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Predicting thermal comfort of residential shower rooms for optimal showering energy use

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Abstract

Showering is a typical daily activity directly related to people's comfort and health, dominating thermal energy consumption in residential buildings. This study developed a mathematical model to predict people's mean skin temperature (MST) and dynamic thermal sensation (DTS) during undressing and standing showering periods to identify the comfortable showering environment for different occupants. The model's validity was supported by comparing the calculated MSTs with the results collected by a previous experimental study. Moreover, 31 subjects (of different sexes, weights, and heights) were involved in the case studies. Results of the case studies showed that female and underweight subjects' MST and DTS varied more significantly than male and overweight subjects during undressing and showering periods. Additionally, it was found that both water and air temperatures significantly impact occupants' MST and DTS during showering, and the impact of water temperature was much more significant than the impact of air temperature. Moreover, by combining a previously developed energy consumption model, an optimal showering environment can be identified where both maintaining comfort and saving energy can be achieved. Based on the simulation results, the water temperature during showering was suggested to be not higher than 40 °C, especially for longer showering, to avoid thermal discomfort and energy overconsumption. However, the model was established based on theoretical deduction, with assumptions made. Additional measurements were needed to validate the model further and improve it.

Keywords

Showering environment; Mean skin temperature; Dynamic thermal sensation; Energy consumption

Nomenclature

Symbols (in order of appearance)			
M	Metabolic rate (W/m^2)	T_a	Air temperature (K)
W	External work rate (W/m^2)	T_r	Radiant temperature (K)
C	Convection heat exchange rate (W/m^2)	P_a	Ambient vapor pressure (Pa)
R	Radiation heat exchange rate (W/m^2)	RH	Relative humidity (%)
E	Heat exchange rates by evaporation (W/m^2)	β	Ratio of the water-covered area to the body segment area
Q	Heat gain or loss of the body (W/m^2)	α_{cw}	Convective heat transfer coefficient between the human skin and water flow (W/(m^2·K))
E_{sw}	Heat exchange rates by sweating (W/m^2)	T_w	Water temperature (K)
E_{diff}	Heat exchange rates by skin diffusion (W/m^2)	$P_{sk,sat}$	Saturated vapor pressure on the skin surface (Pa)
E_{max}	Maximum heat exchange rates by evaporation (W/m^2)	$A_{sk,seg}$	Skin area for each body segment (m^2)
α_c	Convective heat transfer coefficients between the human skin and air (W/(m^2·K))	$M_{sk,seg}$	Skin weight for each body segment (kg)
α_r	Radiative heat transfer coefficients between the human skin and air (W/(m^2·K))	c	Average specific heat capacity of human skin kJ/(kg· K)
T_{skin}	Skin temperature (K)		

1. Introduction

Nowadays, taking a shower is a daily routine for many people since it is an effective way to maintain personal hygiene and reduce stress. In subtropical or tropical developed cities, people might take it multiple times per day. For example, a previous investigation showed that some people in Hong Kong could take as many as four times showers per day in summer [1]. Taking a shower is a relaxing experience during which people can unwind. However, suppose the thermal environment in the bathroom or the showering water is set improperly. In that case, it can be uncomfortable, detract from the overall experience, or even cause health accidents, such as facial pallor, falling, loss of consciousness, and others [2]. Based on a survey conducted among the aging population (aged 40 to 74 years), Hayasaka et al. [2] estimated that the incidence rate of health accidents during bathing or showering was 0.67 per 10000 baths/showers in Japan. Although the rate seems small, it equals about 833000 accidents annually since bath/shower is a daily activity for almost everyone. One possible reason for these accidents might be that the sharp temperature changes between the bathroom and dressing room cause rapid changes in blood pressure and heart rate [3], which lead to hazardous consequences of health complications, such as heart attack, cardiac arrest, etc. [4]. Therefore, it is essential to maintain a comfortable thermal environment in the bathroom.

ASHRAE 55 [5] defines thermal comfort as the “state of mind which expresses satisfaction with the thermal environment”. Many studies have found significant relationships between indoor thermal comfort and human health, indicating that high and low temperatures could cause severe health impacts [6]. In general, the health responses (such as respiratory disorders, cardiovascular conditions, and deaths) of exposure to high temperature occur immediately [7], [8], while the responses to exposure to low indoor temperature, which might be related to dampness and mould, often be delayed and chronic [8], [9]. Thermal comfort was invoked and required to comply with specific standards during building construction and operation to avoid the adverse effects of inappropriate temperatures. Moreover, some thermal comfort models, such as the Predictive Mean Vote (PMV) model, were developed better to predict the thermal comfort level in an indoor environment. Based on these models, more standards were established to improve and maintain thermal comfort in an indoor environment [5], [10]. However, most of these models and standards only focus on people’s reactions when exposed to the air in offices, classrooms, restaurants, bedrooms, etc., and few consider people’s thermal comfort during showering in a bathroom. There is still limited knowledge on predicting people’s thermal comfort based on showering conditions, such as water temperature, air temperature, and water flow rate.

In addition, thermal comfort is closely related to energy consumption. Adjusting the operating temperature of air conditioners or radiators could improve occupants’ thermal comfort. However, it might also lead to an increase in energy consumption. It has always been a challenge to reduce energy consumption without sacrificing occupants' thermal comfort [11]. Many studies have been conducted to try to find the balance between thermal comfort and energy efficiency. Many of them demonstrated that it is possible to save 10%-34.4% of energy by adjusting the temperature within the comfort range [12]–[15]. Kwong et al. [11] concluded that conducting thermal comfort surveys effectively identifies the potential for energy conservation from a review of thermal comfort studies. Although almost all these studies focused on the energy used by air conditioners and energy consumed during showering, including the energy consumed by hot water systems and heating/cooling and ventilating systems, is seldom mentioned, the dilemma between energy efficiency and thermal comfort also exists during showering, and the thermal comfort investigation should also work.

This study develops a thermal comfort prediction model to evaluate people's physiological reactions and comfort levels under different showering conditions. Only standing showering was considered in the current study since it is faster, more water-saving, and more popular in current society compared with bathing [16]. The results can be applied to identify the optimal showering environment considering thermal comfort and energy efficacy. This model could help design and maintain a safe and comfortable showering environment, prevent health complications and bathing-related accidents (especially among the aging population), and save building energy consumption.

