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Measuring Dynamic Thermal Sensation in a Residential Bathroom for Water-Efficient Showering

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Abstract

Showering is a determining activity in domestic water consumption and thermal energy use. Shower room designs under thermal steady-state assumptions are not optimized for energy use and water consumption. This study experimentally explores the relationships between showering environments, individual characteristics, and occupants' dynamic thermal sensations (DTS) during the entire showering process, including undressing and dressing periods. Eighteen subjects participated in this experiment in a typical residential bathroom. Their thermal sensations were recorded every two minutes, and skin temperatures at seven locations were measured every minute. Air temperature and relative humidity, water temperature, and water flow rate were also monitored. Results indicated that water temperature dominated skin temperature, surpassing the effects of water flow rate and air temperature. A significant correlation between mean skin temperature and DTS was also established, and a predictive model was developed. These findings support using water-efficient showerheads to shower at a reduced water flow rate to conserve water. Considering the occupants ' DTS during showering, this study informs comfortable and energy-efficient shower environment designs.

Keywords

Thermal comfort; showering; bathroom; mean skin temperature; dynamic thermal sensation

1 Introduction

In recent decades, reducing carbon emissions and energy consumption have become a critical global priority to address climate change. Various energy-saving technologies have been developed, and most of them focused on the major energy users such as air conditioning, cooking, transportation, lighting, etc. (González-Torres et al., 2022). Conversely, less attention has been paid to improving the energy efficiency of domestic hot water systems, which has led to the percentage of energy consumption in hot water increased significantly in the past decades. This trend is more obvious in Hong Kong- a high-density tropical city where showering frequency is notably high (Pomianowski et al., 2020). According to the Hong Kong Energy/End-use Data 2023, the share of gas and liquefied petroleum gas (LPG) consumption for hot water systems increased from 19% in 2011 to 26% in 2021 (Hong Kong Electrical & Mechanical Services Department (EMSD), 2023). This substantial and continued increase highlights both the necessity and the potential for energy savings in domestic water heating systems.

Although energy conservation is important, it must not come at the expense of occupant comfort or health. Just as the dilemma exists between maintaining comfort and reducing energy consumption in the fields of heating, ventilation, and air conditioning, a similar challenge also exists during showering. Therefore, it is essential to conduct an accurate measurement and analysis to identify the factors that impact occupants' thermal sensation and energy consumption, as well as the relationships between them. Understanding these dynamics will enable the creation of a comfortable as well as energy-efficient showering environment.

Unless the investigation on occupants' thermal comfort and skin temperature exposure in air (such as in offices, schools, or at homes), it is relatively difficult and sensitive to measure them during showering because of the privacy concerns. Consequently, only a few studies have explored the impact of bathroom environment on occupants' thermal comfort and skin temperature (Luo et al., 2023; Mui et al., 2024; Wong et al., 2022). Considering the challenges of measurement during showering, a predictive model for occupants' thermal sensation based on environmental parameters and personal characteristics, such as Fanger's PMV model for the air exposure, could be an effective approach. This model could assist in calculating occupants' sensations and then identifying optimal showering conditions that meet both thermal comfort and energy conservation criteria.

Recently, Mui et al. (2024) developed such a model that could provide relatively accurate skin temperature predictions; however, its performance in dynamic thermal sensation (DTS) prediction is less satisfactory. Unlike static thermal sensation, DTS refers to the perception of changes in thermal conditions over time. It reflects how occupants respond to variations in the thermal environment. The inaccuracy of the model developed by Mui et al. (2024) is caused by the fact that the DTS in their study was calculated using the formula developed by Takada et al. (2013) which focuses on air exposure conditions.

To the best of the authors' knowledge, the relationship between occupants' skin temperature and DTS has not yet been well established. Therefore, this study aimed to develop such a DTS model to establish the relationship between occupants' skin temperature and DTS during water exposure and to predict their DTS under different showering conditions.

