Wise choice of showerheads: understanding the impacts of shower water spray patterns on heat transfer coefficient between water and human skin

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Declarations

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Conflicts of interest/Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Data Availability Statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Authors' contributions

Conceptualization: Dadi Zhang and Ling-Tim Wong; methodology: Dadi Zhang and Ling-Tim Wong; writing_original draft preparation: Dadi Zhang; writing_review and editing: Kwok-Wai Mui and Ling-Tim Wong; supervision: Kwok-Wai Mui and Ling-Tim

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Abstract

Heat transfer coefficients between shower water and human skin could significantly impact occupants' thermal sensation and energy consumption during showering. A recently published study found that heat transfer coefficients varied considerably among showerhead patterns. However, specific effects of the showering heat transfer process on the showerhead patterns are yet to be concluded. Nonetheless, the impacts of water spray patterns on the heat transfer coefficient between water and flat surfaces were investigated and identified by several studies on spray cooling. Similar effects were expected for the heat transfer coefficients between shower water and human skin during showering. Hot water showering can be seen as the opposite process of water spray cooling. This study conducted experiments to quantify the spray patterns during showering and define their impacts on the heat transfer coefficient. Five showerheads with 18 spray patterns were tested in this study. These patterns' resistance factor, water supply pressure, and nozzle area ratio were measured to qualify their shower performance. Each pattern was tested under six showering conditions (two water flow rates × three water temperatures), and the heat transfer coefficient of each condition was calculated using the method proposed by a previous study. Results indicated that the heat transfer coefficient was significantly correlated with the resistance factor ($r=0.336$, $p<0.001$), water supply pressure ($r=0.321$, $p=0.001$), and nozzle area ratio ($r=0.283$, $p=0.004$) of the showerhead patterns in general. Although these correlations were inconclusive for individual showerheads, clear trends can still be observed. The influence of water spray patterns on the heat transfer coefficient could provide residents with scientific references when selecting showerheads in their bathrooms.

Keywords

Showering; showerhead; heat transfer coefficient; water spray pattern

1 Introduction

With the improvement of living standards and the development of health consciousness, showering has become one of the necessary parts of modern people's daily life. Previous studies indicated that choosing optimal showerheads and being smart about using them could improve residents' health and thermal comfort during showering and save energy (Wong et al., 2016; Zhang et al., 2021; Zhou et al., 2019). It is not hard to understand that using a low water flow showerhead could reduce water and energy consumption. However, according to Wong et al. (2016), people usually turn up the water temperature when the water flow rate is low to maintain thermal comfort. This, in turn, would increase the water heater energy consumption. Therefore, the best showerhead does not always have the lowest water flow rate. Thermal comfort also cannot be ignored; the heat transfer process between hot water and human skin governs it. For a hot water shower, the higher the heat transfer efficiency, the less water and energy are consumed to maintain a thermally neutral skin temperature (namely, a comfortable showering environment). For this reason, the heat transfer coefficient, as the principal influence factor of the heat transfer process, should be given more attention when analyzing thermal comfort and energy efficiency during showering.

A recently conducted experiment indicated that the showerhead's water spray pattern significantly impacted the heat transfer coefficient between hot water and human skin during showering (Wong et al., 2023). However, no specific effects for overall showerhead patterns were concluded since only one characteristic parameter of the water flow pattern—the nozzle area ratio—was considered in their study. Although the influence of spray patterns on the heat transfer coefficient was rarely studied during showering, it was investigated by many studies for the industrial spray cooling process (Cebo-Rudnicka et al., 2016; Hnizdil et al., 2016). Several parameters of spray patterns (such as spray pressure, water flux, and distribution of drop diameter) were examined to quantify their impacts on the heat transfer coefficient between water and metal surfaces (Puschmann & Specht, 2004; Somasundaram & Tay, 2013). Water pressure was one of the most studied parameters, and specific effects have been identified. Specifically, Cebo-Rudnicka (2016) observed an increase in heat transfer coefficient when the water pressure increased from 0.5 Mpa to 1 Mpa. However, an inverse effect was reported by Hou et al. (2013). This might be caused by the different liquid and surface temperatures tested in these two studies. Considering the other conditions between showering and spray cooling, the impact of spray patterns might be even more different.