2. Methodology

A numerical simulation method was applied in the current study to investigate the effect of thermal conditions on the human body and to further evaluate thermal comfort in a bathroom during undressing and showering. Figure 1 illustrates this study's research framework and activities, described in detail in the following subsections.

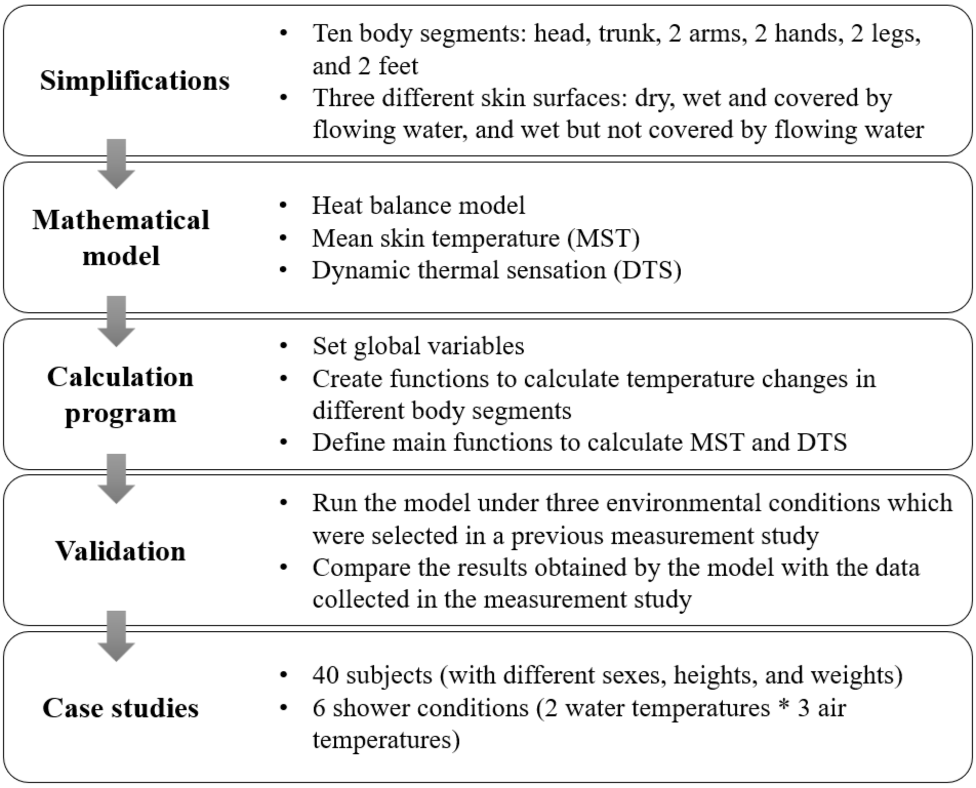


Figure 1. The research process of the current study.

2.1 Assumptions

First, several simplifications were made as follows:

The human body is simplified into six segments (head, trunk, arms, hands, legs, and feet) based on Stolwijk's model [17]. The head is assumed to be a sphere, while the other segments are considered to be cylinders with constant circumferences [17].

The current study considered two processes, namely, undressing and showering. During the undressing process, all the body segments were dry, so the heat was exchanged with the ambient environment by convection, radiation, and evaporation from the skin. During the showering process, when the body areas are continuously covered with flowing water, convection is the dominant form of heat transfer between the human body and the flowing water; for the body areas that are wet but not continuously covered with flowing water, the heat is exchanged by convection, radiation, and evaporation from the water film on the skin, which is the maximum evaporation since the skin is covered by water and has reached its saturated vapor pressure.

2.2 Mathematic models

Second, several mathematic models, including the heat balance model, mean skin temperature model, and dynamic thermal sensation model, were adapted and modified in the current study. The fundamental equation to study the human body's thermoregulatory mechanisms is the heat balance equation:

$$M - W = C + R + E + Q \quad (1)$$

Where M is the metabolic rate, which is 87 W/m^2 (1.5 MET) during showering [18]; W is the external work rate, which is zero during showering; C is the convection heat exchange rate between the human skin and the air or water close to the skin; R is the radiation heat exchange rate between human skin and the ambient environment; E is the heat exchange rates by evaporation which consists of E_{sw} (sweating), E_{diff} (skin diffusion) [19], when the skin is covered by water film, the evaporation from the skin surface reaches to its maximum level (E_{max}) [20]; Q is the net heat gain or loss of the body; Besides, the heat transfer via the respiratory tract, i.e., E_{res} and C_{res} should also be considered [21].

During the undressing period, the body segments are dry, and the heat balance equation can be simplified into Equation 2, and the related variables can be calculated based on Equations 3-7 [19], [21], [22].

$$M = C + R + E + Q \quad (2)$$

$$C = \alpha_c \times (T_{skin} - T_a) \quad (3)$$

$$R = \alpha_r \times (T_{skin} - T_r) \quad (4)$$

$$E = E_{sw} + E_{diff}$$

$$= 0.42 \times (M - 58.2) + 3.05 \times 10^{-3} \times (256 \times (35.7 - 0.0275 \times M) - 3373 - P_a) \quad (5)$$

$$E_{res} + C_{res} = 0.0014 \times M \times (34 - T_a) + 0.0017 \times M \times (58.7 - P_a/133.3) \quad (6)$$

$$P_a = RH \times P_{sat,T_a} = RH \times 133.33 \times 10^{(8.07 - 1730.63/(233.43 + T_a))} \quad (7)$$

Where α_c and α_r are the convective and radiative heat transfer coefficients between the human skin and air ($W/(m^2 \cdot K)$), which are determined based on Stolwijk's estimations (see Table 1) [17]; T_{skin}, T_a, and T_r are skin temperature (K), air temperature (K), and radiant temperature (K), respectively; P_a is the ambient vapor pressure (Pa); RH is the relative humidity (%).

Table 1 Parameters used in the model [17].