2 Method

2.1 Experimental Design and Procedure

A series of experiments, including objective measurement and subjective questionnaire survey, were conducted between17-30 October 2024 in a typical residential bathroom setting (2m (w)*2.2m(l)*2.4m(h)). The bathroom was ventilated through a fan, and there was no air conditioner. Therefore, the showering environment was not consistent. To make sure the environment was back to normal, at least at the beginning of the experiment. There were at least 30 minutes intervals between the two experiments to make sure the humidity was back to 70%. The experiment procedure is shown in Figure 1, while the experiment time depends on each participant's own showering time.

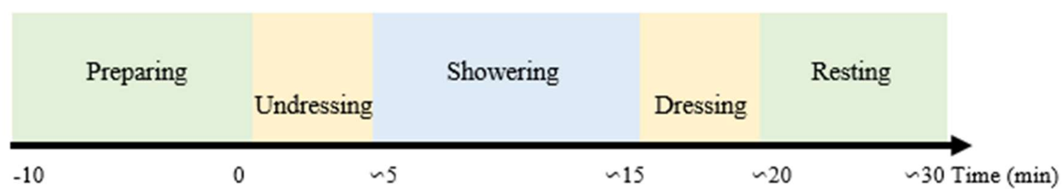


Figure 1-Experiment procedure

In total, six different conditions, combining two water flow rates (WFRs) and three water temperatures (see Table 1), were selected as the normal showering conditions. The selection of these conditions was based on previous showering-related studies (Luo et al., 2015; Wong et al., 2022; Zhang et al., 2023). Each condition was tested by three participants randomly.

Table 1- Investigated conditions

Conditions	Tw (°C)	WFR (l/min)
C1	35	8
C2	38	8
C3	41	8
C4	35	10
C5	38	10
C6	41	10

2.2 Data collection

The objective measurements were conducted at intervals of 1s. Investigated parameters consisted of environmental parameters, i.e., air temperature and relative humidity (RH) in the bathroom, showering-related parameters, i.e., WFR and water temperature, and subjects' physiological parameters, i.e., skin temperatures at seven different body parts (forehead, trunk, arm, hand, thigh, calf, and foot). Then, the mean skin temperature (MST) could be calculated based on the Hardy–DuBois method, i.e., Equation 1 (Munir et al., 2010).

$$MST = 0.07 * T_{fh} + 0.35 * T_t + 0.14 * T_a + 0.05 * T_h + 0.19 * T_t + 0.13 * T_c + 0.07 * T_f \quad (1)$$

For the subjective questionnaires, 18 participants, including 14 males and 4 females, participated in these experiments. Each of them was asked to take a normal shower, as they usually did, in the selected bathroom. Their thermal sensation was asked and recorded every two minutes, starting from the undressing period until the end of the dressing period (as shown in Figure 1).

