Energy & Buildings 179 (2018) 112–120

Contents lists available at ScienceDirect

Energy & Buildings

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

Impact of airflow temperature fluctuations on the perception of draught

Žiga Lampret [a], Gorazd Krese [b], Vincenc Butala [a], Matjaž Prek [a,*]

[a] University of Ljubljana, Faculty of Mechanical Engineering, Aškerčeva 6, Ljubljana SI-1000, Slovenia
[b] Korona inženiring d.d., Cesta v Mestni log 88 a, Ljubljana SI-1000, Slovenia

ARTICLE INFO

Article history:
Received 17 April 2018
Revised 31 August 2018
Accepted 8 September 2018
Available online 19 September 2018

Keywords:
Airflow movement
Thermal comfort
Draught
Temperature fluctuations
Subjective experiment

ABSTRACT

Besides air velocity, turbulence intensity and air temperature there are also other factors, which influence human thermal response to air movement. In this study, the impact of temperature fluctuations in airflow on human thermal sensation and perception of draught was examined. For the purposes of the study an air supply unit was designed for generating airflows with temperature fluctuations and used in a subjective experiment. The experimental study indicates that temperature fluctuations possibly influence the human perception of air movement with a distinct cooling effect. At high values of frequency and amplitude fluctuations a large discrepancy was found between predicted and measured values of draught discomfort.

1. Introduction

In developed countries people spend between 80% and 90% of their time indoors [1]. It is therefore imperative that ventilation and air-conditioning systems in buildings are designed for the health and comfort of the occupants. In ventilated and air-conditioned indoor environments, air movement substantially impacts thermal sensation and comfort of occupants from the point of view of whole body and local thermal sensation. Draught, defined as an unwanted local cooling of the human body caused by the air movement, represents one of the most common causes of thermal discomfort in air-conditioned indoor environments.

Thermal sensation is greatly affected by the skin temperature and its rate of change [2]. Both of these factors are influenced by airflow velocity and temperature changes around the body which cause skin temperature fluctuations and changes in convective heat transfer. For the improvement of indoor thermal sensation it is, thus, essential to establish a better understanding of all the influencing factors on the perception of air movement and draught.

1.1. Fanger's draught model

In the past 70–80 years many thermal comfort researchers examined the effect of various factors on the impact of draught. Houghten et al. [3], Berglund and Fobelets [4] studied the impact of nearly laminar airflow. Since airflow in ventilated real spaces is usually turbulent, Fanger and Pedersen [5] carried out a study in which subjects were exposed to a periodically fluctuating airflow. They observed that a fluctuating flow was more uncomfortable than a constant flow with the same mean velocity, and that thermal discomfort is influenced by the frequency and the velocity amplitude of the fluctuating airflow. Fanger and Christensen [6] first developed a model for predicting the percentage of people dissatisfied due to draught, as a function of velocity and air temperature.

Fanger et al. [7] analyzed the effect of velocity fluctuations in the airflow and expanded the model proposed by Fanger and Christensen by incorporating a term for turbulence intensity *Tu* which describes the impact of airflow turbulent behavior on the sensation of draught:

$$\mathrm{Tu} = \frac{\sqrt{\bar{v}_a'^2}}{\bar{v}_a} \tag{1}$$

where $\bar{v}_a'$ is the instantaneous air velocity (m/s), $\bar{v}_a$ is the mean velocity and $\sqrt{\bar{v}_a'^2}$ is the standard deviation of the velocity.

Furthermore, Fanger adopted Hensel's conclusion about thermoreceptor responses. Hensel and Schafer [8] showed that local thermal sensation is influenced by two different thermoreceptor responses, static and dynamic. Static thermoreceptor response is dependent on the level of skin temperature and corresponds to laminar airflow, which can cause discomfort. Dynamic thermoreceptor response depends on the rate of change of skin temperature. Fanger et al. [7] assumed that the dynamic response is influ-

* Corresponding author.
E-mail address: matjaz.prek@fs.uni-lj.si (M. Prek).