Body segment	Heat transfer coefficients between skin and air ($W/(m^2 \cdot K)$)		Percentage of segment skin area (%)		Percentage of segment skin weight (%)
	Convective α_c	Radiative α_r	Men	Women	Men/ Women
Head	6.4	3.2	7.00	6.49	7.20
Trunk	5.2	2.5	36.02	36.07	36.20
Arms	5.0	3.5	13.41	12.70	13.00
Hands	3.5	3.9	5.00	4.50	5.00
Legs	4.7	3.2	31.74	33.92	32.20
Feet	4.7	3.5	6.86	6.32	6.40

During the showering period, the heat exchange process for the body parts should be considered separately, based on whether the skin is covered with flowing water, and the heat balance equation is modified correspondingly as:

$$M = \beta \times C_w + (1 - \beta) \times (C + R + E_{max}) + E_{res} + C_{res} + Q \quad (8)$$

Where β is the ratio of the area that is continuously covered with flowing water to the area of the whole body segment, which is decided to be 0.4, 0.12, 0.12, 0.46, and 0.46 for the trunk, arms, hands, legs, and feet respectively [23];

For the skin areas continuously covered with flowing water, R and E are 0, and C_w can be calculated based on Equation 9. The E_{max} can be calculated based on Equations 10 and 11 [19], [20] for the wet skin areas not continuously covered with flowing water.

$$C_w = \alpha_{cw} \cdot (T_{skin} - T_w) \quad (9)$$

$$E_{max} = 16.5 \times \alpha_c \times \left(P_{sk,sat} - P_a\right) \times 10^{-3} \tag{10}$$

$$P_{sk,sat} = 225.24 \times (35.7 - 0.0275 \times M) - 2493.1 = 5114.38 \tag{11}$$

Where α_{cw} is the convective heat transfer coefficient between the human skin and water flow (W/(m^2·K)), which is 104 W/(m^2·K) based on Munir's experiment [23]; T_w is the water temperature (K); $P_{sk,sat}$ is the saturated vapor pressure on the skin surface (Pa).

Based on the equations mentioned above and the initial values of the related variables, the Q can be obtained for different body parts. Then, the related skin temperature changes can be calculated using Equation 12.

$$Q \cdot A_{sk,seg} = M_{sk,seg} \cdot c \cdot \Delta T \tag{12}$$

Where $A_{sk,seg}$ is the skin area for each body segment (m^2), which can be estimated with the total skin area (Equation 13) and the ratio of the segment skin area to the total skin area (see Table 1); $M_{sk,seg}$ is the skin weight for each body segment (kg), which can be estimated with the total skin weight (which is approximately 16% of the entire body weight) and the ratio of the segment weight to the total skin weight (see Table 1); c is the average specific heat capacity of human skin, which is 3.4 kJ/(kg· K) [24]; and ΔT is the temperature changes (°C).

$$A_{sk,total} = 0.202 \cdot weight^{0.425} \cdot height^{0.725} \tag{13}$$

After knowing the skin temperature changes at different body segments, the transient mean skin temperature (MST) can be calculated based on the equation developed by Hardy and Dubois [25] since the body regions considered in this equation were similar to body segments tested by Stolwijk [17] and Munir et al. [23]. Nonetheless, it is worth noting that Hardy and Dubois estimated the MST based on the temperature measured at seven different body parts, with one more (thigh) than Stolwijk's model. Considering the slight temperature difference between the leg and thigh, the MST model was modified into Equation 14 in this study to make it consistent with Stolwijk's model,

$$T_{sk,mean} = 0.35 \times T_{trunk} + 0.14 \times T_{arm} + 0.32 \times T_{leg} + 0.07 \times T_{head} + 0.07 \times T_{feet} + 0.05 \times T_{hand} \quad (14)$$

Where $T_{sk,mean}$ is the MST (K); T_{trunk}, T_{arm}, T_{leg}, T_{head}, T_{feet}, and T_{hand} are temperatures on the trunk, arm, leg, head, feet, and hand skin, respectively (K). According to the MST, the dynamic thermal sensation (DTS) of showering people could be predicted since changes in skin temperature are closely related to thermal perceptions [20]. The DTS model (Equation 15) developed by Takada et al. [26] was applied in the current study to predict showering people's DTS based on their MST and its time differential (i.e., $dT_{sk,mean}$).

$$DTS = -25.119 + 0.746 \times T_{sk,mean} + 2.255 \times dT_{sk,mean} \quad (15)$$

2.3 Development of the calculation program

This study used Python as the programming language to calculate human MST and DTS for two processes: undressing in the dressing room and showering in the bathroom. First, all the global variables, including all the environmental conditions and constant coefficients, were defined based on the assumptions and values in Tables 1 and 2. Second, twelve functions were created based on the mathematic models to calculate the skin temperature changes on six body segments during the two periods. Third, the primary function was generated to calculate the MST and DTS for each second during the periods. All the computed results (i.e., MST and DTS) were saved in a worksheet for further analysis.

3. Model validation

The results collected by a previous experimental study conducted by Hashiguchi et al. [3] were selected as references to examine the accuracy of the calculation model. In this experiment, Hashiguish et al. [3] measured the MSTs of eight healthy male subjects under three different thermal environment conditions (i.e., room temperatures: 25°C, 17.5°C, and 10°C) during a seven-minute undressing and 10-minute showering. To compare the results calculated by the program with those collected by Hashiguish et al.

[3], the air temperatures, undressing/showering duration, and the subject's characteristics were set the same as in the experiments (see Table 2).

Table 2 Variable settings for the validation.