2.3 Data analysis

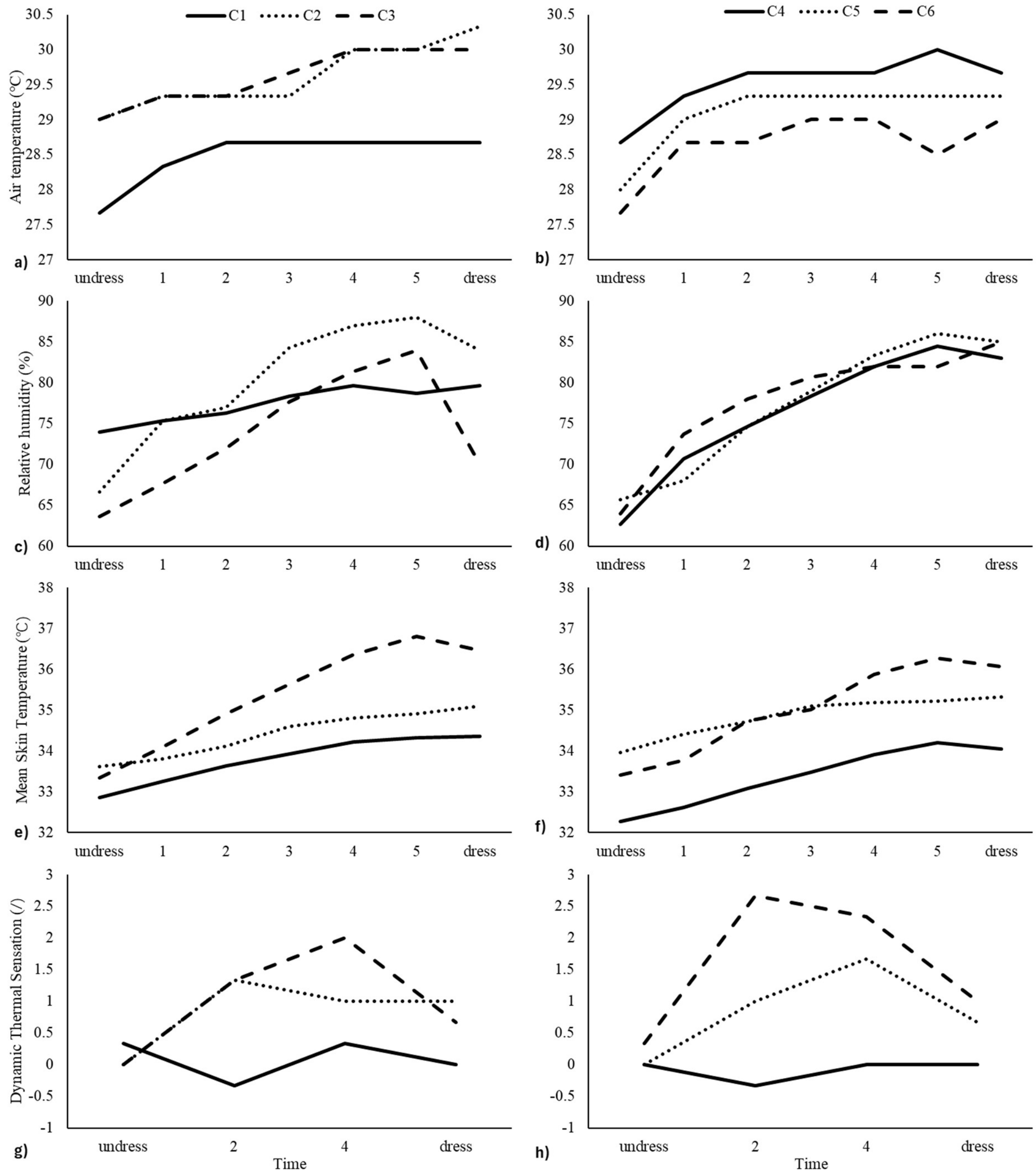
The collected data were imported and analyzed using IBM SPSS Statistics 27.0 (SPSS Inc. Chicago, IL, USA). First, all measurement data were checked for outliers using Z-scores. Descriptive analyses were then conducted, including calculations of the mean and standard deviation (S.D.) for the measured data and the frequencies of the participants' characteristics, to get an overview of the collected data.

Then, a series of correlation analyses were performed to assess the impacts of each environmental parameter (i.e., WFR, air temperature, RH, and water temperature) on participants' DTS and MST. Finally, a multivariate regression model was established to explore the relationship between DTS and these variables, in order to examine their combined effects on participants' thermal comfort and sensation. Additionally, a standardized regression model was developed to identify the most influential variable affecting participants' DTS during showering.

3 Results and Discussion

3.1 Descriptive results

In total, 164 sets of data (including air temperature, RH, WFR, water temperature, skin temperatures, DTS, etc.) were collected from 18 participants. Most participants (56%) were aged between 21 to 25, 22% were between 30-40, while 11% were less than 20, and 11% were older than 40 years old. The average showering time of the 18 participants was 7.1±2.4 minutes. Besides, it was found that participants' average showering time (7.9 min) was much longer when the WFR was low (i.e, C1-C3), compared with the conditions with higher WFR (6.3 min). Moreover, participants' showering time was shortest under C6, namely, when both water temperature and WFR were at high values. Under this condition, two subjects' showering time was less than six minutes. Therefore, the time duration was capped at five minutes in Figure 1 to ensure that each data point in these figures represents the average of results from at least two subjects.



