Experimental study of the heat transfer coefficient between human skin and the flowing water during showering

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Abstract

Showering, as an indispensable part of modern people's daily routine, is closely related to people's comfort and energy consumption. To get an insight into these relationships and further improve people's comfort and energy efficiency, it is crucial to understand the heat transfer coefficient between human skin and the flowing water during showering. Although it was investigated by several studies before, the value varied significantly (from 43.2 to 588 W/(m^2·°C)) among these studies, and no consistent conclusion can be identified. Therefore, this study conducted a series of experiments to deeply understand the heat transfer coefficient under different showering conditions. This experiment used a skin model made of an insulated Styrofoam board and a thin aluminium sheet to simulate human skin exposure to the flowing water. Four showerheads with different patterns, three water temperatures (35, 38, and 41 °C), and three water flow rates (5, 6, and 7 L·min^{-1}) were investigated. Results indicated that the heat transfer coefficient increased significantly with the water flow rate. Moreover, this value also differed with various water patterns. For the same showerhead, the higher the pattern's nozzle area ratio, the higher the heat transfer coefficient. These findings could help to identify the most effective showering condition with the highest heat transfer coefficient between human

skin and flowing water and contribute to people's thermal comfort and energy saving during showering.

Keywords

Showering; heat transfer coefficient; water pattern; water temperature; water flow rate.

1 Introduction

Showering is an indispensable daily activity in modern life, which could significantly impact people's hygiene and comfort. People usually experience significant heat exchange during showering because the whole body is exposed to the water and the heat transfer coefficient between water and skin is higher than between air and skin. Consequently, people's skin temperature, which is stable in normal conditions, also varies significantly during showering (Munir et al., 2010). This directly influences peoples' thermal comfort and health. Moreover, the process, especially the efficiency, of heat exchange between the shower water and human skin is also closely related to energy and water consumption. Therefore, to take a healthy, comfortable, and energy-efficient shower, it is crucial to understand the heat transfer process between the shower water and human skin, and the core of the investigation of the heat transfer process between water and skin lies in the determination of the convective heat transfer coefficient between them.

The investigation of the convective heat transfer coefficient between water and human skin is a topic that has been discussed previously. Some researchers have studied it since half-century ago, using various methods, such as theoretical derivation, model simulation, copper manikin experiment, and human subject experiment (Boutelier et al., 1977; Rnadel et al., 1974). However, because of the different methods and physical conditions (such as various water temperatures, water flow rates, etc.), the results obtained in the previous studies are inconsistent and varied a lot: from 43.2 to 588 W/(m^2·°C). Among the earlier studies on heat transfer coefficients, the method proposed by Munir (named "replicated skin model") was the relatively new and simple one. Besides, unlike other studies that considered water immersion or swimming, this study was, as far as we know, the only one that thought of the showering scenario. However, Munir et al. (2010) only tested one condition with one specific, yet unknown, water temperature and flow rate. They concluded that the heat transfer coefficient for showering between skin and water was 104 W/m^2·K. More conditions should be considered since the heat transfer coefficient varied with the water's thermophysical properties and flow velocity (Laloui et al., 2020).

Therefore, the current study conducted experiments to determine the heat transfer coefficient for showering under different conditions. Like Munir's study, a replicated skin model was applied to simulate the heat exchange process between skin and water during showering. Based on the experiment's results, the heat transfer coefficient can be calculated, which could help determine the most efficient showering condition.

2 Methodology

2.1 Experiment setup

Figure 1 illustrates the experimental setup in the current study. A shower head was mounted on a tripod stand, and a skin model was fixed on the ground using two stand clamp clips. Similar to the model developed by Mumir (2010), this skin model also consists of a Styrofoam board (20cm*50cm) and a thin aluminium board (20cm*40cm) which represents human skin. A high-speed camera was installed in front of the direct shower zone (see Figure 1) to capture and investigate the water flow pattern generated by different showerheads.