Environment conditions	Air temperature:	25 ℃/ 17.5 ℃/ 10 °C
	Water temperature:	41°C
	RH during undressing:	50%
	RH during showering:	80%
Time durations	Undressing:	420s
	Showering:	600s
Subject's characteristics	Gender:	Male
	Weight:	60.2 kg
	Height:	167.2 cm

Figure 2 presents the MSTs obtained from the current study and the study conducted by Hashiguish et al. [3]. The results were similar in most cases, especially during the undressing period. A series of t-tests were conducted to analyse the results further. As shown in Table 3, the results indicated no significant difference in MSTs between these two studies ($p>0.05$), regardless of the settings. During the undressing period, the difference between the average MSTs obtained from these two studies was less than 0.5 ℃, while during the showering period, the differences were slightly larger, i.e., between 0.5 -1 ℃. The differences during the showering period were mainly caused by the last three minutes. As shown in Figure 2, occupants' MST decreased considerably in the last three minutes of showering in the study conducted by Hashiguish et al., which, unfortunately, was not explained in their publication. However, such a decrease in MST during hot water showering is unreasonable. One possible assumption might be that the occupants shut down the hot water and dried their bodies during the last three minutes. Additionally, the real-life MSTs collected by Hashiguish et al. [3] have more fluctuations, while the mathematical model's results changed more smoothly. Although the model cannot accurately predict the fluctuations, the average MSTs during these two periods were quite similar between the collected data and the calculated results of the current study (See Table 3). Therefore, the methods introduced in section 2 were considered validated.

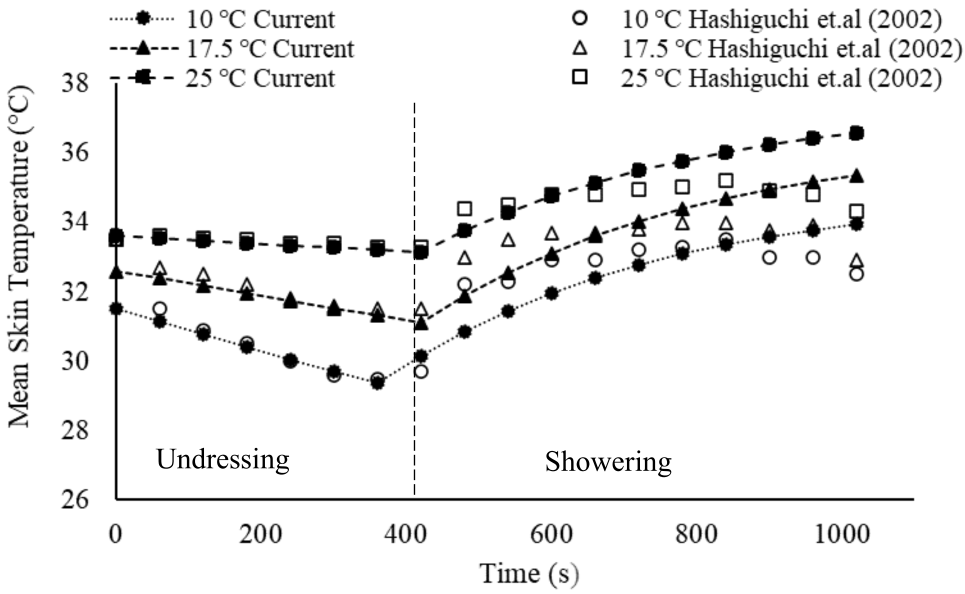


Figure 2. Mean skin temperature comparison between the current study and the study conducted by Hashiguchi et al. [3].

Table 3 Comparison results obtained from paired samples t-tests.

	Undressing		**Showering**		**Whole processes**	
Settings	Current	Hashiguchi et al. [3]	Current	Hashiguchi et al. [3]	t(18)	p
10 °C	30.4 (0.8)	30.8 (1.4)	32.5 (1.3)	32.6 (1.0)	-0.638	0.532
17.5 °C	31.8 (0.5)	32.2 (0.7)	34.0 (1.2)	33.6 (0.4)	0.458	0.653
25 °C	33.4 (0.2)	33.4 (0.1)	35.4 (0.9)	34.8 (0.3)	1.934	0.070

Note: $p<0.05$ was considered statistically significant and marked in bold.

4. Case studies

The showering conditions (e.g., water temperature, air temperature) and characteristics varied greatly, significantly impacting people's thermal comfort during showering. To demonstrate the influence of environmental conditions on people's thermal comfort, this study calculated different people's MST under different showering conditions using the real-life data collected by a previous study. The data includes 31 subjects' personal information, i.e., sex, weight, height, and six showering conditions (see Table 4). Based on this, the optimal showering conditions for different people can be identified.

Table 4 Showering settings corresponding to male/female subjects' cold/neutral/warm sensations.

Showering conditions	C1	C2	C3	C4	C5	C6
Water temperature (℃)	38.6	38.6	38.6	39.2	39.2	39.2
Air temperature (°C)	17.7	25.8	29.8	17.7	25.8	29.8
Radiant temperature (°C)	17.3	25.4	29.4	17.3	25.4	29.4

The showering thermal sensations of 31 subjects, including 12 females and 19 males, were investigated by a previous study (Wong et al., 2022). The average height /weight of the females and males were 155.5 cm/54.6 kg and 173.6 cm/ 66.8 kg, respectively. These subjects were classified into three groups based on their Body Mass Index (BMI) to test the impact of body mass. It should be noted that the classification was not the same as the one used by the Centers for Disease Control and Prevention (CDC) [27]. Since most subjects' BMIs fell into the "Healthy (18.5-24.9) status" of the CDC, this study evenly divided these subjects into three groups to better illustrate the impact of BMI: the relatively underweight group (BMI<21), the average group (21≤BMI<24), and the relatively overweight group (24≤BMI). The detailed anthropological parameters of the twelve subjects are shown in Table 5.

Table 5 Anthropometric parameters of the subjects in the case studies.