Therefore, the current study conducted a series of experiments to determine the heat transfer coefficient for showering under different spray patterns of some showerheads. Each spray pattern was characterized by three parameters: resistance factor, water supply pressure, and nozzle area ratio. Based on the analyses of the experiment data, the impact of spray patterns on the heat transfer coefficient can be calculated, which could help to design and select the optimal showerhead.

2 Methodology

The methodology consists of three parts, as shown in Figure 1. The first part was the measurement of the heat transfer coefficient. Five showerheads (including 18 spray patterns) were tested under six conditions: three water temperatures (35, 38, and 41 ℃) × two water flow rates (5 L/min and 6 L/min). A skin model (consisting of a Styrofoam board and a thin aluminium board) and five platinum resistance thermometers were applied in this measurement. The detailed measurement procedure was introduced in a previous study (Wong et al., 2023). In total, 108 results of heat transfer coefficient were obtained. The second part described in section 2.1 was the experimental study on showerhead characterization. The third part, as described in section 2.2, was the data analysis to identify the relationships between the showerhead patterns and the heat transfer coefficients, which could help to determine the optimal showerhead pattern.

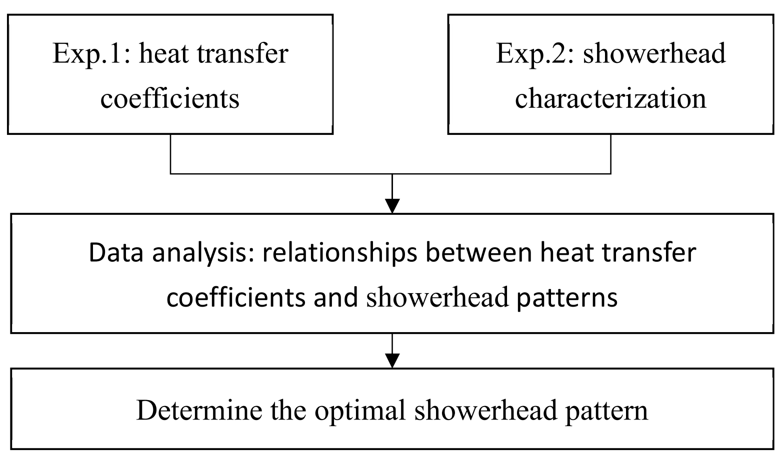


Figure 1. The research process of this study.

2.1 Experiment setup

This study's main experiment was measuring the water pressure of the 18 showerhead patterns. As shown in Figure 2, a pressure transmitter (pressure sensor) model A-10 installed between the water supply tube and the showerhead was used to measure the water pressure, and a data acquisition solution (DA200) was connected to the pressure transmitter to show the signal and record the results. Then, the signal was converted to pressure according to the specification of the pressure transmitter.

Figure 2. The experiment setup.

Five showerheads were tested in this study (see Figure 3). Showerheads A and B have five patterns, showerhead C has one pattern, showerhead D has three, and showerhead E has four. To quantify the shower performance of these patterns, three parameters were measured: nozzle area ratio ($\emptyset_A$), water pressure (P), and resistance factor (K). The nozzle area ratio can be calculated using equation (1). The water pressure can be converted from the measurement data. The resistance factor can be calculated using equation (2) (Zhou et al., 2019).

$$\emptyset_A = \frac{A_s}{A_f} \tag{1}$$

$$K = \frac{P}{Q^2} \tag{2}$$

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); Q is the water flow rate (L/min).

Figure 3. Tested showerheads A - E (from left to right in order).

2.2 Data analysis

The parameters obtained from the two experiments, namely, water temperature, water flow rate, heat transfer coefficient, showerhead pattern, nozzle area ratio, water pressure, and resistance factor, were imported into IBM SPSS statistics 27.0 (SPSS Inc. Chicago, IL, USA) for the data analysis. Then, the imported data was screened based on Z-scores of the heat transfer coefficient and the water pressure, where all the cases with Z-scores higher than two or lower than minus two were considered outliers and eliminated. After that, a series of Pearson correlation analyses were conducted to examine the relationships between the parameters of the showerhead pattern (i.e., nozzle area ratio, water pressure, and resistance factor) and heat transfer coefficient. Lastly, a two-way ANOVA analysis was carried out to investigate the interactive effect of the parameters of the showerhead pattern on the heat transfer coefficient.