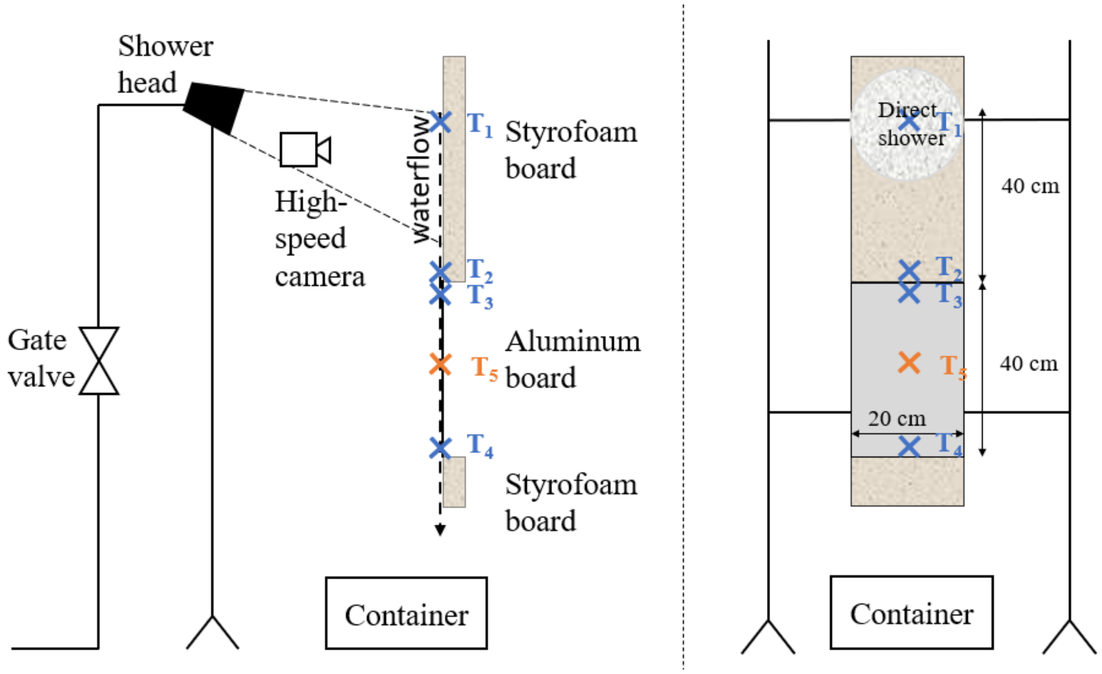


Figure 1 - Experiment setup (side view; right: front view)

Five Pt1000 sensors (1000 ohm temperature sensors) were applied to measure the temperatures at five locations during the experiment. As shown in Figure 1, T1 was the temperature of the water when it first touched the Styrofoam board; T2 was the temperature of the water before it flowed past the Styrofoam board; T3 was the temperature of the water when it first touched the aluminium board; T4 was the temperature of the water before it flowed past the aluminium board; T5 was the temperature of the aluminium board. All the Pt 1000 sensors were attached on the front side of the boards and in the middle of the water flow, except the fifth one. Since T5 was the temperature of the aluminium board, the fifth Pt 1000 was attached at the back of the aluminium board to avoid water interference. Considering that aluminium is a high thermal conductivity material and the board is very thin, the temperatures of both sides of the aluminium board were assumed to be the sawm. The Pt1000 sensors were connected to a data acquisition solution (DA200) to convert the resistance to temperature and record the results. Besides, the water flow rate was measured manually by measuring the water volume collected in the container (see Figure 1) after one minute of continuous "showering".