ID	Sex	Height (cm)	Weight (kg)	BMI (/)	Group*	ID	Sex	Height (cm)	Weight (kg)	BMI (/)	Group*
1	F	154	48	20.24	1	17	F	153	64	27.34	3
2	M	172	73	24.68	3	18	F	155	59	24.56	3
3	M	176	67	21.63	2	19	M	168	75	26.57	3
4	M	177	54	17.24	1	20	F	162	52	19.81	1
5	F	152	57	24.67	3	21	M	178	83	26.20	3

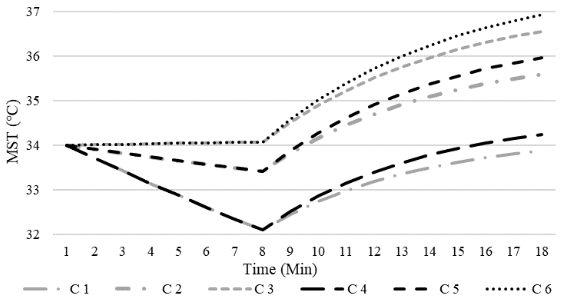
6	M	182	86	25.96	3	22	M	167	56	20.08	1
7	M	171	52	17.78	1	23	M	179	71	22.16	2
8	M	173	58	19.38	1	24	F	147	43	19.90	1
9	M	170	60	20.76	1	25	M	178	76	23.99	2
10	M	165	61	22.41	2	26	F	162	53	20.20	1
11	F	161	56	21.60	2	27	F	158	61	24.44	3
12	M	175	67	21.88	2	28	F	157	63	25.56	3
13	F	149	52	23.42	2	29	M	176	69	22.28	2
14	M	169	71	24.86	3	30	F	156	47	19.31	1
15	M	172	69	23.32	2	31	M	167	62	22.23	2
16	M	184	60	17.72	1						

Note: the group numbers 1, 2, and 3 correspond to the categories of underweight, average weight, and overweight, respectively.

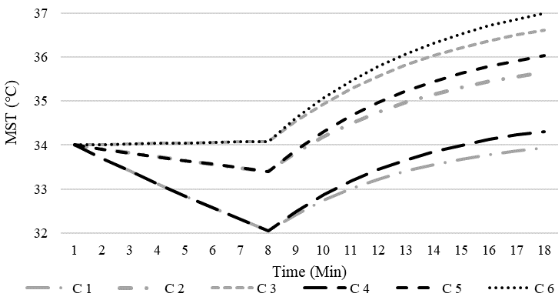
5. Results

5.1 Descriptions of skin temperatures and thermal sensations for different cases

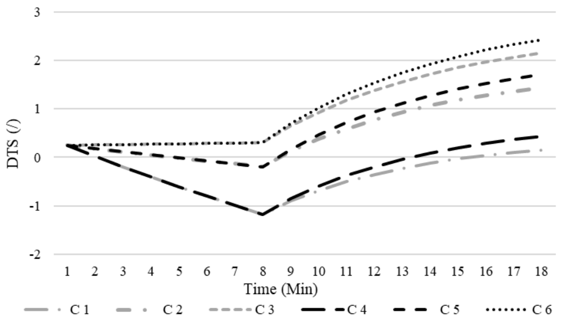
The average MST and DTS of the female and male subjects under six different showering conditions are shown in Figure 3. As can be seen, the variation tendencies of MST/DTS were similar for female and male subjects under the same showering environment. For conditions 1 and 4 (i.e., the air temperature was 17.7 ℃, and the water temperature was 38.6 ℃ and 39.2 ℃, respectively), subjects' MSTs decreased with time during the undressing period, then increased to the original level, i.e., around 34 ℃, during the showering period. The same trends were observed for their DTSs since DTS was calculated based on MST. For conditions 2 and 5 (i.e., the air temperature was 25.8 ℃, and the water temperature was 38.6 ℃ and 39.2 ℃, respectively), subjects' MSTs/DTSs also decreased with time during the undressing period, similar as conditions 1 and 4, but with less amplitude. In contrast with the undressing period, subjects' MSTs/DTSs increased significantly during the showering period in these conditions because of the high water temperature. For conditions 3 and 6 (i.e., the air temperature was 29.8 ℃, and the water temperature was 38.6 ℃ and 39.2 ℃, respectively), subjects' MSTs hardly changed during the undressing period, then increased significantly to almost 37 ℃ during the showering period.



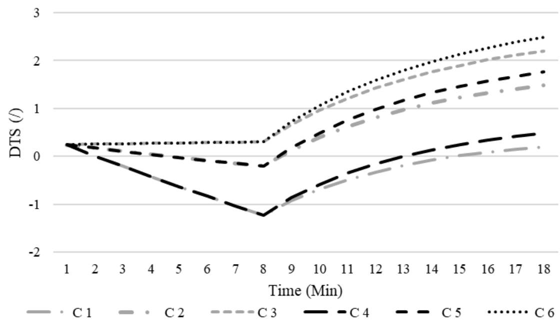
a) Male subjects' MST



b) Female subjects' MST



c) Male subjects' DTS



d) Female subjects' DTS

Note: C1: T_a =17.7 ℃, T_w =38.6 ℃; C2: T_a =25.8 ℃, T_w =38.6 ℃; C3: T_a =29.8℃, T_w =38.6 ℃; C4: T_a =25.8 ℃, T_w =39.2 ℃; C5: T_a =25.8 ℃, T_w =39.2 ℃; C6: T_a =29.8 ℃, T_w =39.2 ℃.

Figure 3 Subjects' MST and DTS under different bathroom environments.

5.2 Difference in MST/DTS between female and male subjects

To identify the impact of gender on people's MST/DTS during showering, a series of paired-sample t-tests were conducted to compare the MST/DTS between female and male subjects with similar BMIs and under the same environments. Related results are shown in Table 6. It can be found that, in general, females' MST/DTS were significantly higher than males. However, the opposite difference was observed in the undressing period; females' skin temperatures and thermal sensations were considerably lower than males', although the absolute difference was relatively small. On the contrary, females' skin temperatures and thermal feelings were significantly higher than males' during the showering periods. This effect can also be seen from the comparison between the two columns of figures shown in Figure 3. Although females' MST/DTS were lower than males before showering, they increased much faster than males in the showering period, so the final MST and DTS of females were higher than males. These results indicate that females were more sensitive to thermal environments since in the (cold) environment where subjects' MST/DTS decreases with time (i.e., undressing period), females' declining rates were faster than males, and in the (hot) environment where subjects' MST/DTS increases with time (i.e., showering period), females' rising rates were also faster than males.

Table 6 Differences in MST/DTS between female and male subjects.

