Analysis of draught discomfort prediction models

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Abstract. One of the common local thermal discomforts that happen in an indoor environment is draught. Because of the importance of draught, many studies have been carried out to develop equations to calculate the draught rate. But because these equations are obtained from experimental tests in narrow experimental windows, their accuracy under wider environmental conditions should be analyzed. In this paper, the accuracy of equations obtained from the literature were investigated. Each equation predicted the draught rate with high accuracy and mean error of 5.3, 6.8, and 2.2% under the thermal conditions in which the equation was obtained. When applying the equations to different thermal conditions, the mean and maximum errors significantly increased and showed errors in predicting the draught rate with a maximum deviation of 63.5, 51.6, and 49.7%. These equations in some cases, even could not predict the draught rate of the reported draught discomfort percentage. Based on the results, each equation had its limitations and none of the studied equations could accurately predict the draught rate in all experimental conditions. An index that considers all relevant parameters in predicting draught discomfort can lead to a better draught rate prediction.

1. Introduction
One of the common local thermal discomforts that happen in an indoor environment is draught. It defines as an undesired local cooling of the human body caused by air movement [1]. This is the most annoying environmental factor in many indoor spaces such as ventilation in buildings, automobiles, trains, and aircraft [1, 2]. It mostly occurs when the body’s thermal sensation is below neutral [3] but it may occur both at neutral and warmer whole-body thermal sensations. It depends on the whole-body thermal sensation, air velocity, air temperature, activity level, turbulence intensity, and clothing insulation which all can affect the draught rate [3].

One of the first studies was carried out by Houghten et al. [4]. They worked on draught temperatures and velocities concerning skin temperature and feeling of warmth. In 1977, Fanger and Pedersen [5] investigated discomfort due to air velocities in spaces. Fanger and Christensen [6] investigated the perception of draught rate. Berglund and Fobelets [7] introduced an equation based on subjective human response to low-level air currents. Fanger et al. [8] analyzed the air turbulence’s impact on the sensation of draught and presented an equation for predicting draught. Toftum [9] carried out a field study of draught complaints in the industrial work environment in 1994. Toftum and Nielsen [10,11] investigated the effects of overall sensation and metabolic rate on draught sensitivity. Xia et al. [12] studied the effects of turbulent air on human thermal sensation in a warm isothermal environment. Zolfaghari et al. [13,14] investigated the draught sensation by air movement acceptability in an office with UFAD system.
In the earlier studies, mostly draught discomfort was reported, and based on these experiments, researchers suggested equations for predicting draught rate. But because these equations are obtained from experimental tests with limited environmental scope, their accuracy under other conditions should be analyzed. Among these equations, Fanger et al. [8] equation is accepted by ASHRAE[3] standard. Berglund and Fobelets [7] and Xia et al. [12] equations selected because each of them obtained in different thermal conditions. This paper aims to investigate the accuracy of these equations for predicting draught rate compared to the Fanger et al. [8] standard equation under different thermal conditions.

2. Methods

We used the PD equations which means predicted percentage of dissatisfied caused by draught, reported from experimental investigations by other researchers such as Fanger et al. [8], Berglund and Fobelets [7], and Xia et al. [12]. We investigated the accuracy of the models under various thermal conditions. Equation (1) shows the relation introduced by Berglund and Fobelets [7].

\[
PD = 113(V - 0.05) - 2.15t_o + 46
\]

where \( t_o \) (°C) and \( V \) (m/s) are air temperature and mean air velocity. Equation (2) shows the relation introduced by Fanger et al. [8].

\[
PD = (34 - t_o)(V - 0.05)^{0.62}(0.37VT_o + 3.14)
\]

where \( Tu \) (%) represents turbulence intensity. Also, Xia et al. [12] presented the following relation for draught rate:

\[
PD = 100/[1 + \exp(15.5538 - 0.4124t_o - 0.0872RH - 0.0774Tu + 0.00219Tu_t + 0.000372t_oRH
+ 0.00078RHT_o)]
\]

where \( t_o \) (°C) and \( RH \) (%) are operative temperature and relative humidity, respectively.

