Showering thermal physiology and energy consumption

Dadi Zhang[1][0000-0002-1293-0542], Kowk-Wai Mui [1][0000-0003-2505-1261]

, and Ling-Time Wong[10000-0001-8449-4973]

[1] The Hong Kong Polytechnic University, Hong Kong, China

Abstract. The thermal environment in buildings, including bathrooms, is essential to occupants' health and energy consumption. Many thermal comfort models have been developed in recent decades. However, only a limited number of models are available that attempt to forecast individuals' thermal sensations while showering, and these models rarely take into account people's thermal physiology. This study applied a dynamic thermal sensation (DTS) model developed by a recent study to predict people's thermal comfort during the undressing and showering processes under different settings. The results were compared with the subjects' self-reported thermal sensations collected during a previous field study, and the differences between them indicated the necessity of improving the DTS model during showering. Additionally, these findings showed that the water temperature preferred by most people (about 39 °C) might lead to a hot thermal sensation during showering. Considering the greater influence of water temperature compared to air temperature on energy consumption, it is recommended to maintain relatively lower water temperatures and higher air temperatures during showering. This setting could ensure a comfortable thermal sensation for undressing and showering while promoting energy conservation.

Keywords: Showering, Thermal Energy Consumption, Energy Conservation, Dynamic Thermal Sensation, Mean Skin Temperature.

1 Introduction

Many thermal comfort models have been developed in recent decades to identify the relationships between the built environment and occupants' thermal sensations and to create a healthy and comfortable indoor environment [1]. However, most existing thermal comfort models focus on people exposed to air, such as in the working and learning spaces. Only a few evaluated thermal sensations during people's showering, and hardly any considered people's thermal physiology [2]. Users' thermal comfort is closely related to their well-being and the thermal energy used to maintain a thermal environment [3]; the showering environment is no exception. People's thermal sensation could directly affect their showering behaviour, such as adjusting water temperature and flow rate, significantly impacting energy use [4]. Therefore, understanding the relationships between the showering conditions and people's thermal sensations could create the optimal showering environment that improves thermal comfort and saves energy.

A recent study developed a Python program to predict people's skin temperature and dynamic thermal sensation (DTS) during undressing and showing processes [5]. By setting the showering conditions, including water temperature, air temperature, and relative humidity, and user information, including height, weight, and gender, the DTS predicting program could predict the user's thermal sensation per minute [5]. The current study aims to identify the comfort and energy-efficient showering conditions. The DTS model determines the relative comfort conditions and, hence, the most energy-efficient setting by utilizing the showering energy consumption model.

2   Method

Based on a previous field study on showering thermal sensation, six representative showering settings were identified, corresponding to the different cold, neutral, and warm conditions for female and male subjects in Hong Kong (see Table 1) [2]. These settings, together with the subjects' heights and weights (male: 174cm/66.8 kg; female: 156cm/54.6 kg), were applied in the current study as the inputs to calculate people's DTS during the undressing and showering processes.

Table 1. Showering settings corresponding to males/females' cold/neutral/warm sensations.

| Showering settings	Males' thermal sensation			Females' thermal sensation		
	Cold (-0.60)	Neutral (0)	Warm (0.60)	Cold (-0.71)	Neutral (0)	Warm (0.80)
Water Temperature (℃)	38.6	38.6	38.6	39.2	39.2	39.2
Air Temperature (℃)	17.7	25.8	29.8	17.7	25.8	29.8

The calculation was assisted by Python code. First, the environmental conditions and subjects' information were defined based on the previous study. Second, the skin temperature changes on different body segments during the two processes were calculated separately. Last, the DTS was calculated for each second. All the computed results were saved in a worksheet for further analysis. After the calculation, the DTSs were compared with the empirical data (i.e., the subjects' self-reported thermal sensations after showering) collected by a previous study [2]. At last, the optimal showering environment, in terms of thermal comfort and energy saving, can be identified based on the relationships between the DTS and the showering settings.

