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Thermal energy consumption in comfortable showering environments for residential buildings

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SUMMARY
This study developed a mathematical energy consumption model for different showering conditions to find effective energy-saving methods without sacrificing occupants' thermal comfort during showering. Air temperature, water temperature, ventilation rate, and water flow rate were potentially influential factors. Results indicated that water flow and ventilation rates are the most and least significant variables regarding energy consumption. Therefore, the ventilation rate was suggested to be at least 0.03 kg/s (to maintain a relatively good air quality), and the water flow rate was suggested to be lower than 0.15 kg/s (corresponding to the first grade of the Water Efficiency Labelling Scheme (WELS) on Showers). The findings of this study could help residents and facility managers easily find out the optimal showering environment setting in terms of thermal comfort, energy consumption, and environmental effects.

KEYWORDS
Energy consumption, showering, thermal comfort, ventilation rate, water flow

1 INTRODUCTION
Despite increased awareness about energy conservation in the past decade, the energy consumed for water heating increased by 7% from 2008 (17%) to 2018 (24%) in Hong Kong. According to a previous study, the average shower frequency in Hong Kong is more than once per day, and the average shower time is about 14 minutes in the summer and 18 minutes in the winter (Wong et al., 2022). This showering behaviour leads to 60% more energy consumption per capita in Hong Kong than in its nearby cities. Additionally, to improve showering comfort in winter, bathroom heaters/thermo ventilators have become popular recently and have been adopted in many residential bathrooms in Hong Kong. However, the power of most bathroom heaters is relatively high, indicating that much more energy was consumed during showering. Therefore, there is considerable potential for energy conservation in bathrooms in Hong Kong.

Showering behaviour (including water flow rate and showering temperature) and indoor bathroom environment (including air temperature and ventilation rate) could vary significantly between individuals. For example, the preferred shower temperature and the range of water flow rate in Switzerland are 36 ℃and 7.6-14.7 L/min (Ableitner et al., 2016), in the United States are 40 ℃ and 4.9-12.9 L/min (Wilkes et al., 2005), while in Hong Kong are 38.6 ℃ (Wong et al., 2016) and 9-16 L/min (Hong Kong water supplies department, 2018). All these variables could have significant impacts on energy consumption. However, the integrated effects of these variables are rarely studied because there are interactions (for example, increasing the ventilation rate might decrease air temperature) and complementary results between them (for example, if the air temperature drops, the water temperature needs to increase).

Thus, the current study developed a regression model to find out the integrated effects of air temperature, water temperature, ventilation rate, and water flow rate on total energy consumption in Hong Kong's bathrooms in winter. By analyzing the coefficients in the models, the impacts of these variables on energy consumption during showering can be qualified. Based on that, the best showering condition can be identified which could not only keep the occupant feeling comfortable but also consume relatively less energy.

2 METHODS

2.1 Assumptions and parameters values settings

To describe the energy consumption during showering in a mathematical model, three simplifying assumptions were made: i) It was assumed that the human is in a thermal balanced state, namely, no energy is emitted or absorbed by the human body. ii) The energy absorption by the bathroom surface and the energy emission by the lighting system is neglected. Therefore, only two energy sources, i.e., hot water and a radiator, are assumed in the bathroom. iii) The energy efficiency of the water heater is assumed to be 100%.

Besides the assumptions, four initial conditions were adopted in this study: i) Based on the typical winter temperature in Hong Kong, the outdoor ambient temperature was assumed to be 15℃. ii) The ventilation rate in the bathroom is set to be 0.01-0.03 kg/s since the ASHRAE requirement for bathroom ventilation which considers contamination elimination is 50 CFM (0.03 kg/s). If to keep the CO_2 concentration in the bathroom is below 1000 ppm (without the consideration of contamination), then the required ventilation rate is around 0.01 kg/s. iii) The range of water flow rate for showering is assumed to be 0.08-0.27 kg/s, based on the water flow rate recommended by the Institute of Plumbing (2002) and the levels mentioned in WELS (water efficiency labelling scheme) (Hong Kong water supplies department, 2018). iv) The water temperature is set to be 32 - 40 ℃, based on the range of comfort water temperature during a shower (Wong et al., 2022). To keep a thermal comfort showering environment, the range of air temperature can be calculated based on the given water temperature and the following comfort thermal sensation equation (Wong et al., 2022):

$$\mathrm{TSV} = c_a\left(T_a - T_{a,o}\right) + c_w\left(T_w - T_{w,o}\right) \tag{1}$$