Tested variable	**Periods**	**Average (standard deviation) of MST or DTS**			**t**	**p**
		Female	Male	Difference		
MST (℃)	Whole	34.31 (0.92)	34.29 (0.89)	0.025 (0.03)	17.88	<0.001
	Undressing	33.75 (0.27)	33.75 (0.26)	-0.005 (0.01)	-9.95	<0.001
	Showering	34.71 (1.00)	34.66 (0.98)	0.46 (0.25)	32.25	<0.001
DTS (/)	Whole	0.45 (0.85)	0.42 (0.83)	0.024 (0.04)	15.53	<0.001
	Undressing	-0.07 (0.17)	-0.07 (0.17)	-0.003 (0.004)	-10.135	<0.001
	Showering	0.81 (0.95)	0.76 (0.93)	0.04 (0.002)	21.336	<0.001

Note: Results were obtained from paired-sample t-tests; a p-value less than 0.05 means statistical significance.

5.3 Difference in MST/DTS between underweight, average, and overweight subjects

Figure 4 illustrates the MST and DTS of subjects with different BMIs during the underdressing and showering periods. What can be seen in this figure is that underweight subjects seem to be more sensitive to the thermal environment. Similar to females, underweight subjects' MST and DTS were the lowest, compared with other subjects, during the underdressing period, when all the subjects' skin temperatures were gradually decreasing, while their MST and DTS were the highest during the showering period when all the subjects' skin temperature was increasing progressively. The opposite trend was found for overweight subjects. In other words, under the same thermal conditions, skin temperature and thermal sensation fluctuations were more significant for underweight subjects and lower for overweight subjects than average subjects. However, no statistically significant differences in MST/DTS were identified between these three groups of subjects (i.e., the p-values of the one-way ANOVA tests were more significant than 0.05, as shown in Figure 4). This result might be caused by the slight differences in the mean values of MST/DTS between these subjects, especially during the showering period. Although underweight subjects experienced marked changes in MST/DTS, their MST and DTS were the lowest at the beginning of showering and the highest at the end of it. Their mean MST and DTS were not so different from the other subjects.

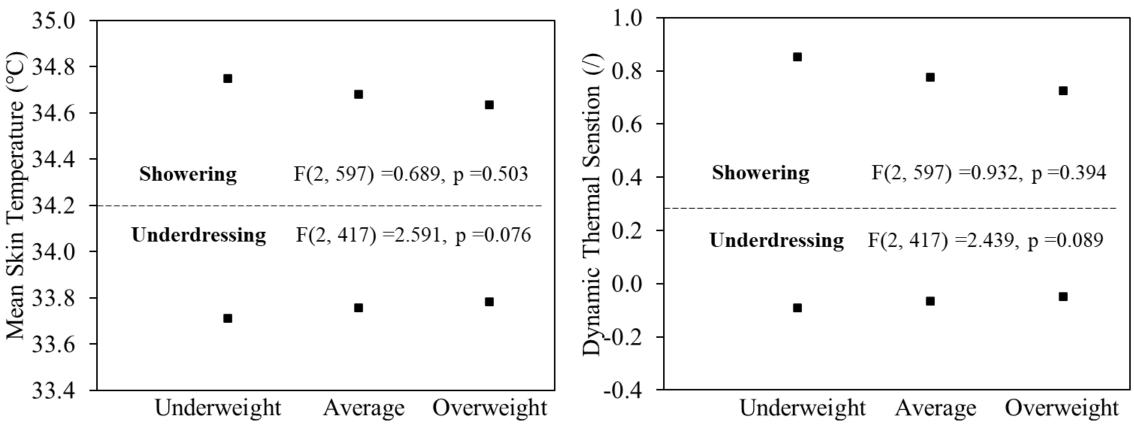


Figure 4. The MST and DTS of underweight, average, and overweight subjects.

To further verify the impact of BMI on the variation of subjects' MST/DTS, the difference in the change rates of MST/DTS over time (i.e., the regression coefficients between MST/DTS and time) were checked among the three groups of subjects. As shown in Table 7, there were statistically significant differences in the change rates of MST/DTS among underweight, average, and overweight subjects. All subjects' change rates were negative during the undressing period and positive during the showering period. Moreover, the absolute change rates of MST/DTS were the highest for the underweight subjects and lowest for the overweight subjects. These results demonstrated again that underweight subjects are more sensitive to thermal environments than average and overweight subjects, as discussed in the above paragraph.

Table 7 Differences in the change rates of MST/DTS over time among underweight, average, and overweight subjects.

Tested variable	Periods	Change rates of MST/DTS over time (Regression coefficients between MST/DTS and time)			F	p
		Underweight	Average	Overweight		
MST (℃)	Undressing	-0.069 (0.00)	-0.059 (0.00)	-0.053 (0.00)	441.96	<0.001
	Showering	0.146 (0.01)	0.143 (0.00)	0.135 (0.00)	297.33	<0.001
DTS (/)	Undressing	-0.041 (0.00)	-0.035 (0.00)	-0.032 (0.00)	9.09	0.007
	Showering	0.140 (0.00)	0.139 (0.00)	0.133 (0.00)	8.26	0.009

5.4 Impacts of air temperature and water temperature on subjects' MST/DTS during showering

A series of linear regression analyses were conducted to identify the impacts of air temperature and water temperature on subjects' MST/DTS during the undressing and showering periods. Results are presented in Table 8. Since there was no water in the undressing period, the water temperature was not considered in the undressing period. Additionally, viewing both MST and DTS changed with time, and to better explain their variations (i.e., to get higher R^2 values), time was included as one independent variable in the regression analyses. As shown in Table 8, air and water temperatures significantly impacted subjects' MST and DTS. Besides, it can be found that during the undressing period, the impacts of air temperature on MST and DTS were quite significant (the Standardized β were larger than 0.7) since the air temperature was the only environmental variable that could affect subjects' skin temperature during undressing. However, its impact decreased during showering, and the water temperature was the most dominant factor of skin temperature in this period.

Table 8 Impact of air and water temperatures on subjects' MST and DTS.

