained to assess these parameters: thermal acceptability, comfort, preference and sensation, air movement acceptability and preference, local thermal sensation and comfort, and perceived air quality. Subjects were more sensitive to ankle draft than expected. For all the tested conditions, between 20 and 37% of the subjects found the overall thermal environment not acceptable, while between 23 and 57% of the subjects found air movement at the ankle unacceptable. These dissatisfaction percentages are higher than those of international, American and European standards, indicating the need to develop a draft risk model for displacement ventilation and underfloor air distribution systems.

1. Introduction

Draft is defined as unwanted local convective cooling of the body caused by air movement [1]. McIntyre [2] gave a broader definition of draft, describing it as an unwanted local cooling of the body. However, this broader definition, including also the effect of radiant heat transfer, has never been adopted in thermal comfort standards.

The main factors that affect draft are air temperature and air speed [1,3,4], air turbulence [5,6], metabolic rate [7,8], body parts exposed and their clothing insulation level, and overall thermal comfort and sensation [4,9–12]. The characteristics of air velocity fluctuation (e.g. turbulence, spectral frequency, etc.) are also factors that may affect draft [13,14].

International [15] and European [16] thermal comfort standards specify permissible air speeds as a function of air temperature and turbulence intensity to avoid more than a certain percentage of persons dissatisfied owing to draft. The draft-risk criterion is based on the model developed by Fanger et al. [6], focusing on draft perceived at the rear neck. Fanger's draft-risk model was included in prior versions of ASHRAE Standard 55 [17], but has been absent since the 2010 release because it overestimates the percentage of unsatisfied people. Toftum et al. [11], based on human-subject tests, showed that there is a discrepancy between the percentage of subjects who were dissatisfied owing to draft and the number estimated by the model. This difference was most likely caused by lower-than-neutral thermal sensation of subjects during the original draft-risk tests conducted by Fanger. McIntyre [9] showed, based on human subject tests in a laboratory, that draft is linked to person's pre-existing feeling of warmth or cold. Air movement in air-conditioned and naturally ventilated spaces assumes a different connotation depending on a subject's thermal sensation. The same breeze that provides relief for subjects feeling warm can be perceived as a draft for those who feel cool. Toftum [12] has

* Corresponding author. Center for the Built Environment, University of California Berkeley, 390 Wurster Hall, Berkeley, CA 94720-1839, USA.
E-mail address: stefanoschiavon@berkeley.edu (S. Schiavon).

http://dx.doi.org/10.1016/j.buildenv.2015.11.009
0360-1323/

described this dualistic aspect of air movement and its underlying causes.

According to the experiments performed by Fanger [18] subjects were found to be significantly less draft-sensitive on their unclothed ankles than on the neck. No difference was found between the draft sensitivity of men and women. Historically, the literature on draft focused on thermal discomfort at the neck, in part because most mechanical systems supplied air from ceiling diffusers. In modern buildings, however, it is less appropriate to characterize draft risk only at the neck level. The advent of alternative air distribution systems, such as underfloor air distribution (UFAD) and displacement ventilation (DV), and the possibility of downdraft generated by large glass façades when outdoor temperatures are low makes it necessary also to investigate the draft effect for other body parts, such as ankles [19–21].

A field survey of 227 occupants' response to the indoor environment in ten Danish office buildings with displacement ventilation showed that 24% complained that they were daily bothered by draft, mainly at the lower leg [22]. A study with smaller sample size (33 occupants) in a Canadian office building conditioned with a UFAD system did not show issues related to draft at the ankles [23]. Draft risk at the ankle was also not found in a lab study utilizing 33 human subjects considering UFAD systems in which air speeds at the feet area were kept below 0.1 m/s [24].

In 1938, Houghten et al. found that equal declines in skin temperature at the neck and at the ankles produced equal discomfort sensations [3]. However, since the subjects were wearing trousers, socks and shoes, the air temperature at the ankle level had to be lower and the air velocity higher than at the neck level to obtain the same reduction in skin temperature. Nowadays, owing to the widespread use of UFAD systems and also to shifts in common dress codes that allow for uncovered ankles in offices, a new need has emerged for an assessment of draft risk at the ankles [25–28].