Where T_a and T_w are air temperature and water temperature, ℃; $T_{a,o}$ and $T_{w,o}$ are air temperature and water temperature in a thermal neutrality state (TSV=0), measured by a previous experiment as 25.8 °C and 38.8 °C, respectively; c_a and c_w are the unit changes of TSV for the air and shower water temperatures respectively, determined by a previous experimental study as:

$$c_a = \begin{cases} 0.17 & T_a > T_{a,o} \\ 0.088 & T_a < T_{a,o} \end{cases}, \quad c_w = \begin{cases} 0.73 & T_w > T_{w,o} \\ 0.33 & T_w < T_{w,o} \end{cases} \tag{2}$$

2.2 Energy consumption during showering

The total energy released by water and the radiator can be calculated based on the method of Foote, Pagni, and Alvares (1986):

$$\frac{\Delta T_g}{T_\infty} = 0.63\left(\frac{\dot{Q}}{m_a c_p T_\infty}\right)^{0.72}\left(\frac{h_k A_T}{m_a c_p}\right)^{-0.36} \tag{3}$$

Where ΔT_g is the temperature difference between T_a and the ambient air temperature (T_∞), K; $\dot{Q}$ is the energy release rate of the sources, kW; m_a is the compartment mass ventilation rate, kg/s; c_p is the specific heat of gas, kJ/kg·K, which is 1.005 kJ/kg·K for air at constant pressure; A_T is the total area of the bathroom surface, m^2; h_k is the effective heat transfer coefficient, which is 0.08 kW/m·K in the bathroom during showering. Therefore, the total energy release rate of the sources can be calculated as follows:

$$\dot{Q} = m_a c_p T_\infty \left(\frac{T_a - T_\infty}{0.63 T_\infty}\right)^{1.389} \left(\frac{h_k A_T}{m_a c_p}\right)^{0.5} \quad (4)$$
$$= m_a \times 1.005 \times T_\infty \times \left(\frac{T_a - T_\infty}{0.63 \times T_\infty}\right)^{1.39} \left(\frac{0.08 \times 24.3}{m_a \times 1.005}\right)^{0.5}$$

Among the total energy release rate, the part contributed by water (Q_w) can be calculated as:

$$Q_w = m_w \times c_w \times \Delta T_w \quad (5)$$

Where m_w is the water flow rate for showering, kW; c_w is the specific heat capacity of water kJ/kg/°C, which is 4.18 kJ/kg/°C; ΔT_w: Temperature difference between the shower head and the drain, °C, which can be calculated based on the following equation (Wong et al., 2010) :

$$\Delta T_w = 3.6 \times 10^{-10} \times T_w{}^{6.673} \times T_a{}^{-0.530} \quad (6)$$

So, the energy release rate contributed by the heater (Q_h) can be calculated as follows:

$$Q_h = \dot{Q} - Q_w = m_a \times 1.005 \times T_\infty \times \left(\frac{T_a - T_\infty}{0.63 \times T_\infty}\right)^{1.39} \left(\frac{0.08 \times 24.3}{m_a \times 1.005}\right)^{0.5}$$
$$- m_w \times 4.18 \times 3.6 \times 10^{-10} \times T_w{}^{6.673} \times T_a{}^{-0.530} \quad (7)$$

To heat the water from the supply temperature to the comfort temperature, the water heater also needs to consume energy, which can be calculated as follows (Wong et al., 2010):

$$Q_{wh} = m_w \times c_w \times \Delta T = 0.183 \times 4.18 \times (T_w - 10.4 \times T_\infty{}^{0.29}) \quad (8)$$

