

ORIGINAL ARTICLE

Effects of ventilation openings in industrial safety helmets on evaporative heat dissipation

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Abstract

Objectives: This study aimed to investigate the effects of ventilation openings in commercial industrial safety helmets (ISHs) on evaporative heat dissipation.

Methods: Seven models of commercial ISH were examined quantitatively by a sweating thermal head manikin (SHM) with six separate zones. To simulate summer outdoor conditions, the measurements were done in a climate chamber, with the room temperature and relative humidity set at 34.0°C and 50%, respectively. The shell temperature of SHM was set at 34.0°C. Wind was blown from the front or left side at 1.0, 2.0, and 3.0 m/s. The necessary heat flux to keep the manikin skin temperature at 34.0°C was counted as evaporative heat dissipation in each zone.

Results: Openings at the front and back, and openings between the body and brim of the helmet played a significant role in increasing the heat flux in Forehead zone, but in all zones as a total, the effects were not significant. Heat flux for ISH with openings on both the right and left sides was not significantly different from that without openings.

Conclusions: Our study utilizing SHM showed that ventilation openings on both the right and left sides or front and back sides of commercial ISHs were not significantly effective in increasing total evaporative heat dissipation under an equivalent temperature of ambience and manikin shell. Further improvements on ISH are needed to increase evaporative heat dissipation.

KEYWORDS

evaporative heat dissipation, industrial safety helmet, openings, thermal head manikin, wind

1 | INTRODUCTION

Industrial safety helmets (ISHs) are essential for protecting the heads of workers from falling or flying objects, or electrical shock and burns.¹ In Japan, the ratio of head injury to the whole body was 8.4%, according to reports of casualties and illness lasting less than four days off.² As such, wearing ISH in construction and the forestry industry is mandatory per Article 539 of the *Occupational Health and Safety Regulations* in Japan.³ However, wearing ISH in hot-working conditions may result in workers discomfort and could

increase the risk of heat disorders, as the head is one of the most susceptible regions to heat stress.

To protect the brain from heat stress, the head is cooled. Headskin sweats at about 1.0 mg/cm²/min for medium exercise intensity,⁴ which is comparable to that of the forearm. Venous blood under the head skin cooled by sweat evaporation is perfused to the system of dural sinuses and cools the brain.⁵ The human head functions as a heat sink with a heat loss capacity higher than the heat produced by the brain and the heat received from the arterial blood during mild hyperthermia.⁶ If some parts of the head skin are covered by a helmet, sweat evaporation

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on the head skin decreases, and thus the temperature of head skin increases and cooling of the brain by subcutaneous venous blood becomes less effective. For outdoor workers in construction or forest industry in the summer, occupational heat stress would be more elevated when wearing ISH because they also usually wear long pants or sleeves for safety reasons.

For cycling helmets,⁷ vent cross-section was found to be correlated with heat dissipation from the head. As such, to increase air ventilation inside the helmet, ISHs with openings are now beginning to be distributed in the market. However, openings dramatically decrease impact resistance and eliminate the electrical insulation properties of ISH.¹

The *Japanese Industrial Standard (JIS)* in JIS T 8131⁸ describes that the summation of the area of ventilation holes on ISH should be less than 450 mm², which is about 0.4% of the total surface area of the helmet. A previous paper⁹ reported that small openings were effective for alleviating worker heat stress, but another paper¹⁰ did not support this. Therefore, the effectiveness of small openings in ISH is unclear.

In midsummer daytime conditions in Japan, the ambient temperature frequently reaches body surface temperature, and the wind blows outdoors at about 3 m/s on average.¹¹ In such environmental conditions, convection does not play a role in heat dissipation in the pathway from the body to the environment, and sweat evaporation becomes the only method available for heat dissipation. Thus, to study the effects of opening in ISH on heat stress, it is necessary to measure evaporative heat dissipation from the head.

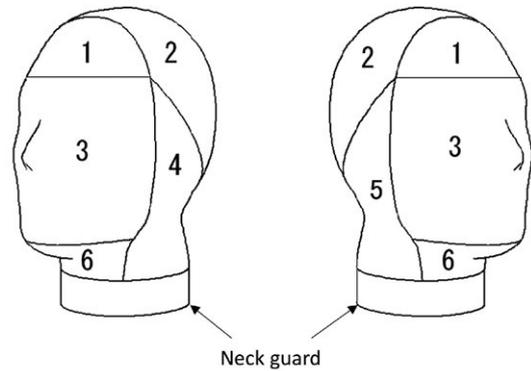
This study aimed to investigate the effects of the ventilation openings in ISH on evaporative heat dissipation in hot and windy conditions by using a sweating thermal head manikin (SHM).