https://doi.org/10.1016/j.enbuild.2018.09.014
0378-7788/

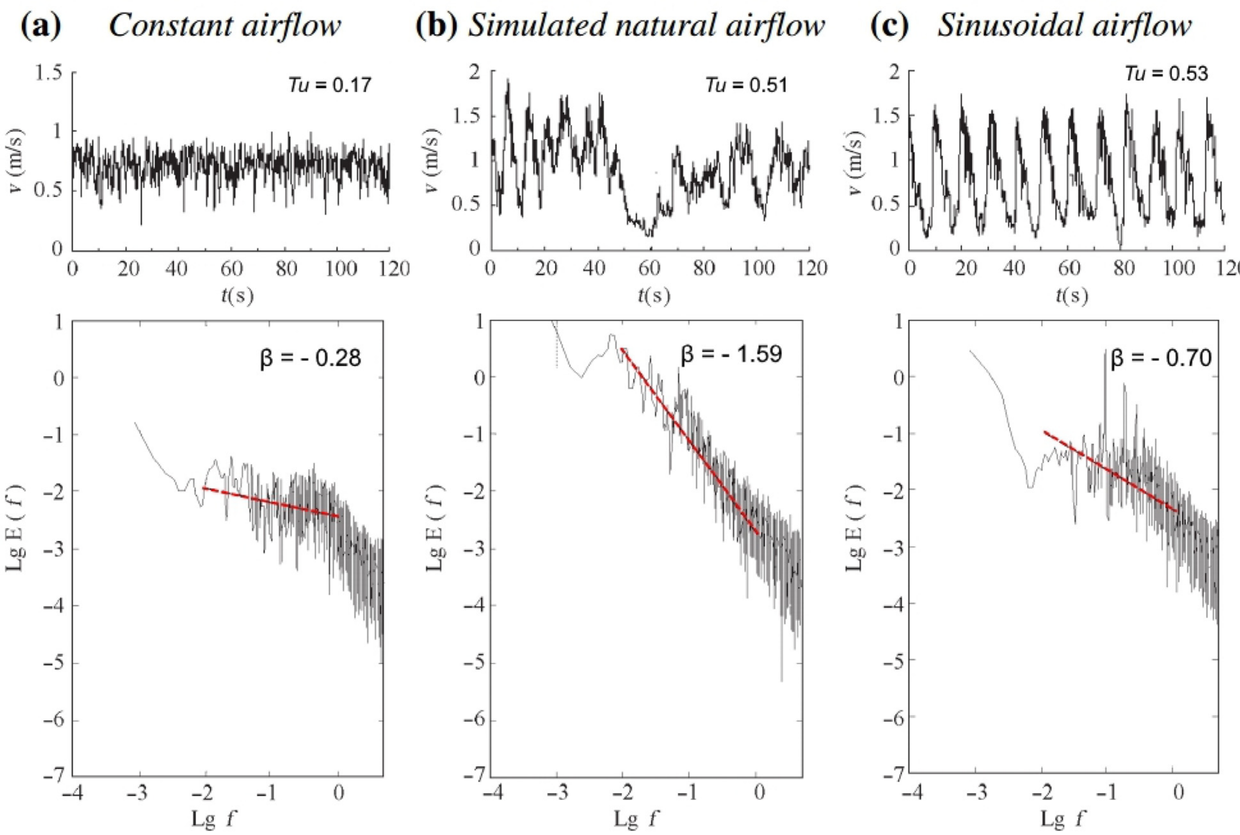

Fig. 1. Time series of air velocity and power spectrum curves for constant, simulated natural and sinusoidal airflow; logarithmic power spectrum curves β noted in red [22].

enced by the airflow velocity fluctuations, which causes changes in convective heat transfer and is reflected as fluctuations of the skin temperature. Thus, a model was presented, which predicts the percentage of dissatisfied due to draught (PD or DR – draught rate) as a function of mean airflow velocity $\bar{v}_a$, air temperature θ_a and turbulence intensity *Tu*:

$$\begin{aligned} PD = & \ 3.143 \cdot (34 - \theta_a) \cdot (\bar{v}_a - 0.05)^{0.6223} \\ & + 0.3696 \cdot \bar{v}_a \cdot Tu(34 - \theta_a) \cdot (\bar{v}_a - 0.05)^{0.6223} \end{aligned} \tag{2}$$

The model is valid for sedentary, thermally neutral persons in normal indoor clothing. It has been included in several national, European and international thermal comfort standards and guidelines [9–11].

1.2. Additional factors on perception of draught

Several field studies have observed a discrepancy between occupant responses and the aforementioned draught model [12,13]. As it was mentioned, the draught model is valid for thermally neutral persons, whereas people in buildings often fell slightly cool or slightly warm, which affects their perception of air movement. Palonen and Seppänen [14] demonstrated that the influence of draught is affected by the thermal sensation of individuals, while Toftum and Nilsen [15] have shown that people who felt cold or slightly cold were more likely to complain because of draught compared to those who felt thermally neutral or warm sensation.

The direction of the airflow was also shown to have an effect on the sensation of draught. Zhou [16] showed that at the same airflow velocities the highest percentage of complaints will occur when the airflow is injected from below and the lowest percentage will occur when the airflow is injected from above the head. Toftum et al. [17] further noted that the effect of the direction depends on the air temperature, i.e. at lower temperatures (20 °C and 23 °C) most people complained when the airflow was injected from below whereas at a higher temperature (26 °C) most people complained about the airflow injected from above.

1.3. Airflow velocity fluctuations

The influence of fluctuating airflow velocity is inherited in the aforementioned Fanger's model of draught [7] through the turbulence intensity *Tu* (Eq. (2)). Even though airflow fluctuations are included in the draught model, specific properties of velocity fluctuations, which can also affect the sensation of draught, are not taken into account. It is already established that thermal sensation in naturally ventilated and air-conditioned spaces differs [18]. Natural and mechanical airflows differentiate in the properties of the fluctuating velocity and in the power spectrum curve, which indicates the distribution of the energy of vortices with different frequencies. The slope of the logarithmic power spectrum curve β can be used as the index in spectrum analysis. The relationship between the power spectrum density function *E(f)* and the power spectrum curve β can be expressed with the following equation:

$$E(f) = 1/f^{\beta} \tag{3}$$

where *f* if the frequency (Hz) of airflow velocity fluctuations. Values of β typically range from 0 to −2. Research has shown that negative values of β for mechanical airflows are between 0 and 0.5, whereas β values of natural wind are between 1.1 and 2.0 [19]. This means that the vortices energy in natural wind is mostly distributed in the low frequency range. Jia [20] and Cui et al. [21] showed in an experiment that humans are more acceptable to artificially generated airflows with dynamic properties similar to natural airflows. Zhou et al. [22] draw similar conclusions in com-