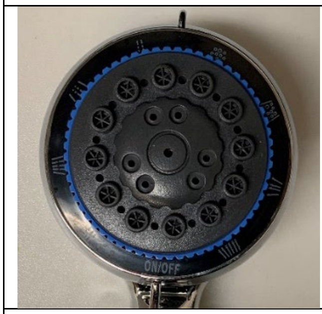
2.2 Testing scenarios

Four different water flow rates and three water temperatures were selected in the current study to investigate the heat transfer coefficient under different conditions. Based on the Voluntary Water Efficiency Labelling Scheme on Showers recommended by the Hong Kong Water Supplies Department (2018), the water flow rates tested in the experiment were set as 5, 6, and 7L/min. Considering the occupant's thermal comfort during showering identified by Wong et al. (2022), the water temperature was set as 35, 38, and 41 °C. In addition, four showerheads with several different spray patterns (see Table 1) were applied to investigate the impact of the water flow pattern. The nozzle area ratio, as equation (1), was used to qualify the spray distribution of different showerhead patterns.

$$\emptyset_A = \frac{A_s}{A_f} \qquad (1)$$

Where A_s is the total area of the working nozzles (m^2), A_f is the area of the whole faceplate of the showerhead (m^2). Therefore, in total 126 (3 water flow rates × 3 water temperatures × 14 water flow patterns) scenarios were tested in this study.

Table 1 - Information on the selected showerhead patterns

	Description of different patterns	Diameter(mm)	Number of 1/2/3mm Nozzles, n1/n2/n3	Nozzle area ratio
A				
	1 The outermost (blue) circle	70	60/0/0	0.0122
	2 The outermost & second outermost	70	60/12/0	0.0220
	3 The outermost & middle point	70	60/0/1	0.0141
	4 The outermost & third outermost	70	60/6/0	0.0171
	5 The second outermost	70	0/12/0	0.0098
B				
	1 The innermost circle	100	0/0/9*	0.0036
	2 The outermost & the innermost	100	47/0/9*	0.0083
	3 The outermost	100	47/0/0*	0.0047
	4 The outermost & middle	100	47/10/0*	0.00695
	5 The middle	100	0/10/0*	0.00225
C				
	1 One circle	90-50	15/0/0	0.00625
D				
	1 The outermost (blue) circle	70	60/0/0	0.0122
	2 The outermost & middle	70	60/15/0	0.0245
	3 The outermost & the innermost	70	60/0/6	0.0233

* For showerhead B, the diameters of the three types of nozzles are 1/1.5/2mm.

2.3 Experiment procedure

The experiment was conducted in an indoor lab. During the investigation, the temperature in the lab was around 23°C and the relative humidity was around 50%, which was controlled and maintained by an HVAC (heating, ventilation, and air-conditioning) system. The experiment procedure was straightforward. After the setup was completed and the parameters were adjusted to the specific levels, the researcher turned the showerhead on and counted for one minute. The camera was also on and recording the water movements on the board continuously. The Pt1000 measured all the temperatures and automatically recorded them per second in the DA200. After one minute, the researcher turned off the showerhead and measured the water amount in the container with the measuring cup.

2.4 Data processing

In this experiment, the heat exchange between the hot water and the skin model can be divided into two parts. For the Styrofoam board part, the heat was only transferred from the water to the air since the Styrofoam is adiabatic. The heat was transferred from the hot water to the air and the aluminium board (i.e., the skin) for the aluminium board part. Regarding the heat loss of the water flowing through the Styrofoam board (Q_{w_s}), it can be calculated based on the water temperature difference using equation (2).

$$Q_{w\_s} = mc_p(\overline{T_1} - \overline{T_2}) \tag{2}$$

Where m is the water flow rate (kg/s); c_p is the heat capacity of water, which is 4184 J/(kg·°C); $\overline{T_1}$ and $\overline{T_2}$ are the average temperatures measured at the corresponding positions marked in Figure 1. This amount of heat was all transferred to the air. Similarly, the heat loss of water during its flowing through the aluminium board (Q_{w_a}) can be calculated using equation (3).

$$Q_{w\_a} = mc_p(\overline{T_3} - \overline{T_4}) \tag{3}$$

This amount of heat can be divided into two parts. One part was transferred to the air, which was assumed to be equal to the Q_{w_s} since the area of the Styrofoam between T1 and T2 was the same as the area of the aluminium board between T3 and T4. The other part was transferred to the aluminium board, which can be calculated using equation (4).