2 | MATERIALS AND METHODS

We investigated evaporative heat dissipation from the head under various wind speeds while wearing a commercial ISH by using a SHM (Measurement Technology Northwest, Seattle).

2.1 | Sweating thermal head manikin (SHM)

The size of the SHM was the mean size of an adult male. The surface of the SHM was divided into six thermal zones: Face, Forehead, Chin, Head Top, Head Left, and Head Right (Figure 1). Head Top is by far the largest zone of the six zones. To measure evaporative heat dissipation from the manikin surface, the manikin surface was covered tightly by a wicking fabric sweating skin to wet uniformly. The surface temperature of SHM was measured by a distributed wire sensor embedded just under the shell skin. Software on a laptop controlled the heat flux in each zone to maintain the skin temperature at 34.0°C for every zone.



Zone number	1	2	3	4	5	6
Zone name	Forehead	Head top	Face	Head left	Head right	Chin
Area (cm ²)	94.4	624	293	156	156	64

FIGURE 1 Six-zone thermal head manikin segmentation. Neck guard served to insulate thermally from the stand of manikin to head

Distilled water stored in a plastic bottle was pumped to the fluid controller, warmed to the same temperature of the manikin shell, and supplied to the sweating skin from small holes on the manikin surface.

2.2 | Experimental settings

All experiments were conducted in a climate chamber sized 5.1 m in width, 8.3 m in depth, and 2.6 m in height. Room temperature in the climate chamber was controlled at 34.0°C, and the relative humidity was 50% during the experiment to simulate the hot midsummer outdoor conditions. Since the room temperature and shell temperature were set at 34°C, almost all of the heat was lost by water evaporation. The level of precision for the room temperature in our climatic chamber was $\pm 0.5^\circ\text{C}$, and that of relative humidity is $\pm 3.0\%$ relative humidity. Six pieces (two pieces in the horizontal direction and three pieces in the vertical direction: $2 \times 3 = 6$) of a ventilating fan (SCF-50FF3, Suiden, Osaka, Japan) were used to blow the wind at the inlet of a wind tunnel. The wind tunnel was a rectangular parallelepiped whose size was 1.3 m in width, 2.0 m in height, and 2.0 m in depth and was placed between the ventilating fan and SHM. A hexagonal honeycomb made of aluminum (20 cm in length and 2.0 cm in the distance between opposite sides of the hexagonal) and four sheets of wire mesh was placed in the wind tunnel to regulate the turbulent air flow from the ventilating fan. SHM was placed in the middle of the aperture of the wind tunnel. The air speed was measured at the center of the SHM by using a thermal anemometer (Testo 445, Testo, Yokohama, Japan).

2.3 | Industrial safety helmet (ISH)

Seven models of commercial ISH were evaluated (Table 1). Helmet A and Helmet B were of almost the same size

TABLE 1 Characteristics of tested industrial safety helmets

Helmet	Size (mm) length × width × height	Opening position (opening area [mm ²])	Slide	Inner	Material	Color
A	282 × 222 × 162	×	×	×	ABS	White
A_O	282 × 222 × 162	Both temporal regions (283)	×	×	ABS	White
AS	282 × 222 × 162	×	105 × 167 mm slide (inside)	Shock absorbance inner (expanded polystyrene)	ABS	White
AS_O	282 × 222 × 162	Both temporal regions (283)	105 × 167 mm slide (inside)	Shock absorbance inner (expanded polystyrene)	ABS	White
AS_S	282 × 222 × 162	×	105 × 167 mm slide (outside)	Shock absorbance inner (expanded polystyrene)	ABS	White
AS_O_S	282 × 222 × 162	Both temporal regions (283)	105 × 167 mm slide (outside)	Shock absorbance inner (expanded polystyrene)	ABS	White
B	280 × 220 × 155	Front (170) and back (315) near the top, between brim and body (650)	×	Shock absorbance inner (expanded polystyrene)	ABS, PC (Brim)	White (body), blue (Brim)

The opening size of Helmet A_O was calculated by its drawing. The opening size of Helmet B was measured by a caliper. Thus, measurement error of the opening area could be caused by measuring method.

