Study on prediction model of thermal sensation under local draft in low pressure environment

Baowei Ge1, Haiying Wang1*, Zan Xu1, Jiankai Li1, and Dongyang Chen1
1 School of Environment and Municipal Engineering, Qingdao University of Technology, Qingdao, China

Abstract. Local draft experiments were conducted to establish the overall thermal sensation prediction model under low pressure environment. Head, chest, hand, and ankle were exposed to local airflow under three pressure environments: 1 atm, 0.87 atm, and 0.74 atm, respectively. The skin temperature was measured and the subjective questionnaires were collected. The results showed that in cooler environment, the mean skin temperature decreased with the decrease of pressure, and people maybe more sensitive. When the environmental pressure decreased, the overall thermal sensation decreased correspondingly. Compared with the normal pressure condition, as the pressure decreased, the weight of local thermal sensation on overall thermal sensation changed a little. The weight of chest decreased while the weight of hands increased. When exposed to local draft, the four body parts showed similar influence on the overall thermal sensation under lower pressure conditions. Based on influence of pressure, temperature, and local draft speed, the overall thermal sensation prediction model for each body part was established respectively. The results indicated that the predicted values were highly correlated with the measured values. The models could be used to predict thermal sensation of people who are exposed to local draft in low pressure environment.

1 Introduction

When people stay in non-uniform thermal environment, their body parts may be exposed to different local environments, resulting in differences in the local thermal sensation of each body part. The overall thermal sensation is affected by the comprehensive reaction of local thermal sensations. Therefore, the change of local thermal sensation will have impact on the overall thermal sensation [1]. However, the influencing weight of each body part on the overall thermal sensation is different. In the study of individual ventilation, Li [2] obtained that the weight of local body parts on the overall thermal sensation using the weight analysis method, and found that the weight of head and neck is the highest, followed by the upper body (including chest and abdomen), and the lower body is the lowest. Zhang et al. [3] conducted studies on the relationship between thermal sensation and thermal comfort of the human body in steady-state uniform environment, transient uniform environment, local heating or local cooling environment. They found that the chest, back and hip dominated the overall thermal sensation, while the influence weight of hands and feet were small.

Under different atmospheric environment, the change of air density in low pressure environment will affect the heat dissipation characteristics of the human body [4]. In addition, some physiological parameters relating to thermal comfort of the human body will also change [5]. In previous studies, Xu et al. [6] found that the core temperature is affected by hypoxia in low pressure environment, which will reduce the core temperature. Wang et al. [7] also reported that under hypobaric hypoxia environment, subjects’ mean thermal sensation decreased. Mean skin temperature also decreased a little. However, the decrement of mean skin temperature in low pressure environment was not significant. Fan [8] conducted an experiment on the effect of air velocity on thermal comfort in low pressure environment. It was found that with the decrease of pressure, the mean thermal sensation gradually decreased. In the range of breeze velocity (< 0.2m/s), the mean thermal sensation was not affected by the air velocity, and the sensitivity of human body to air flow decreased with the decrease of pressure. These studies implied that low pressure environment has some impact on mean thermal sensation, and may influence some of the physiological parameters.

In this study, the changes of human physiological parameters in low pressure and non-uniform thermal environment will be explored. The weight of local thermal sensation on overall thermal sensation would be analysed based on the collected data (mean skin temperature and subjective votes) in local draft experiments conducted under different pressure environments.

2 Brief introduction of previous study

In this study, the data used were from previous experiments. The details of local draft experiments have

* Corresponding author: why3305@126.com
been explained in reference [9]. The experiments were
carried out under each pressure environment. The results
of ANOVA analysis, in this paper the measured physiological
parameters (mean skin temperature) will be analysed further. Moreover,
predicting models of thermal sensation based on local
body draft under low pressure environment will be
discussed too.

3 The mean skin temperature

The mean skin temperature is an important parameter
representing the physiological regulation of human body
to thermal environment and the external expression of
human thermal sensation. In the experiments, the mean
skin temperature was measured by the five-point
method. The five local skin temperature (forehead, chest,
back, upper arm and thigh) were collected by using
iButtonDS1923 temperature sensor. And the mean skin

| Parameter            | Sum of square of deviations | df | Mean square | F       | p      |
|----------------------|-----------------------------|----|-------------|---------|--------|
| Temperature (°C)     | 38.08                       | 2  | 19.04       | 615.3   | 0.000  |
| Air velocity (m/s)   | 0.05                        | 2  | 0.02        | 0.74    | 0.48   |
| Pressure (atm)       | 0.22                        | 2  | 0.11        | 3.59    | 0.03   |
| Local body draft     | 1.35                        | 3  | 0.45        | 14.52   | 0.000  |

Note: * indicated a significant correlation at the level
of 0.05, 0.01, 0.001, respectively. (Two-sided test)

4 Correlation analysis between mean skin temperatures and overall thermal sensation

The overall thermal sensation is an important subjective
evaluation to thermal environment, while mean skin
temperature is objective reflection of environment. In
order to explore the relationship between subjective
index (mean thermal sensation, MTS) and the objective
physiological parameters (mean skin temperature, tₘ), the
linear fitting and correlation analysis of MTS-tₘ was
carried out under each pressure environment. The results
were shown in Table 2 and Fig. 2.
Under normal pressure environment, the weight of head and chest was slightly larger, while the weight of limbs was smaller. This conclusion was similar to those in current studies [3,10,11], in which it was stated that the trunk (head, chest and back) had a greater influence on the overall thermal sensation. With the decrease of pressure, the influence weight of four body parts tended to be similar. The weight of head and ankle did not change much as the pressure decreased. With the decrease of pressure, the influence weight of chest decreased, while the influence weight of hand increased. The reason for this condition may be that the sensitivity of human body to airflow is reduced under low pressure environment [8]. Hands exposed to air flow are the body parts with abundant distribution of nerve endings, and the draft sensation of hand also increases gradually with the decrease of pressure.