Therefore, the total energy consumed during showering is:

$$Q_{total} = Q_h + Q_{wh} \quad (9)$$

2.3 Data generation and analysis

To represent the energy consumption during showering, a database was generated by Python in the following steps: i) assigned ten values between 0.01-0.03 to ventilation rate; ii) for each given ventilation rate, assigned ten values between 0.08-0.27 to water flow rate; iii) for each given water flow rate, set ten values between 32-40 to water temperature; iv) for each given water temperature, a comfortable air temperature range can be calculated, then assigned ten values within this range to air temperature; v) based on these assigned values, estimated the total energy consumption using the equations as mentioned above; vi) screened the cases based on the heating radiator energy Q_h. For typical bathroom radiators, the size range is from 0.3 m^2 to 1.1 m^2, and the output range is from 835 watts/m^2 (single steel) to 2354 watts/m^2 (double convector), so, the minimum radiator energy output rate is about 0.3 kW. Accordingly, the cases with Q_h lower than 0.3 were filtered out from the database with radiator.

The database was then imported into IBM SPSS Statistics 26.0 (SPSS Inc. Chicago, IL, USA) for further analysis. To investigate the impact of these variables on energy consumption, a multivariate regression model was established between the energy consumption and ventilation rate, water flow rate, air temperature, and water temperature. After that, to further identify the most influential variable in energy consumption during showering, a standardized regression model was developed by first standardizing these four variables and then fitting the model using the standardized variables.

3 RESULTS

Air temperature and water temperature are the main variables influencing the occupants' thermal comfort during showering. According to a previous study (Wong et al., 2022), to keep a comfortable showering environment (the percentage of dissatisfaction is 10%), the air temperature and water temperature should follow the relationship described by equation (1). For the water temperature assumed in the current study, to maintain the occupant's thermal comfort, the air temperature should be kept within the range illustrated in Figure 1. For example, when the water temperature is set as 34 °C, the air temperature must be kept above 30 °C. Under these conditions, if the ventilation rate in the bathroom is fixed, which is quite common in residences, and if the water flow rate is known, then the maximum and minimum energy consumption can be calculated based on the equations listed in section 2.

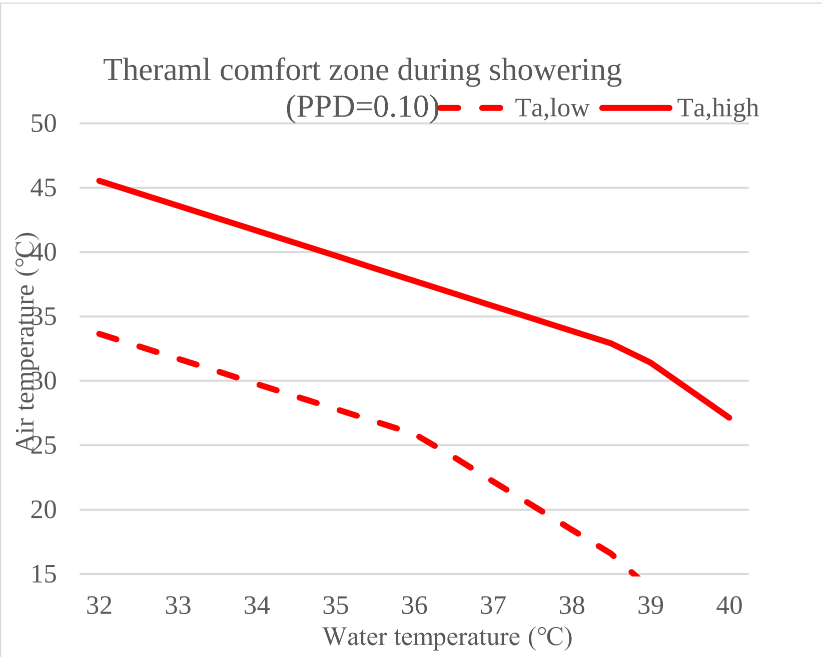

Figure 1. Comfort air and water temperatures during showering

Since the current study aims at energy conservation, more attention was paid to the minimum energy consumption. Consequently, the total energy consumption (Q_{total}) in this paper also refers to the minimum energy consumption.