3 Results and discussions

3.1 General results

The results obtained from the two experiments are shown in Table 1. The impacts of water flow rate and water temperature were reported in a previous paper. The water flow rate positively impacts the heat transfer coefficient, while no significant effect of water temperature was identified. The current study only focuses on the impacts of showerhead-related parameters, i.e., nozzle area ratio, water pressure, and resistance factor, on the heat transfer coefficient.

Table 1. Results obtained from the two experiments.

Showerhead	Pattern	Water flow rate (l/min)	Heat transfer coefficient (W/(m2·°C))			Nozzle area ratio (/)	Pressure (kPa)	Resistance factor (/)
			Tw=35	Tw=38	Tw=41			

A	1	5	62.2	91.8	71.9	0.012	38.0	1.5
		6	65.4	88.6	68.3	0.012	85.0	2.4
	2	5	86.4	87.4	*147.2*	0.022	65.0	2.6
		6	111.9	72.9	85.7	0.022	88.3	2.5
	3	5	46.9	36.2	123.4	0.014	37.5	1.5
		6	138	77.3	85.9	0.014	110.0	3.1
	4	5	82.3	101.7	91.6	0.017	75.0	3.0
		6	69.6	74.3	90.8	0.017	67.5	1.9
	5	5	63.6	44.6	*10.7*	0.010	25.0	1.0
		6	122.1	98.1	55.5	0.010	82.5	2.3
B	1	5	101.8	85.1	98.1	0.004	52.5	2.1
		6	122.6	140.1	67	0.004	115.0	3.2
	2	5	*147.3*	96.4	112.7	0.008	55.0	2.2
		6	117.1	115.8	*147.1*	0.008	120.0	3.3
	3	5	119.6	129.6	79.2	0.005	62.5	2.5
		6	72	86	97.4	0.005	90.0	2.5
	4	5	104.5	114.7	55.3	0.007	51.3	2.1
		6	69.2	130.9	100.3	0.007	107.5	3.0
	5	5	*164.1*	73.6	55.5	0.002	47.0	1.9
		6	78.7	73.7	65.2	0.002	88.5	2.5
C	1	5	66	102.7	83.5	0.006	49.2	2.0
		6	74.4	103.2	101.4	0.006	132.8	3.7
D	1	5	70.3	81.7	32.3	0.012	37.5	1.5
		6	94.7	57.6	65.4	0.012	87.5	2.4
	2	5	95.6	113.5	115	0.025	45.0	1.8
		6	*148.4*	77.6	142.8	0.025	105.0	2.9
	3	5	105.9	65.4	81.9	0.023	40.0	1.6
		6	109.9	104.5	83.3	0.023	97.5	2.7
E	1	5	59.0	50.2	47.7	0.004	37.5	1.5
		6	50.0	74.1	55.5	0.004	120.0	3.3
	2	5	50.3	55.5	67.0	0.008	62.5	2.5
		6	60.2	67.5	80.2	0.008	*152.5*	4.2
	3	5	41.2	47.6	63.6	0.006	35.0	1.4
		6	53.0	64.1	80.3	0.006	100.0	2.8
	4	4	44.5	45.7	37.4	0.003	25.0	1.0
		5	46.6	54.0	54.0	0.003	92.5	2.6

Note: The outliers were marked in italics and eliminated from the database.

Table 2 shows the general relationships among the nozzle area ratio, water pressure, and resistance factor of the showerhead patterns and the heat transfer coefficient. As can be seen, all the parameters of the showerhead pattern had significantly positive impacts on the heat transfer coefficient between the water flow and human skin ($p<0.05$). Wong et al. (2023) and Cebo-Rudnicka et al. (2016) reported similar nozzle area ratios and water pressure effects. It is easy to understand the impact of the nozzle area ratio. The larger the nozzle area, the larger the contact area between the water and the skin. Thus, more heat could be transferred through the conduction and convection. Regarding the impact of water pressure, as explained by Cebo-Rudnicka et al. (2016) in their study, higher pressure could increase the water dispersion and water velocity, resulting in more heat transfer between the water and skin. Since the resistance factor was calculated based on water pressure and they are closely related to each other (see Table 2), the same explanation should also work for the impact of the resistance factor on the heat transfer coefficient.