$$Q_{skin} = \alpha A\left(\overline{T_4} + \frac{\overline{T_3} - \overline{T_4}}{2} - \overline{T_5}\right) = mc_p(\overline{T_3} - \overline{T_4}) - mc_p(\overline{T_1} - \overline{T_2}) \tag{4}$$

Where, A is the area of the aluminium board (m^2). Therefore, the heat transfer coefficient between water and skin (α) can be calculated as follows:

$$\alpha = \frac{mc_p(\overline{T_3}-\overline{T_4})-mc_p(\overline{T_1}-\overline{T_2})}{A\left(\overline{T_4}+\frac{\overline{T_3}-\overline{T_4}}{2}-\overline{T_5}\right)} \quad (5)$$

After calculations, the collected temperatures, water flow rate, and the calculated heat transfer coefficient, together with the experiment conditions (i.e., water temperature, showerhead no. and pattern), were imported and analysed in three steps using SPSS version 27.0 (SPSS Inc. Chicago, IL, USA). First, the z-scores of the heat transfer coefficients were calculated and the cases where the absolute values of the z-scores were larger than 3 were considered outliers and excluded. Second, descriptive analyses were conducted to get a basic understanding of the collected data. Third, the impacts of water temperature, water flow rate, and showerhead patterns were investigated using one-way ANOVA.

3 Results and discussion

3.1 Descriptive results of the collected data and the heat transfer coefficients

In total, 126 conditions were tested in the current study. Figure 2 illustrates the average temperatures measured under these conditions and their changes with time. As can be seen, T1-T4 remained relatively steady after 15 seconds, while T5 continuously increased during the experiment. Besides, since the locations of T2 and T3 are very close, their water temperatures measured at these positions are similar.

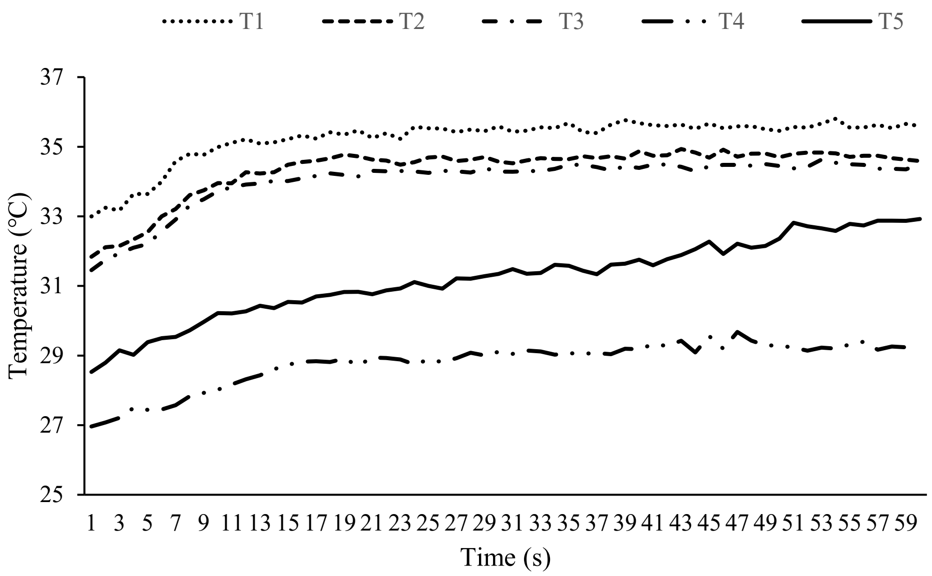
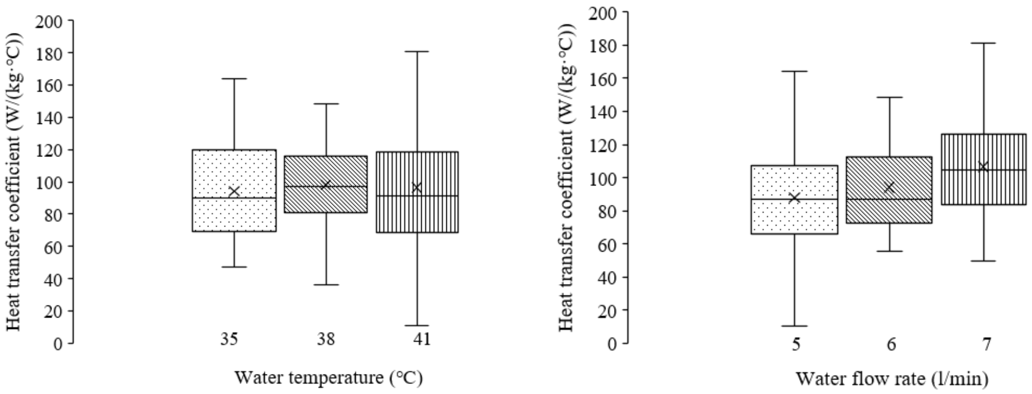