(Table 1), and the covered area of the SHM by each helmet could be considered as the same area. About half of the SHM surface was covered by the tested helmet. Helmet A and Helmet A_O were the same except for five small slits on both the right and left sides of the helmets. The slit was rectangle attached by semicircles on both of the shorter sides. The drawing of Helmet A shows that the longer side of the slit was about 6.0 mm and shorter side was 3.3 mm. Helmet AS had a shock absorbance inner lining made of expanded polystyrene and a slider up inside the helmet, which could be lowered to nose level to protect a worker's eyes from flying objects. Helmet AS_O was the ventilation form of Helmet AS with five small slits on both the right and left sides of the helmet. Helmet AS_S was the same as Helmet AS except for the position of slider which was lowered to nose level. Similarly, Helmet AS_S_O was the ventilation form of Helmet AS_S with five small slits on both the right and left sides of the helmet. To elucidate the ventilation effects of five small slits on both the right and left sides of the helmets, we compared the heat flux of SHM between Helmet A and A_O, AS and AS_O, AS_S and AS_S_O. There were three opening sites in Helmet B: the front, back of the head near the top, and between the body and the brim. The opening size of Helmet B was measured by a caliper (Mitutoyo, Kawasaki, Japan) (Table 1). To estimate the ventilation effects of openings at the front and back of the head, we compared the heat flux of SHM between Helmet A and Helmet B. The body of all the ISHs was made of Acrylonitrile Butadiene Styrene (ABS) resin. The color of every ISH was white.

2.4 | Measurement

Each ISH was placed on SHM during the test, and the wind was blown from the front or the left side of SHM. Tested air speed was set at 1.0, 2.0, and 3.0 m/s because the average outside air speed during summer in Japan is about 3 m/s. Two zones (Forehead and Head Top) of SHM were covered by ISH, but the other four zones (the Face, Head Left, Head Right, and Chin) were not covered by ISH. The heat flux of each zone of SHM was controlled by software on a laptop computer in order to keep the shell temperature of SHM at 34.0°C. The necessary heat flux to keep the manikin skin temperature at 34.0°C was counted as evaporative heat dissipation in each zone. Each ISH was tested at least two times for every experimental condition. The measurement time was 1 hour for each test, and the last 10 minutes of the data of the measured heat flux were used for analysis.

2.5 | Data analysis

We performed multiple pairwise comparison tests (PCTs) in Excel 2013 by using Bonferroni correction to examine four kinds of effects on evaporative heat dissipation: wearing

ISHs, side openings, front-back openings, and wind direction. Seven PCTs between the average heat flux of Nude and those of seven ISHs were performed to examine the effect of wearing ISHs. Three PCTs between the average heat flux of Helmet A and Helmet A_O, Helmet AS and Helmet AS_O, Helmet AS_S and Helmet AS_S_O were executed to investigate the effects of side opening. Three PCTs between Helmet B and Helmet A_O, Helmet AS_O, Helmet AS_S_O were performed to investigate the significant difference in the effect of side openings and front-back openings. Seven PCTs between a front wind and a left wind were compared within each seven ISHs. All the tests were calculated for both a front and a left wind for uncovered zones, forehead zone, head top zone, and all zones. We set the statistically significant level at $0.05/N$, where N is the number of pairwise comparison.

3 | RESULTS

Figure 2 shows the differences in the heat flux of each SHM zone. The heat flux of each zone in nude and wearing Helmet A is displayed at a wind speed of 1 m/s from the front and left side, respectively. SHM was covered by Helmet A in Forehead and Head Top zones. PCTs to examine the effect of wearing Helmet A showed that the heat fluxes of Nude were significantly larger than that of Helmet A in Forehead and Head Top zone for both a front and a left wind. The average heat flux of all six zones was also significantly larger in Nude than Helmet A. However, for Face, Head Left, and Chin, where SHM was not covered by the Helmet A, the heat flux of Nude was not significantly different from that of Helmet A. Only in Head Right for a wind at 1.0 m/s from left side, Nude was significantly larger than Helmet A. However, the relative difference of average heat flux in Head Right was similar to that of other parts. Thus, we considered the Forehead and Head Top as a helmet-covered zone and the Face, Head Left, Head Right and Chin as an uncovered zone.