Table 2. Correlations between the heat transfer coefficient and the showerhead performance parameters.

	Nozzle area ratio	Water pressure	Resistance factor
Heat transfer coefficient	**0.283 (0.004)**	**0.321 (0.001)**	**0.336 (<0.001)**
Nozzle area ratio		-0.024 (0.811)	-0.035 (0.721)
Water pressure			**0.936 (<0.001)**

Note: Results were obtained from Pearson correlation analyses; p-values were shown in parentheses; p<0.05 was considered statistically significant and marked in bold.

Additionally, significant differences in the heat transfer coefficients were observed between the five showerheads ($F(4, 97)=11.10$, $P<0.001$) and between the 18 spray patterns ($F(17, 84)=4.56$, $P<0.001$). As shown in Figure 4, showerhead B had the highest average heat transfer coefficient (about 95 W/(m^2·°C)), showerheads C and D had similar average values (about 88 W/(m^2·°C)), followed by showerhead A (about 82 W/(m^2·°C)), and showerhead E had the lowest average heat transfer coefficient (about 56 W/(m2·°C)).

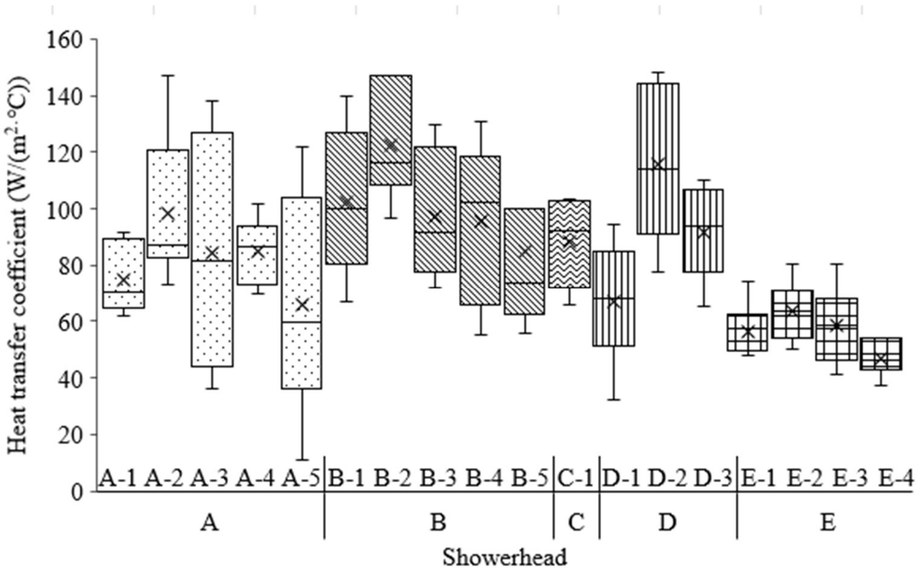
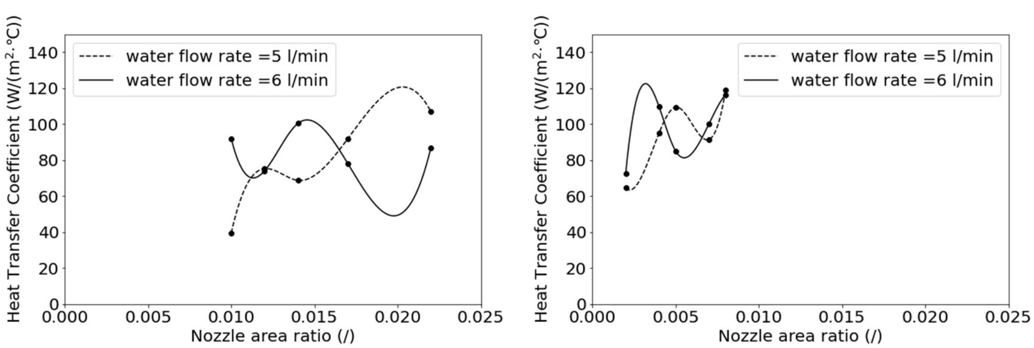