Considering the interaction between the air temperature, water temperature, water flow rate, and ventilation rate, a multiple regression model was established between these variables and the total energy consumption to understand their integrated impact better. Detailed information about this model is shown in Table 1. All the variables had significant effects on energy consumption, and no multicollinearity was identified between these variables (VIF<4). In addition, the R^2 of this model is 0.983, which means this regression model can explain 98% of the variability observed in energy consumption.

$$Q_{total} = 0.20 \times T_a + 0.53 \times T_w + 72.56 \times m_a + 44.39 \times m_w - 24.04 \ (R^2=0.983) \quad (12)$$

Table 1. Multivariate regression model of energy consumption.

Variables	β coefficient	95.0% Confidence Interval for β	P value [a]	VIF [b]
Air temperature (°C)	0.202	0.200 - 0.2004	<**0.001**	1.519
Water temperature (°C)	0.525	0.520 - 0.5330	<**0.001**	1.521
Ventilation rate (kg/s)	72.557	771.426 – 773.689	<**0.001**	1.013
Water flow rate (kg/s)	44.385	444.264 – 444.507	<**0.001**	1.039

Note: a. p value less than 0.05 means the observed impact is statistically significant; b. variance inflation factor represents how well other independent variables explain the variable.

Since units and ranges of air temperature, water temperature, water flow rate, and ventilation rate are very different, the β coefficients identified in the multivariate regression model cannot be used to compare the influence of these variables. To find out the most important/influential variable in terms of energy consumption during showering, a standardized regression model was established by using the standardized air temperature, water temperature, water flow rate, and ventilation rate. As shown in Table 2, among the four variables, the water flow rate has the most significant impact on energy consumption, followed by water temperature and air temperature, and the ventilation rate has the most negligible impact.

Table 2. Standardized multivariate regression model of energy consumption.

Variables	β coefficient	95.0% Confidence Interval for β	P value [a]	VIF [b]
Standardized air temperature	0.887	0.878 - 0.896	<**0.001**	1.519
Standardized water temperature	0.944	0.935 – 0.953	<**0.001**	1.521
Standardized ventilation rate	0.458	0.451 - 0.466	<**0.001**	1.013
Standardized water flow rate	2.647	2.6640- 2.654	<**0.001**	1.039

Note: a. p value less than 0.05 means the observed impact is statistically significant; b. variance inflation factor represents how well other independent variables explain the variable.

4 DISCUSSION

According to the models listed in Tables 1 and 2, although the absolute coefficient of the ventilation rate was the highest, the impact of the ventilation rate on the total energy consumption was the least since the value of the ventilation rate itself was very low (i.e., 0.01-0.03 kg/s). Therefore, considering the importance of ventilation on health, highlighted in the past two years because of the spread of COVID-19, the ventilation rate in the bathroom is suggested to be at least 0.03 kg/s, as the minimum ventilation rate that could remove particles (ASHRAE 62.2, 2013). Moreover, as shown in the regression model, the water flow rate was the most influential factor regarding energy consumption during showering. When the ventilation rate is fixed at 0.03 kg/s, reducing the water flow rate from 0.26 kg/s (corresponds to the maximum level of WELS grade 3) to 0.15 kg/s (corresponds to the minimum level of WELS grade 1) could save around 33% energy during a ten-minute showering. Therefore, the most effective way to save energy consumption during showering should be to reduce the water flow rate.

5 CONCLUSIONS

This study aimed to develop an energy consumption model for an optimal showering environment by considering occupants' thermal comfort and energy consumption in bathrooms. Four variables (including air temperature, water temperature, ventilation rate, and water flow rate) that influence thermal quality and energy consumption were considered. Their impacts on energy consumption were analyzed. All these variables were significantly related to energy consumption, and the water flow rate was found to be the most influential one. Therefore, reducing the shower flow rate should be the first task, and low-flow rate shower appliances were suggested to be adopted. The impact of temperature (both water and air) was relatively small compared to the water flow rate. Additionally, the ventilation rate was found to have the least effect on energy consumption in bathrooms, and considering its importance on air quality and occupants' health, a high ventilation rate was suggested, and the minimum value should be 0.03 kg/s, which is the same value require by AHRAE to eliminate pollutants in bathrooms.

This study could help residents and facility managers establish the optimal showering environment in terms of occupants' comfort and health, and energy consumption. In particular, it could help them decide which variable should be given more attention and which appliance should be selected. Further work is still needed to validate and improve the accuracy of the energy consumption models.

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