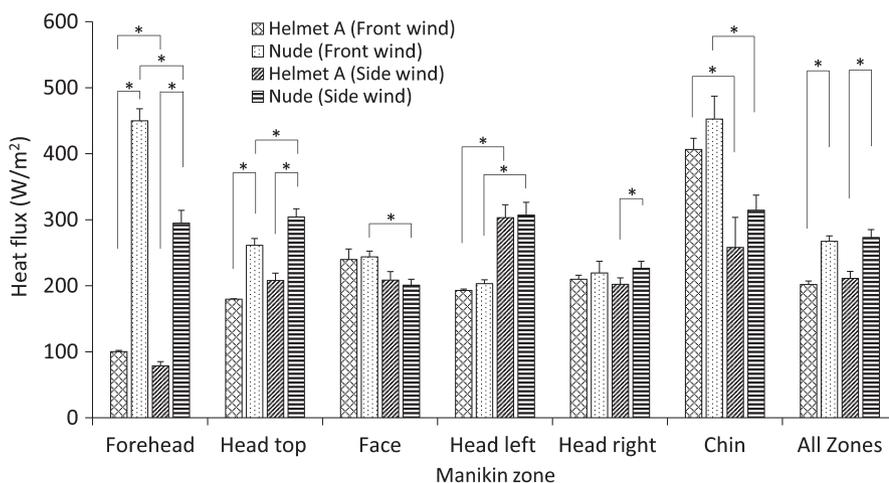


FIGURE 2 Average heat flux required to maintain the surface of head manikin covered by wet skin at 34.0°C for Helmet A and nude at a wind speed of 1.0 m/s for a front wind and a left wind, respectively. The error bar stands for the standard deviation. Student's t test was used to determine the significant difference between the average heat fluxes. * $P < 0.004$

PCTs to examine the effects of wind direction on heat flux showed that heat flux in a front wind was significantly larger than that in a left wind in Forehead and Chin for both in nude and when wearing Helmet A. In Face, heat flux of Nude in a front wind was significantly larger than that in a left wind. On the other hand, in Head Left, heat flux in a left wind was significantly larger than that in a front wind for both in nude and when wearing Helmet A. In Head Top, heat flux in a left wind was significantly larger than that in a front wind in nude.

The heat flux of an uncovered zone (Figure 3A), Forehead (Figure 3B), Head Top (Figure 3C) and all zones (Figure 3D) generated in SHM for the seven models of ISH and Nude are shown for both a front and a left wind at wind speeds of 1.0, 2.0, and 3.0 m/s. PCTs were conducted at a wind speed of 3.0 m/s both from the front and the left.

3.1 | Uncovered zones

For the uncovered zone, the average heat flux of three non-opening, three side-opening, one front-opening helmets, and Nude at an air velocity of 3.0 m/s were 424, 412, 404, and 419 W/m^2 for a front wind and 384, 386, 376, and 390 W/m^2 for left wind, respectively (Figure 3A). Average heat flux in uncovered zones of Nude was not significantly different from those of every kind of ISHs for both a front and a left wind.

3.2 | Forehead zone

For the Forehead zone, the average heat flux of three non-opening, three side-opening, one front-opening helmets, and Nude at an air velocity of 3.0 m/s were 174, 204, 479, and 651 W/m^2 for a front wind and 129, 133, 329, and 588 W/m^2 for a left wind, respectively (Figure 3B). The average heat flux of Nude was significantly larger than those of seven ISHs for both a front and a left wind except for Helmet B in a front wind. The heat flux of ISHs with side openings was not significantly different from those without. However, the