Figure 2 - Average temperatures of different conditions.

Based on equation (5), the corresponding heat transfer coefficients between the water and the skin model were calculated. The results varied a lot between different experimental conditions. The average value was 96 W/(m^2·°C), and most of the results were between 74 and 117 W/(m^2·°C) (representing the first and third quartile of the results respectively). The result obtained by Munir et al. (2010), which was 104 W/(m^2·°C), also falls in this range.

3.2 Impact of water temperature and water flow rate on the heat transfer coefficient

According to the one-way ANOVA test results, there was no significant difference in the heat transfer coefficient between the conditions with different water temperatures ($F(2,125)=0.166$, $p=0.847$). Figure 3 a) shows that the average heat transfer coefficient between the water and the aluminium board was always around 96 W/(m^2·°C). This does not consist with the results found by previous studies that the convection heat transfer coefficient was positively correlated with the temperature difference between the surface and the liquid (Kurazumi et al., 2008). The limitation of the experiment conditions might cause this inconsistency. More temperature settings with more extensive ranges should be tested in the future.



a) impact of water temperature b) impact of water flow rate

Figure 3. Heat transfer coefficients in conditions with different water temperatures (a) and water flow rates (b).

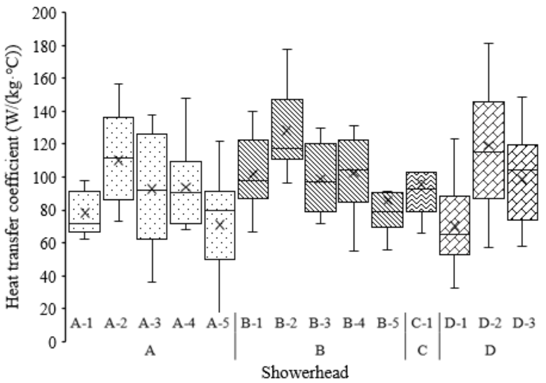
A significant difference was identified in the heat transfer coefficients between the experimental conditions with different water flow rates ($F(2,125)=4.093$, $p=0.019$). As shown in Figure 3 b), the higher the water flow temperature, the higher the heat transfer coefficient, which agrees with the statement mentioned by Laloui et al. (2020). Moreover, a Tukey post hoc test revealed that the statistically significant difference in the heat transfer coefficient was only found between the conditions when the water flow rate was

5 l/min and 7 l/min (p = 0.016). At the same time, there was no statistically significant difference between other pairwise comparisons.