6 The overall thermal sensation prediction model

Previous studies had found that when the four human body parts (head, chest, hand, ankle) were exposed to local draft respectively, the environmental temperature, air velocity and pressure had significant influence on the overall thermal sensation [9]. Especially, the overall thermal sensation had a significant linear correlation with pressure and air velocity [9]. In this experiment, three parameters (environmental temperature, air velocity and pressure) were set at three levels, respectively. And an orthogonal experimental design was carried out, which means environmental temperature, air velocity and pressure were controlled independently in each experimental condition. Furthermore, the results of correlation test showed that the effects of these three parameters on the overall thermal sensation were significantly correlated with p-value < 0.05. Afterwards, multiple linear regression based on three environmental parameters was carried out for the four body parts exposed to local draft. The prediction model of overall thermal sensation corresponding to local body draft was obtained, the models are shown in Table 3.

5 The weight factor of local body part

In order to study the influence of different body parts on overall thermal sensation, weight analysis was used. Because the thermal sensation of each body part is not independent, and multicollinearity exists between independent variables (local thermal sensation of different body parts). Therefore, principal component analysis was used to eliminate multicollinearity, and then multiple linear was applied to get the multivariate linear formula representing the relationship between overall thermal sensation and local thermal sensation of four body parts. Meanwhile, from these formulas, the influence weights of each body part were obtained respectively in each local draft condition.

Additionally, in order to further get the influence weight of a certain body part, and to compare the influence of pressure on the weight of each body part, all the calculated influence weights were averaged and normalized. The final results are shown in Fig. 3.

| Pressure (atm) | Correlation coefficient R | p     | Fitting formula        |
|---------------|---------------------------|-------|------------------------|
| 1             | 0.556                     | 0.003*** | $MTS = 0.485t_{sk} - 16.208$ |
| 0.87          | 0.545                     | 0.000*** | $MTS = 0.683t_{sk} - 23.033$ |
| 0.74          | 0.833                     | 0.000*** | $MTS = 0.734t_{sk} - 24.967$ |

Fig. 2. The relationship between MTS and $t_{sk}$

From Table 2, the overall thermal sensation was significantly correlated with $t_{sk}$ ($p<0.05$) under each pressure environment. The overall thermal sensation could be predicted based on skin temperatures. From Fig. 2, the change rate of MTS-$t_{sk}$ were all positive, which meant that the thermal sensation increased with the increase of $t_{sk}$. This finding was consistent with the current findings [10,11].

| Local body part | Model parameters | t    | p         | Adjusted $R^2$ |
|-----------------|-----------------|------|-----------|---------------|
| Head            | Constant        | -8.46| 0.000***  |               |
|                 | Temperature(℃)  | 9.509| 0.000***  | 0.803         |
|                 | Air velocity(m/s)| -3.785| 0.001**  |               |
|                 | Pressure(atm)   | 2.079| 0.023*    |               |
| Chest           | Constant        | -10.274| 0.000*** |               |
|                 | Temperature(℃)  | 11.102| 0.000***  | 0.858         |
|                 | Air velocity(m/s)| -5.270| 0.000***  |               |
|                 | Pressure(atm)   | 2.943| 0.07       |               |
| Hand            | Constant        | -9.854| 0.000***  | 0.842         |
|                 | Temperature(℃)  | 10.317| 0.000***  |               |

Fig. 3. The influence weight of each body parts under different pressure environment
Air velocity(m/s) | -4.901 | 0.000*** |
| --- | --- | --- |
| Pressure(atm) | 3.294 | 0.03* |

| Constant | -9.376 | 0.000*** |
| --- | --- | --- |
| Temperature(℃) | 8.715 | 0.000*** |
| Air velocity(m/s) | 4.359 | 0.000*** |
| Pressure(atm) | -3.189 | 0.004** |

From Table 3, the overall thermal sensation prediction model for each body part was:

\[
\begin{align*}
\text{MTS} &= \begin{cases} 
0.120t_e - 0.573v + 0.606p - 3.43 & \text{(Head)} \\
0.158t_e - 0.902v + 0.969p - 4.73 & \text{(Chest)} \\
0.139t_e - 0.794v + 1.026p - 4.29 & \text{(Hand)} \\
0.150t_e - 0.282v + 1.729p - 5.21 & \text{(Ankle)} 
\end{cases} 
\end{align*}
\]

Where \( t_e \) is environmental temperature, °C; \( v \) is local air velocity, m/s; \( p \) is pressure, atm.

In order to verify the validity of the model, the measured data were compared with the predicted values. The correlation between measured and predicted values were analyzed. The results are shown in Fig. 4.

2) The overall thermal sensation was significantly correlated with \( t_e \) under each pressure environment, and increased with the increase of mean skin temperature.

3) With the decrease of pressure, the weight of chest decreased but the weight of hand increased, and the difference of the weight of the four body parts on the overall thermal sensation became smaller.

4) The overall thermal sensation prediction models were established for head, chest, hand and ankle, respectively. And the predicted values were highly correlated with the measured data. The models could be used to predict the overall thermal sensation of people exposed to local draft in low pressure environment.

Acknowledgments: This study has been financed by the National Natural Science Foundation of China (No. 51678314)

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