Independent Variable	Periods	Independent Variables	β	Standardized β	95.0% Confidence Interval for β	P value*
		Air temperature	0.094	0.790	0.089 - 0.099	<0.001

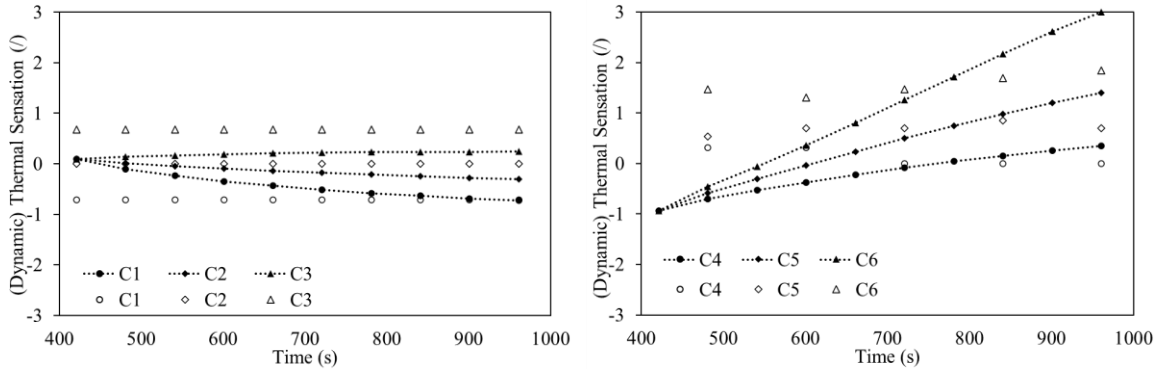
MST (℃)	Undressing (R^2=0.83)	Time	-0.060	-0.451	-0.065 - -0.055	<0.001
	Showering (R^2=0.44)	Air temperature	0.210	0.475	0.199 - 0.221	<0.001
		Water temperature	0.388	0.710	0.374 - 0.401	<0.001
		Time	0.141	0.409	0.133 - 0.150	<0.001
DTS (/)	Undressing (R^2=0.84)	Air temperature	0.061	0.815	0.058 - 0.064	<0.001
		Time	-0.036	-0.431	-0.039 - -0.033	<0.001
	Showering (R^2=0.44)	Air temperature	0.186	0.446	0.174 - 0.199	<0.001
		Water temperature	0.355	0.690	0.340 - 0.371	<0.001
		Time	0.137	0.421	0.127 - 0.147	<0.001

Note: Results were obtained from linear regression analyses, and a p-value less than 0.05 means the observed impact is statistically significant.

6. Discussions

6.1 Accuracy and application of the prediction model

The model developed by this study, as described in section 2.2, has been validated by comparing the predicted MST with the results obtained by a previous experiment study [3]. However, since no data about DTS could be gathered from earlier studies, no related validation was conducted before the case studies. For those who investigated people's thermal sensations during showering (e.g., [28] and [29]), no subjects' anthropometric information was mentioned. Considering DTS was calculated based on MST, the prediction of MST can be seen as the basis of this study. Thus, the validation of MST's prediction was more critical and necessary. Nonetheless, the evaluation of the DTS's prediction should not be ignored. Although no subject information was known in previous studies, results obtained in these studies could be compared with the average values of all the subjects tested in the current study. Therefore, the thermal sensations (TSV) collected by two previous studies (i.e. [28] and [29]) in eight showering conditions were applied to conduct the comparison with the DTS calculated by this study under the same conditions. Since the TSVs were collected after showering in the study conducted by Wong et al. [28] and no specific time was mentioned, these results were assumed to be the same during the showering. As shown in Figure 5 a), the DTSs calculated in the current study at the end of a ten-minute shower were similar to the TSVs observed by Wong et al. [28] after showering.



a) Comparison with Wong et al. [28]   b) Comparison with Luo et al. [29]

Note: The solid markers represent the results obtained from the current study and the hollow markers represent the results obtained from the previous studies; C1-C3 were the showering conditions examined by Wong et al. [28] at T_w=38.8 °C and T_a =17.7 °C, 25.8 °C, 29.8 °C respectively; C4-C6 were the showering conditions examined by Luo et al. [29] at T_a=25 °C and T_w =38 °C, 40 °C, 42 °C respectively.

Figure 5. Comparison of thermal sensations obtained from the current study and previous studies.

However, apparent differences were identified by comparing the calculated DTSs during showering with the TSVs collected by Luo et al. [29]. Figure 5 (b) shows that people's real thermal sensations didn't change much during showering, while the calculated DTSs kept increasing under the examined showering conditions. Although the thermal senses measured by Luo et al. [29] at the end of showering were relatively lower than the DTSs calculated by this study, the MSTs were similar, as people's MSTs measured by them were about 35.9 ℃, 36.3 ℃, and 37.0 °C at the end of showering with 38 °C, 40 °C, and 42 °C hot water, while the results calculated by the current study were 35.0 ℃, 36.0 ℃ and 37.1℃ respectively. What is exciting and worth noting is that in the survey conducted by Luo et al. [29], even though people's skin temperature kept increasing during the hot water shower (e.g., increased from 33.5 °C to 35.9 °C during 38 °C hot water shower), their thermal sensations were decreasing (e.g., fell from 0.4 to 0). The relationships between human MST and DTS might differ in terms of exposure to water and air. Since the DTS in the current study was calculated based on the equation (i.e., Equation 15) developed for people exposed to air [26], it undoubtedly led to inaccurate DTS predictions for people exposed to water. Therefore, an equation to describe the relationship between DTS and MST during showering is still needed, and a related experiment is suggested for future studies.

6.2 Individual differences in thermal comfort during showering

This study demonstrated significant differences in MST/DTS between females and males. Based on the equations and coefficients shown in section 2.2, two reasons can be found to explain this difference. The first concerns the different percentages of segment skin area between females and males. As shown in Table 1, the rate of female legs' skin area (33.92) was much higher than males (31.74), and the temperature of the leg plays a relatively important role in the MST (see Equation 14), while the opposite trend was found for other body segments. Additionally, although the BMI (= weight/height^2) was similar for males and females in the same BMI groups (underweight, average, and overweight), the proportion of height$^{0.725}$/weight$^{0.575}$, which is the coefficient, decides the ΔT (see Equation 16, deduced from Equations 12 and 13), was not similar. Specifically, for people with equal BMI, the shorter the proportion is, the larger the skin temperature changes. Since females are usually shorter than males (for those with similar BMIs), their skin temperatures change larger than males.

$$\Delta T = \frac{Q\times 0.202\times \%\, skin\ area}{\%\, skin\ weight\times c}\frac{height^{0.725}}{weight^{0.575}} = \frac{Q\times 0.202\times \%\, skin\ area}{\%\, skin\ weight\times c}\frac{1}{BMI^{0.575}height^{0.425}} \quad (16)$$

Besides, it was also found that the underweight subjects were more sensitive to the thermal environment than the average and overweight subjects. The reason was similar. As shown in Equation 16, for subjects with similar height, the smaller the BMI, the larger the value of 1/ BMI$^{0.575}$, and the more considerable skin temperature changes.