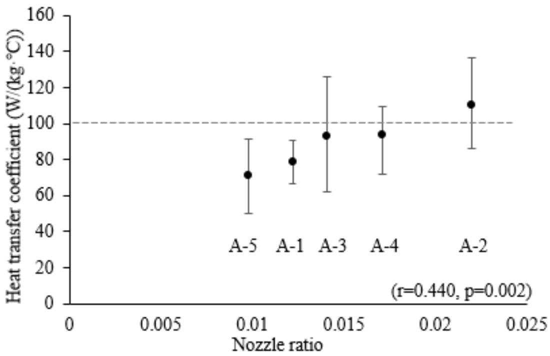
3.3 Impact of water flow patterns on the heat transfer coefficient

Regarding the showerhead type's impact, no significant difference was identified in the heat transfer coefficients between the conditions with different showerheads (F(3, 122)=1.661, p=0.179). However, if comparing the results between different showerhead patterns, significant differences were identified, as shown in Figure 4a (F(13, 112)=3.215, p<0.001). Based on the Tukey post hoc test results, the significant differences in the pairwise comparisons were only identified between the two highest results (B-2 and D-2) and the three lowest (A-1, A-5, and D-1).

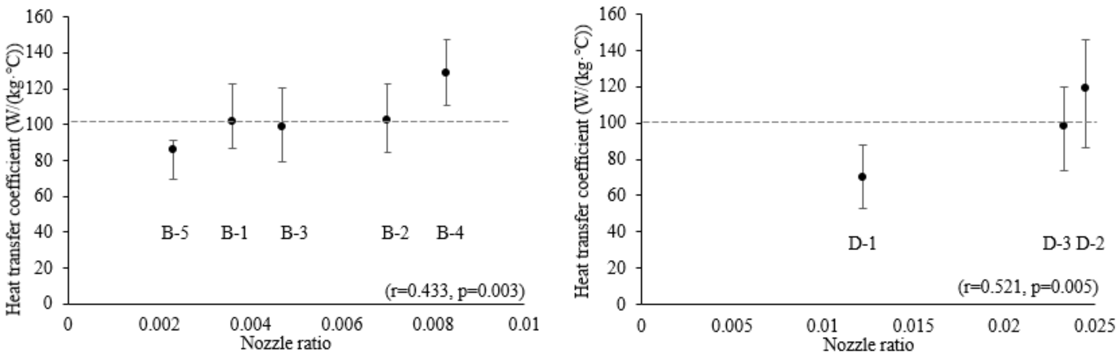
Additionally, regarding the nozzle ratio's impact, no significant correlation was found between it and the heat transfer coefficients (r=0.118, p=0.188), either. Nevertheless, if comparing the results among the same showerhead, significant moderate correlations were observed (0.4<r<0.5, p<0.05). As shown in Figure 4b-d, the higher the nozzle ratios for the same showerhead, the higher the heat transfer coefficient. These findings demonstrate the importance of the wise choice of the showerhead pattern. Considering that different showerheads could significantly impact energy and water saving (Wong et al., 2016), more profound research on the influence of the showerhead pattern should be conducted in the future.



a) Impacts of showerhead type



b) Impact of nozzle ratio of showerhead A



c) Impact of nozzle ratio of showerhead B d) Impact of nozzle ratio of showerhead D

Note: the dush line in figures b-d represents the result obtained by Munir et al. (2010).

Figure 4. Heat transfer coefficients in conditions with different showerhead patterns.

4 Conclusion

This study conducted a series of experiments to measure the convection heat transfer coefficient between hot water and a skin model to understand the heat transfer between water and human skin during showering. A skin model, namely a thin aluminium board, was adopted by a previous study. Three water temperatures (35, 38, and 41 °C), three water flow rates (5, 6, and 7 L/min), and four showerheads with several different patterns were tested. Results indicated that the heat transfer coefficient varied significantly with other experiment conditions, and the average result was about 96 W /(m^2·°C), which was compatible with the result identified by previous studies. Moreover, it was found that both the water flow rate and showerhead pattern (nozzle area ratio) had significant impacts on heat transfer coefficients. The higher the water flow rate and the nozzle area ratios, the higher the heat transfer coefficient between the water and skin was observed. However, the small amount and randomly selected showerhead samples might lead to misreading the results obtained in the current study. Considering the remarkable impacts of these factors on energy and water saving, more profound studies on these impacts should be conducted in the future.

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