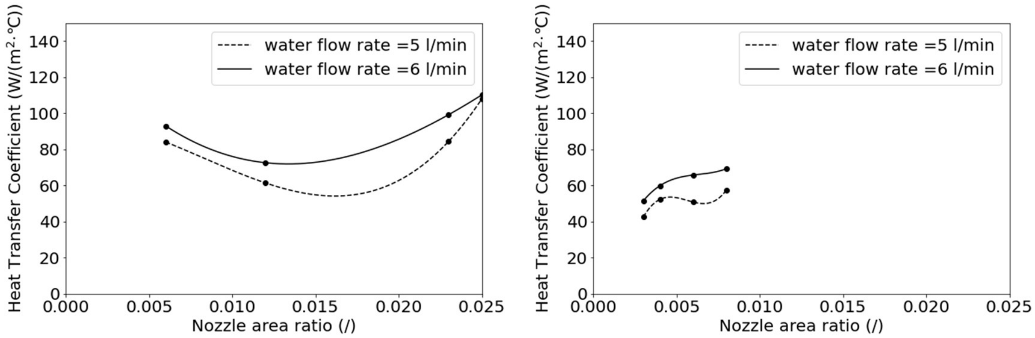
Figure 4. Heat transfer coefficients of different showerhead patterns.

3.2 Impacts of spray patterns on the heat transfer coefficient for the same showerhead

Since showerhead C has only one spray pattern and performs similarly (in terms of the average heat transfer coefficient) to showerhead D, showerhead C and D were considered one showerhead with four spray patterns in this section. Figure 5 shows the relationships between the nozzle area ratio and the heat transfer coefficient for each tested showerhead. Related Pearson correlation coefficients were mentioned in the subtitles. Although the nozzle area ratio had a significantly positive impact on the heat transfer coefficient when considering the tested showerheads as a whole (see Table 2), this impact was insignificant for most showerheads (except for showerhead E) when considering them separately.



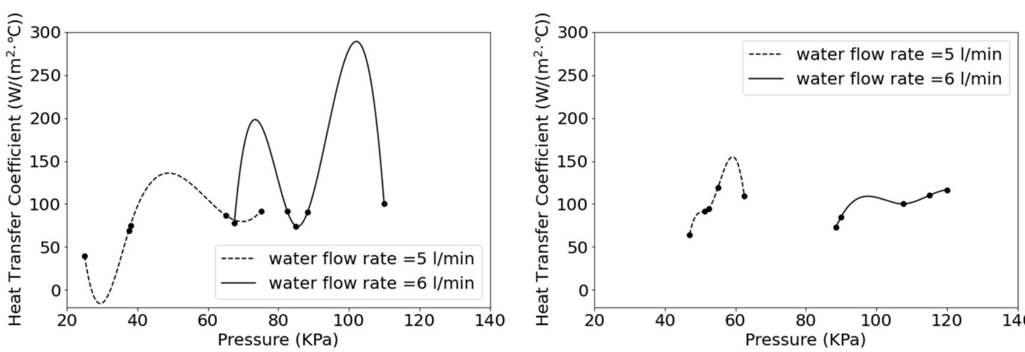
a) Showerhead A (r=0.197, p=0.316) b) Showerhead B (r=0.317, p=0.057)



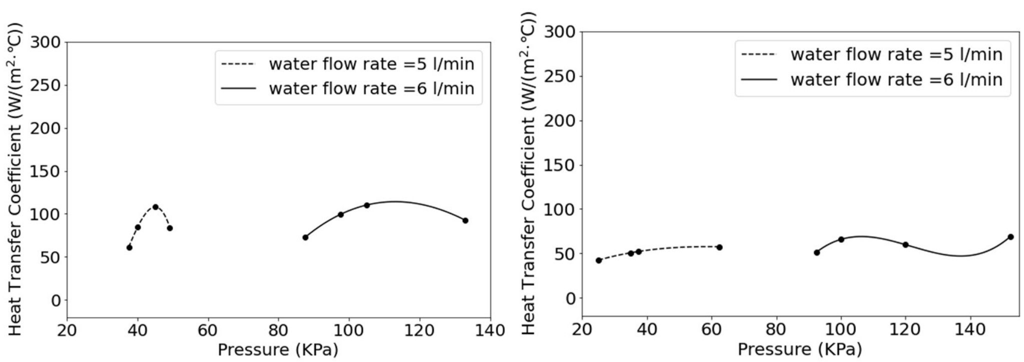
c) Showerheads C&D (r=0.369, p=0.083) d) Showerhead E (**r=0.493, p=0.014**)

Figure 5. Relationships between the nozzle area ratio and the heat transfer coefficient.