The experimental conditions used by Fanger et al. [8], Toftum and Nielsen [10], and Xia et al. [12], which their thermal condition are shown in Table 1, were used to evaluate differences between reported thermal discomfort and PD equations. Subjects’ PDs were extracted from experiments [8,10,12] and compared to model predictions. The results were compared to real draught local discomfort which was stated by subjects in the experiments, and their maximum and mean absolute difference have been evaluated based on equations (4) and (5), respectively.

\[
\text{Err}_{\text{mean}} = \frac{\sum_{j=1}^{N_{\text{exp}}}[PD_j - PD_{\text{eq}}]}{N_{\text{exp}}}
\]

(4)

\[
\text{Err}_{\text{max}} = \text{Max}[PD_j - PD_{\text{eq}}] ; i=1,6; j=1,N_{\text{exp}}
\]

(5)

In these equations, \( i \) represents each experiment shown in Table 1. \( N_{\text{exp}} \) represents the number of experimental conditions investigated in each experiment and \( j \) varies from 1 to \( N_{\text{exp}} \). PD\(_i\) and PD\(_{\text{eq}}\) are the percentages dissatisfied due to draught observed and predicted under each experimental exposure condition in an experiment.

**Table 1.** Thermal conditions of selected experiments.

| Experiment number | Reference           | Thermal condition                        |
|-------------------|---------------------|------------------------------------------|
| 1                 | Fanger et al. [8]   | Temperature=23 °C, Low turbulence intensity |
| 2                 | Fanger et al. [8]   | Temperature=23 °C, Medium turbulence intensity |
| 3                 | Xia et al. [12]     | Turbulence intensity=25%, Relative humidity=35% |
| 4                 | Xia et al. [12]     | Turbulence intensity=40%, Relative humidity=65% |
| 5                 | Toftum and Nielsen [10] | Temperature=11 °C, –0.9 < Thermal sensation < -0.3 |
| 6                 | Toftum and Nielsen [10] | Temperature=17 °C, 0 < Thermal sensation < 0.5 |
3. Results and Discussion

The maximum and mean errors between PD equations and the reported local discomfort for mentioned experiment conditions are shown in table 2. Based on table 2, none of the studied models can accurately predict the draught rate in all experimental conditions, probably because they did not consider the effect on the draught rating of all the effective parameters. This underlines the need to develop a new index that considers all effective parameters for predicting the percentage of draught discomfort with reasonable accuracy.

Table 2. The maximum and mean errors between PD equations and reported local discomfort.

| Investigated model | Error (%) | Experiment number |
|--------------------|-----------|-------------------|
|                    |           | 1     | 2     | 3     | 4     | 5     | 6     |
| Berglund, Fobelets[7] | Mean     | 7.1   | 5.3   | 48.9  | 47    | 22.4  | 9.75  |
|                     | Maximum  | 11.8  | 8.9   | 63.5  | 62.7  | 30.6  | 17.7  |
| Fanger et al. [8]   | Mean     | 6.8   | 8.4   | 28.1  | 42.7  | 23.4  | 16.6  |
|                     | Maximum  | 11    | 9.6   | 34.9  | 51.6  | 43    | 27.2  |
| Xia et al. [12]     | Mean     | 10.4  | 9.1   | 3.6   | 2.2   | 17.9  | 16.6  |
|                     | Maximum  | 27.1  | 22.8  | 4.2   | 2.9   | 49.7  | 38.6  |

4. Conclusions

- Berglund and Fobelets [7] model had the best prediction under Fanger et al. [8] experimental conditions with the mean error of 7.1 and 5.3%.
- Berglund and Fobelets [7] equation over predicted results in high velocity and temperature with maximum errors from 17.7% to 63.5%.
- Fanger et al. [8] correlation has shown its highest accuracy under Fanger et al. [8] experimental conditions with the mean error of 6.8 and 8.4%.
- Fanger et al. [8] correlation such as Berglund and Fobelets [7] over predicted results in high velocity and temperature with mean errors from 16.6% to 42.7%.
- Xia et al. [12] correlation under predicted the results in many experimental cases.
- None of the models accurately predicted the draught rate in all experimental conditions, because they did not consider all of the effective parameters on draught rate.

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