There are few scientific data available on the optimal operating conditions (air speed and temperature) for design of displacement ventilation and underfloor air distribution systems. The REHVA guidebook on displacement ventilation recommends keeping people outside the area near a diffuser in which the air speed is higher than 0.15 m/s in winter and 0.25 m/s in summer [20]. In this document, guidance is lacking about discharge temperatures or about the fact that people might have either covered or uncovered lower legs. In the study reported herein, we want to focus on conditions with high draft risk, i.e., for women with uncovered lower legs, ankles and feet. It is established that females are more likely than males to express thermal dissatisfaction, especially in cooler conditions [29], and that they are more likely to dress with slightly less thermal insulation than males during summer [30], including the common practice of having their lower legs uncovered.

The purpose of the present study is to experimentally evaluate ankle draft risk for women with uncovered ankles as would be associated with displacement ventilation and underfloor air distribution.

2. Methods

2.1. Experimental facilities

The experiments were carried out at the environmental chamber at the Center for the Built Environment (CBE), University of California Berkeley.

2.1.1. Climatic chamber

The CBE climate chamber (Fig. 1A) measures 5.5 m × 5.5 m × 2.5 m, and features controlled air temperature to an accuracy of ±0.5 °C and controlled relative humidity to ±3%. The chamber is described in detail by Arens et al. [31]. The chamber is configured to appear as a realistic office, so as to attenuate the psychological influence of being a human subject in a laboratory experiment. The chamber has windows on two sides, which face south and west. The windows are well shaded by fixed external shades. The surface temperature of the windows is controlled by a dedicated air supply system. The temperature of the inner glass pane is controllable and was kept isothermal with the bulk interior air temperature throughout the experiments.

Fig. 1 shows the experimental configuration. The chamber simulated a typical open plan office. Three workstations (WS) were arrayed so that three subjects could be tested simultaneously. Each workstation was equipped with a displacement diffuser, a laptop computer and an office chair. Mesh office chairs were used, with a measured clothing insulation of 0.02 clo.

2.1.2. Air distribution system

2.1.2.1. Diffuser. A displacement diffuser unit (0.51 m by 0.20 m) was built using two layers white painted perforated metal panels and plywood. The perforated face of the diffuser was painted white to mimic commercially available displacement diffusers. To obtain a homogeneous air velocity at the face of the diffuser, two different styles of perforated panels were used. The distance between the panels was 30 mm. The panel facing the outside had a free area of 20%. The panel facing the inside of the diffuser had a free area of 13%. The diffuser was positioned at a minimum distance of 0.7 m away from the legs of the subjects. An air damper regulated the flow and the air speed at more than five duct diameters from the inlet of the diffuser. The average turbulence intensity due to the tested diffusers within the foot placement area was 30% (SD = 5.4%).

Air was brought to the three tested diffusers from an independent air-handling unit through an insulated duct. The difference between the air temperatures coming out from the three diffusers was less than 0.2 °C. The diffusers were located behind the chair and therefore the airflow came from behind the subjects.

2.1.2.2. Overall system. An underfloor air system was employed to bring conditioned air into the space so as to maintain the desired room temperature at head height. Ten linear diffusers were used (0.46 m by 0.09 m). The incoming air speed was less than 0.3 m/s at 0.1 m above the diffuser. The diffusers were situated far from the desk and close to the wall perimeter where the subjects rested during breaks. The air was exhausted through a 0.61 × 0.61 m ceiling return grill. The outdoor flow rate in this study was higher than 105 L/s. Since the maximum number of occupants was seven (six subjects and one experimenter), the minimum outdoor air supply.

2.1.3. Measuring instruments and measurement uncertainty

Air temperature was measured at 0.1 and 1.1 m at less than 0.5 m away from each person at each of the three workstations. The air temperatures were monitored continuously with thermistors (TMC1-HD connected to HOBO U12-013, Onset Computer Corporation, MA, USA). All the sensors were shielded against radiant heat transfer with an aluminized Mylar cylinder. The sensors were calibrated prior to the measurements (Fluke 9102S dry-well calibrator, WA, USA). The obtained accuracy was ±0.2 °C or better. Floor temperature was not measured.

A multichannel low velocity thermal anemometer with omnidirectional velocity transducers (Sensor HT-400, Poland) was used to perform mean air speed, turbulence intensity and air temperature measurements at 0.1 m height, corresponding to where the ankles were located during the tests. The characteristics of the