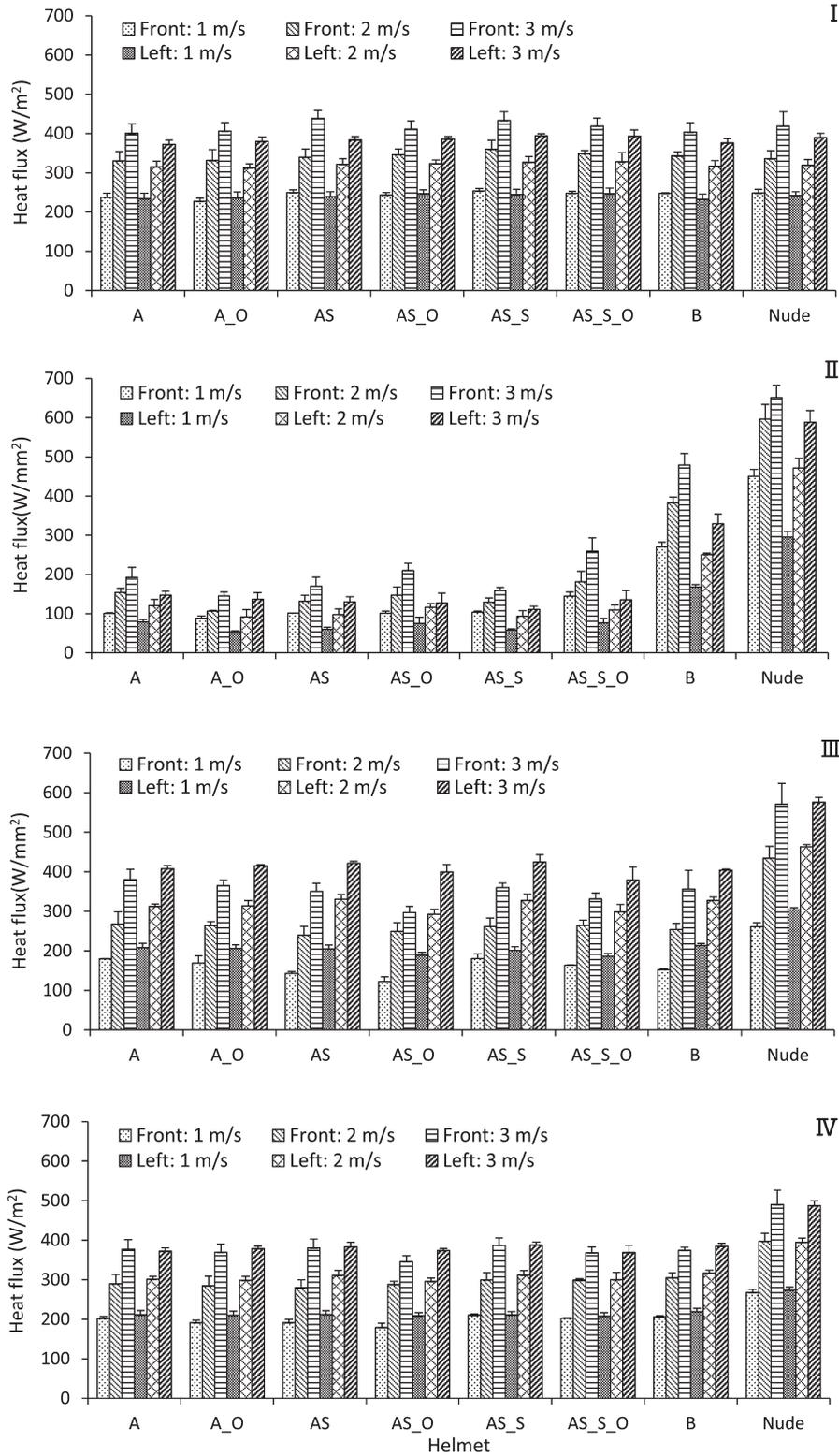


FIGURE 3 Average heat flux required to maintain the surface of head manikin covered by wet skin at 34.0°C for seven kinds of industrial safety helmet and nude at a wind speed of 1.0, 2.0, 3.0 m/s for a front wind and a left wind, respectively. (A) Average heat flux of uncovered zone (the Face, Head Left, Head Right, Chin) at a wind speed of 1.0, 2.0 and 3.0 m/s for both a front and a left wind; (B) Average heat flux of Forehead at a wind speed of 1.0, 2.0 and 3.0 m/s for both a front and a left wind; (C) Average heat flux of Head Top at a wind speed of 1.0, 2.0 and 3.0 m/s for both a front and a left wind; and (D) Average heat flux of all zones at a wind speed of 1.0, 2.0 and 3.0 m/s for both a front and a left wind. The error bar stands for the standard deviation

heat flux of Helmet B was significantly larger than those of ISHs with side openings. For Helmet AS_O, Helmet AS_S, Helmet AS_S_O, and Helmet B, the average heat flux in a front wind was significantly larger than that in a left wind.