Note: The left figures are for C1-C3; The right figures are for C4-C6; detailed settings of C1-C6 are described in Table 1.

Figure 2 - Variations of the parameters over time

As shown in Figure 2, the air temperature in the bathroom initially increased slightly at the start of the shower and then remained almost consistent throughout the showering period. RH steadily increased during the entire showering duration and dropped slightly during dressing. A similar pattern was observed for MST, which increased during showering and decreased slightly during dressing. This decrease was more pronounced at higher water temperatures (i.e., C3 and C6). For the DTS, it remained around neutral during the showering process when the water temperature was low (i.e., C1 and C4). In contrast, at higher water temperatures, the DTS increased significantly during showering and decreased during dressing, similar to the MST.

3.2 Correlations between the parameters

Table 2 presents the Pearson correlation results between MST, DTS, satisfaction, and environmental parameters. Overall, both RH and water temperature had significant positive effects on occupants' MST and DTS, while air temperature significantly affected only MST. Surprisingly, WFR had a significant negative impact on occupants' satisfaction. This may be due to the fact that only two WFR values were examined in this study. This result suggests that using a lower WFR showerhead could both save water and enhance satisfaction during showering. Additionally, MST and DTS were found to be significantly positively correlated with each other.

Table 2- Pearson correlation coefficients between the investigated parameters

	Air temperature	RH	Water temperature	WFR	DTS	Satisfy
All:						
MST	**0.438 (<0.001)**	**0.375 (<0.001)**	**0.541 (<0.001)**	-0.084 (0.286)	**0.527 (<0.001)**	0.093 (0.369)
DTS	0.155 (0.133)	**0.308 (0.002)**	**0.602 (<0.001)**	-0.013 (0.897)		0.172 (0.096)
Satisfy	0.036 (0.730)	0.096 (0.353)	0.046 (0.657)	**-0.260 (0.011)**		
Female:						
MST	**0.842 (<0.001)**	**0.653 (<0.001)**	**0.682 (<0.001)**	-0.255 (0.118)	**0.580 (0.004)**	0.447 (0.553)
DTS	**0.613 (0.002)**	0.334 (0.119)	**0.582 (0.004)**	-0.054 (0.806)		0.210 (0.336)
Satisfy	0.003 (0.988)	-0.101 (0.648)	-0.053 (0.811)	0.017 (0.940)		
Male:						
MST	**0.293 (0.001)**	**0.309 (<0.001)**	**0.495 (<0.001)**	-0.073 (.420)	**0.507 (<0.001)**	0.359 (0.207)
DTS	-0.001 (0.990)	**0.314 (0.007)**	**0.562 (<0.001)**	-0.084 (0.484)		0.062 (0.832)
Satisfy	0.031 (0.796)	0.138 (0.248)	-0.006 (0.960)	**-0.391 (0.001)**		

Note: the correlations are significant at the 0.05 level (2-tailed) are marked in bold.

Since males' average DTS (0.88) was significantly higher than females (0.26) (t(93)=0.016), the correlations were checked again for females and males, separately.

Similar results were observed for male participants. However, when focusing on female participants, the results were different. Specifically, air temperature showed a significant positive correlation with females' DTS, while RH did not. Furthermore, none of these parameters were significantly correlated with females' satisfaction.

Figure 3 illustrates the relationship between satisfaction and DTS, which can be expressed as a polynomial regression equation, i.e., Equation 2 ($F(1, 92)=31.44$, $p<0.001$).

$$Satisfaction = -0.489DTS^2 + 0.949DTS + 0.761 \quad (R^2 = 0.406) \qquad (2)$$

According to the Equation, participants preferred warm showering environment, and when participants' DTS was 0.97, their satisfaction reached to the highest. This is different from people's thermal sensation when exposed to air, such as Fanger's PMV-PPD model (Fanger, 1973) and the results found by Shahzad et al. (2018) who indicated that most satisfied participants in office buildings had a "neutral" sensation.