Figure 6 shows the relationships between the tested showerheads' water pressure and the heat transfer coefficient. Significantly positive correlations were identified for showerheads A and D. In addition, it can be seen that the water pressure was positively correlated with the water flow rate. The larger the water flow rate was set, the higher the water pressure was detected.



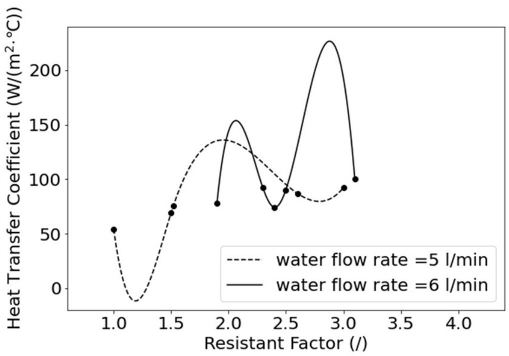
a) Showerhead A (**r=0.442, p=0.018**) b) Showerhead B (r=0.231, p=0.247)



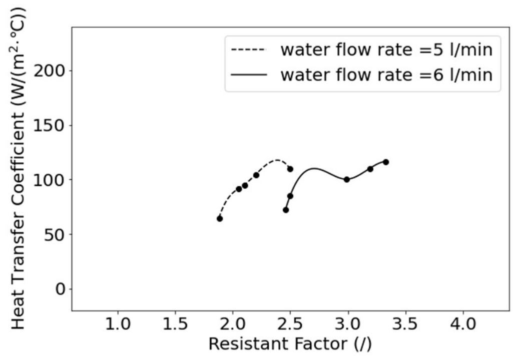
c) Showerheads C&D (r=0.243, p=0.263) d) Showerhead E (**r=0.503 p=0.020**)

Figure 6. Relationships between the pressure and the heat transfer coefficient.

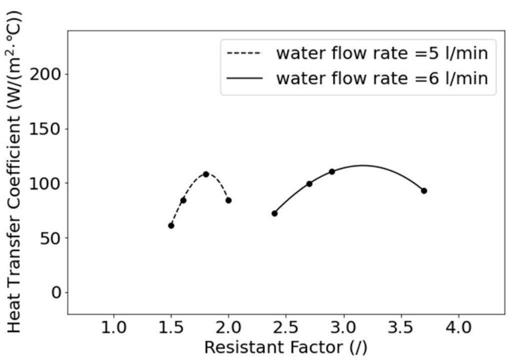
Since the resistant factor was calculated based on water pressure, its impact on the heat transfer coefficient was similar to water pressure (as shown in Figures 6 and 7). However, the correlations between the resistant factor and heat transfer coefficient were more substantial than the correlations between the water pressure and heat transfer coefficient (see the Pearson correlation coefficients). The impacts of the resistant factor were significant for almost all the tested showerheads.



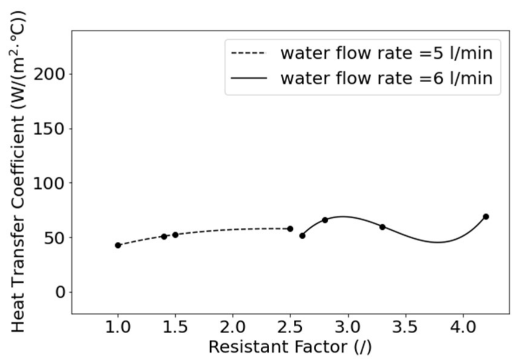
a) Showerhead A (**r=0.470, p=0.012**)



b) Showerhead B (**r=0.390, p=0.044**)



c) Showerheads C&D (r=0.281, p=0.194)



d) Showerhead E (**r=0.655, p<0.001**)

Figure 7. Relationships between the resistant factor and the heat transfer coefficient.