3   Results

Figure 1 shows the calculated DST under different conditions during the undressing and showering. In the cold environment, subjects' thermal sensations decreased significantly with time during the undressing period, while after exposure to hot water, they increased to the thermal neutral level; in the neutral and warm environments, subjects' thermal sensations were around neutral during the undressing period, while they

increased significantly during the showering period. These findings indicated that the air temperature in the bathroom should be kept at a neutral level, and the showering water temperature should be kept at a relatively lower level to maintain a thermally comfortable environment during both the undressing and showering processes. Moreover, according to the showering energy consumption model developed by Zhang et al. [7], water temperature has a relatively larger impact on energy consumption during showering than air temperature (see equation (1)). Therefore, the air temperature is suggested to be kept at 25.8°C (same as the neutral condition) and the water temperature is kept at 38°C (slightly lower than the users' preferred setting) for people with average height and weight in Hong Kong. Under this condition, the thermal sensation of both males and females could be maintained between 0-1 in the bathroom (See the grey line in Fig.1). Additionally, if the water flow rate and ventilation rate were kept the same, then the suggested setting could save about 0.08 and 0.20 kWh of energy during a 10-minute shower, compared with the neutral and warm conditions, based on equation (1).

$$Q_{total} = 0.20 \times T_a + 0.53 \times T_w + 72.56 \times m_a + 44.39 \times m_w - 24.04 \qquad (1)$$

a) Male   b) Female
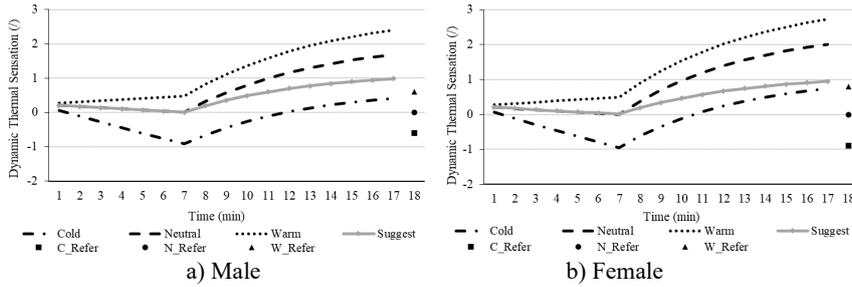
Note: the air temperatures in cold, neutral, and warm conditions were 17.5, 25.8, and 29.8 °C, respectively; the water temperature was 38.6°C for males and 39.2 for females [2].

Fig. 1. Comparison between the calculated thermal sensations and the references.

4   Discussions

As shown in Fig.1, the calculated DTSs were higher than the subjects' reported thermal sensations (the points marked at 18 min). It should be noted that subjects' thermal sensations were asked after showering, and the subjective thermal sensations might drop sharply without exposure to the hot water. In addition, the accuracy of the DTS model might also affect the results. Since the DTS was calculated based on the model developed by Takada et al. [6], which was targeted at people exposed to air, it might not be suitable for predicting subjects' DTS during showering [5]. Therefore, this DTS model is suggested to be improved to make it ideal for showering conditions.

Moreover, it is important to acknowledge that the findings of this study may not be easily replicated on a larger scale due to the limited number of cases examined. The study primarily relied on simulations and drew upon data from a previously conducted field study, which only provided average information for male and female subjects.

Consequently, the current study involves only two average subjects. More subjects' information and thermal sensations should be collected in future research, and a whole showering process monitoring (undressing, showering, and dressing) shall be conducted under different conditions. This additional information would validate and enhance the accuracy of the DTS model and identify the optimal showering conditions for different user profiles.

5   Conclusion

This study applied a previously developed DTS model to predict subjects' thermal comfort during the undressing and showering processes in a bathroom. Three thermal settings were considered for male and female subjects separately. Results indicated that keeping the air temperature at a neutral level and slightly lowering the water temperature could help to maintain a comfortable and energy-saving showering environment. Specifically, for people with average height and weight in Hong Kong, the air and water temperatures during showering are suggested to be 25.8 and 38 ℃. Besides, the differences were identified between the calculated thermal sensations and the previously collected self-evaluations. Therefore, the DTS model was suggested to be improved to better predict the DTS during showering. Moreover, the findings of this study could enhance the understanding of people's thermal response during showering, which could help residents and public facility managers create a comfortable and energy-saving showering environment.

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.

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