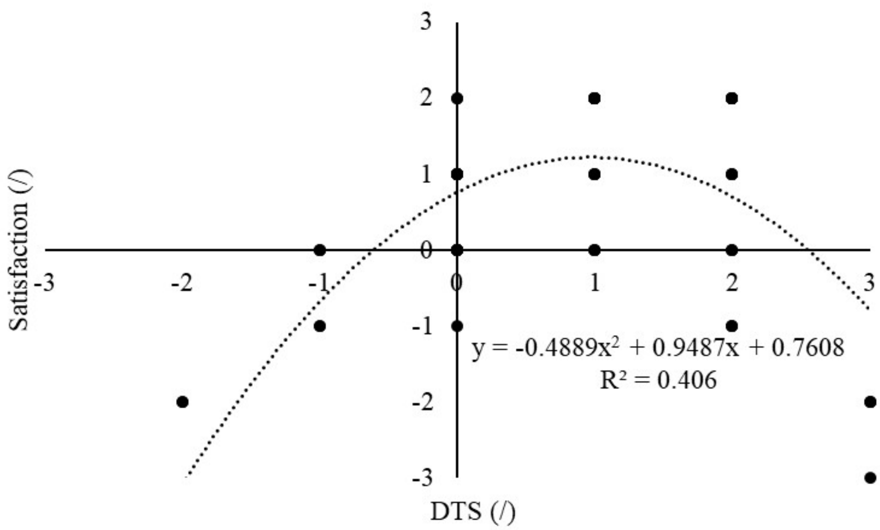


Figure 3 - Relationship between participants' DTS and satisfaction

3.3 Multivariate regression analysis

Taken all the potential influencing factors in Table 1, i.e., air temperature, water temperature, RH, and MST, into consideration in the regression analysis, then, a linear model can be obtained to calculate the DTS. Results showed that air temperature was not significant to the prediction, thus it was removed from the model (see Equation 3), and then the adjusted R^2 of the model increased from 0.477 to 0.478. Since personal characteristics, such as gender and BMI (Choi & Yeom, 2017), also could impact DTS, these parameters were included in the analysis, and a more accurate model was obtained, see Equation 4.

$$DTS1 = 0.059MST + 0.261Tw + 0.04RH - 13.134 \quad (R^2 = 0.499) \tag{3}$$

$$DTS2 = 0.053MST + 0.082G - 0.017BMI + 0.243Tw + 0.041RH - 13.273 \quad (R^2 = 0.514) \tag{4}$$

Where, G is gender, 1 represents female, while 2 represents male.

According to the standardized coefficients Beta, water temperature and RH were the most significant factors that decide participants' DTS, followed by BMI, MST, and gender. This indicated that environmental factors, especially water temperature was the main parameter that impact people's DTS during showering.

3.4 Limitations and future study

This study was limited to its small sample size of 18 participants, with a notable small number of females. Although the sample size was sufficient for the statistical analysis, a larger database would enhance the analysis accuracy, especially for the DTS model. Therefore, future study was suggested to include larger and gender-balanced participants to further analyse the effect of personal characteristics. Moreover, different air temperatures were suggested to be tested in the future to better understand the impact of environmental factors on people's DTS during showering.

4 Conclusion

This study investigated the impact of environmental factors and personal characteristics on individuals' MST and DTS during showering. A series of showering experiment was conducted in a typical residential bathroom under six conditions with different water temperature sand water flow rates. 18 subjects participated in this experiment and their skin temperature and thermal sensation during showering were recorded. Results indicated that air temperature, water temperature, and RH significantly impacted participants' MST, while water temperature and RH significantly impacted their DTS. In addition, it was found that people generally preferred a warm sensation during showering. Moreover, a DTS model was developed based on participants' personal characteristics and environmental factors. These findings could provide insights in designing comfortable and energy-saving bathroom and developing personalized showering environment. More participants and more showering conditions are suggested to be considered in the future, and a more accurate DTS model is expected to be established using machine learning techniques.

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6 Presentation of author(s)

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