Although the individual differences in thermal comfort during showering were rarely reported before, they were well-studied in other life scenes (such as working in offices, studying in classrooms, or sleeping in bedrooms) when exposed to the air. According to previous studies, age and gender are the two significant factors that cause individual differences [30], [31]. It seems that female and elderly occupants are more sensitive to uncomfortable thermal environments than male and young occupants

[32]–[34]. Additionally, the impacts of BMI on thermal comfort were also summarized. It was found that overweighted occupants were more resistant to the cold environment [30], similar to the results identified by the current study. However, they were also found to be less comfortable (or more sensitive) in the hot environment [35], [36], contrary to the results shown in Section 5.3. This might be because the metabolic rate of all the subjects, whether overweight or underweight, was assumed to be the same in the current study. However, according to White and Seymour [37], humans' basal metabolic rate is positively related to their body mass, which means overweight (underweight) subjects should have higher (lower) metabolic rates than subjects with healthy weights and thus larger (smaller) changes in skin temperature. Therefore, a more accurate metabolic rate should be provided to improve the model's accuracy, which might also reflect the impact of age.

6.3 Impact of water and air temperature on thermal comfort during showering

This study demonstrated significant positive impacts of water and air temperature on subjects' skin temperature and thermal sensation during showering. Besides, it was found that water temperature was more influential than air temperature. Similar results, namely, the water temperature has a more significant impact on occupants' thermal sensation than the air temperature, were also identified by Wong et al. [28]. The different impacts of water and air temperatures might result from a larger heat transfer coefficient between human skin and water flow than between human skin and air (as shown in section 2.2). Considering the results shown in Figure 3 and the significant impact of water temperature, the water temperature during showering was suggested to be controlled under 40 °C to avoid thermal discomfort during a long showering time.

Additionally, it should be noted that the impact factors of water and air temperatures (see Table 8) calculated in the current study were quite different from the results shown by Wong et al. [28]. This might be caused by the fact that the impact factors were determined from actual measurement data in the study conducted by Wong et al. [28], while they were calculated based on theoretical deduction and simulated data in the current study. For the impacts of temperature settings during showering on occupants' skin temperature, most published studies only focused on one factor, either water temperature [29], [38] or air temperature [3]; hardly any studies investigated the combined impacts of water and air temperature. Considering the significant effects of the thermal environment during showering on occupants' health, as mentioned in Section 1, future studies are suggested to conduct related measurements to confirm the exact impacts of water and air temperature on subjects' skin temperature and thermal sensation during showering.

6.4 Identify the optimal showering environment considering both thermal comfort and energy-saving

Recently, Zhang et al. [39] developed a mathematical energy consumption model to investigate the relationship between showering conditions and the energy consumption rate, as shown in Equation 17.

$$Q_{total} = 0.19 \times T_a + 0.51 \times T_w + 62.08 \times m_a + 43.37 \times m_w - 23.85 \quad (17)$$

Where m_a is the compartment mass ventilation rate ($kg\cdot s^{-1}$), and m_w is the water flow rate for showering ($kg\cdot s^{-1}$). According to this study, water flow rate had the most significant impact on total energy consumption during showering, followed by water temperature, air temperature, and ventilation rate. Since water flow and ventilation rates were not considered in the current study, no related discussion will be given here. Regarding the air temperature and water temperature, it was found that the influence of water temperature on total energy consumption was 2.7 times higher than the influence of air temperature (see Equation 17). In contrast, the effect of water temperature on the occupants' thermal comfort was 1.8 times higher than the influence of air temperature (see Table 8). This indicates that water temperature plays a more critical role than air temperature in managing energy consumption and thermal comfort during showering, and the predominance of water temperature is more evident in determining energy consumption. Specifically, based on the results shown in Table 8, occupants should have similar thermal feelings during showering if the water temperature decreases by 1°C while the air temperature increases by 1.8 °C. Nevertheless, according to Equation 17, this adjustment could save 0.03 kWh of energy consumption during a 10-minute shower. Therefore, the water temperature is suggested to be set at a lower level. As compensation, the air temperature could be higher to maintain thermal comfort while reducing energy consumption.

7. Conclusion

This study developed a mathematical model to predict human skin temperature and thermal sensation before and during showering in a bathroom. The model was validated by comparing the obtained results with a previous measurement study. Then, case studies were conducted to identify the comfortable showering environment for different occupants. Five environment settings (i.e., five combinations of water and air temperatures) and 31 subjects (12 females and 19 males) were considered in the case studies. According to the analysis results, the following conclusions were drawn:

1. Female and underweight subjects were more sensitive to the thermal environments in bathrooms, and their skin temperature and thermal sensations varied more significantly during showering. In contrast, male and overweight subjects' skin temperature and thermal sensations were more stable.
2. Water and air temperatures significantly positively impact occupants' skin temperatures and thermal sensations during showering, and the impact of water temperature was much bigger than that of air temperature.
3. Even with the same skin temperature, people might have different thermal sensations between water and air exposure.
4. It is suggested that water and air temperatures be kept lower to reduce energy consumption and maintain thermal comfort during showering.

The mathematical model proposed by this study could predict skin temperature relatively accurately based on bathroom temperature, water temperature, and occupants' gender, weight, and height. This could provide a reference for people to set a comfortable and energy-efficient showering environment. However, since the mathematical model proposed by this study was purely based on theoretical deduction and empirical coefficients gathered from previous studies, many assumptions and simplifications were made during the calculation, which might lead to some deviation from the exact results. Related measurements are suggested to validate this model further, especially for the thermal sensation.

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