In general, the showerhead pattern's investigated parameters significantly positively impact the heat transfer coefficient between water and skin during showering. However, if these impacts are analyzed per showerhead, only the impact of resistant factors was significant for most showerheads. Therefore, the resistance factor should be paid more attention when selecting a showerhead. In winter, the showerhead pattern with a higher resistant factor is suggested to be chosen to increase skin temperature at the beginning of showering quickly. In contrast, in summer, the showerhead pattern with a lower resistance factor is suggested to be selected to avoid overheating the body.

3.3 Interactive impacts of the parameters of showerhead pattern on the heat transfer coefficient

Three parameters of showerhead pattern were investigated in the current study. Considering that water pressure and resistance factor are closely related, only the interaction between resistance factor and nozzle area ratio was examined. As seen in Table 3, the nozzle area ratio and resistance factor significantly impacted the heat transfer coefficient individually. However, there was no significant interactive impact of these two parameters.

Table 3. Interactive impact of nozzle area ratio and resistance factor on the heat transfer coefficient.

Parameters	df	Mean square	F	p
Nozzle area ratio	2	1731.217	3.380	0.038
Resistance factor	2	5829.931	11.383	<0.001
Nozzle area ratio* Resistance factor	4	331.450	.647	0.630

Note: Results were obtained from two-way ANOVA analyses; $p<0.05$ was considered statistically significant and marked in bold.

Figure 7 illustrates the detailed interactive impacts of the resistance factor and nozzle area ratio on the heat transfer coefficient. For the showerhead patterns with similar nozzle area ratios, the ones with higher resistance factors always result in higher heat transfer coefficients. However, the relationships between the nozzle area ratio and the heat transfer coefficient were only sometimes positive for the showerhead patterns with similar resistance factors. The heat transfer coefficient was the highest when the nozzle area ratio was between 0.0075-0.015 and the resistance factor was larger than 3.0.

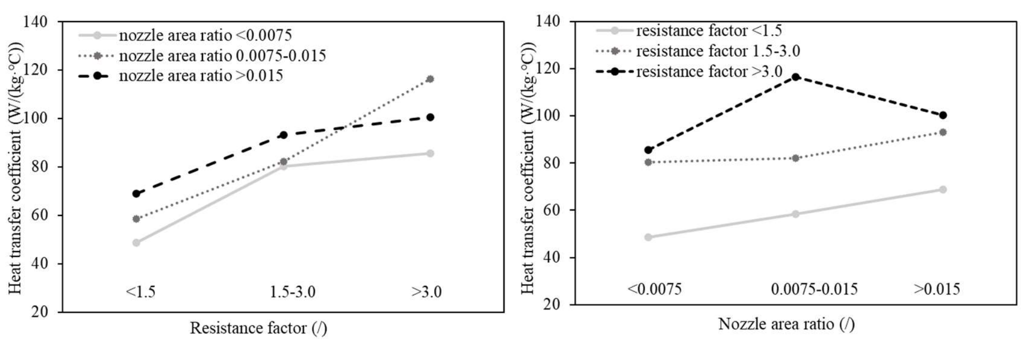


Figure 7. Interactive impact of nozzle area ratio and resistance factor on the heat transfer coefficient.

4 Conclusions

Heat transfer coefficients between shower water and human skin are vital in determining occupants' thermal comfort and energy consumption during showering. This study experimented to identify the impacts of three showerhead-related parameters, i.e., nozzle area ratio, water pressure, and resistance factor, on the heat transfer coefficient. Five showerheads with 18 patterns were tested under six showering conditions (two water temperatures × three water flow rates). The general results indicated that all the tested parameters positively impacted the heat transfer coefficient. However, if each showerhead was examined individually, only the impacts of the resistance factor were significant for almost all the showerheads. Moreover, the Pearson correlation coefficient between the resistance factor and the heat transfer coefficient was the highest compared with the other two parameters. Therefore, the resistance factor of the showerhead pattern should be given more attention when selecting showerheads. In addition, the two-way ANOVA test result showed that the showerhead pattern with a nozzle area ratio of 0.0075-0.015 and a resistance factor of 3.0 or above resulted in the highest heat transfer coefficient between water and human skin during showering. The insights gained from this study could assist residents and facility managers in wisely selecting showerheads for comfortable and energy-saving showering.

5 Acknowledgments

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