3.3 | Head top zone

The average heat flux of three non-opening, three side-opening, one front-opening helmets, and Nude at an air velocity of 3.0 m/s were 364, 331, 356, and 571 W/m² for a front wind, and 418, 398, 404, and 576 W/m² for left wind (Figure 3C). Nude was significantly larger than ISHs except Helmet B. The heat fluxes of ISHs with openings were not significantly different from those without openings. In head top zone, Helmet B was not significantly larger than those of ISHs with side openings. In Helmet A_O, Helmet AS_O, and Helmet AS_S, the average heat flux in a left wind was significantly larger than those in a front wind.

3.4 | All zones

The average heat flux of three non-opening, three side-opening, one front-opening helmet, and Nude at an air velocity of 3.0 m/s were 381, 361, 374, and 490 W/m² for a front wind, and 381, 374, 385, and 487 W/m² for left wind (Figure 3D). The average heat flux of Nude was not significantly larger than those of ISHs except for Helmet A of a left wind. The average heat flux of ISHs with side openings and front-back openings were not significantly different from those without. The average heat flux of ISH with front-back openings was not significantly different from ISHs with side openings, neither. The average heat flux of all zones was not significantly different between in a front wind and a left wind.

In nude, the heat flux averaged for all zones at 3.0 m/s wind speed increased by 1.83 times for front wind and 1.78 times for left wind in comparison with 1.0 m/s wind speed. For seven tested ISHs, the average heat flux of all zones at 3.0 m/s increased by 1.88 and 1.79 times for a front, and a left wind in comparison with 1.0 m/s, respectively.

4 | DISCUSSION

The effects of small openings in ISH on evaporative heat dissipation were quantitatively investigated by a SHM. Seven models of commercial ISH were examined in a climate chamber. In the helmet covered zone (Forehead and Head Top) of SHM, the heat flux was less than that of Nude. For Forehead, the heat flux of the Helmet B with openings in the front and back, and between the body and brim of the helmet was larger than the other ISHs. However, the effect of front-back openings on the averaged heat flux over

all zones was not significant. This study found that small openings on both the right and left sides of the helmet did not have an effect on evaporative heat dissipation over all zones (Figure 3D).

Our data showed that SHM is a reliable tool to measure evaporative heat dissipation. SHM was also sensitive to wind direction. Significantly larger heat flux at Head Left in a left wind compared to a front wind and a larger heat flux at the Forehead zone for a front wind than a left wind (Figure 2) showed that the heat flux of the SHM zone facing the wind increased.

Liu and Holmer¹² showed that the heat dissipation of a helmet with 30 circular openings of 4.5 mm in diameter was not relatively larger than that without openings when an air velocity of 1 m/s. Using the same helmets, Liu et al¹⁰ found that a helmet with openings was less comfortable than without openings in the subject experiment. In contrast, Kim and Park⁹ reported the cooling effects of openings on ISH by comparing the subjects' physiological parameters when wearing ISH with 18 holes of 5 mm diameter on both sides versus ISH without a hole. Core temperature, the forehead skin temperature, and blood pressure were significantly lower for ISH with holes than without a hole. Holland et al¹³ showed in their paper that the ventilation of ISH with side openings of 226 mm² was 7.8 L/min, which was nearly the same as that of a non-opening helmet with an average of 7.6 L/min. An ISH with top openings of 288 mm² had more ventilation of 10.1 L/min than side opening or non-opening ISH. They also reported that the temperature, humidity, and sweat rate of the head were lowest for ISH with openings at the top of the helmets. In this experiment, the heat flux averaged over the zones covered by the helmets with side openings was not significantly different from those for helmets without side openings. Our results agreed with Holland's ventilation experiments.

In contrast, Abeysekera et al¹⁴ found that ventilation in a helmet with 64 circular openings of 6 mm in diameter, which corresponds to total opening area of 1800 mm², increased heat dissipation by 19% when compared to without openings. The total opening area of 1800 mm² was four times larger than the 450 mm² maximum limits set for ISH total opening area by the Japanese Industrial Standard Committee.⁸ Much larger opening area than standard limitation suggests that the impact resistance of the helmet with ventilation openings was insufficient. Davis et al¹⁵ found that when wearing a passive helmet with ventilation openings with 37 holes of 9.5 mm in diameter, core temperature decreased by 0.05°C and the temperature inside the helmet decreased by 2.0°C. Our study showed that only making openings on the helmet did not serve to increase heat dissipation under the maximum open area limitations set for helmets.

In a paper by Hsu et al,¹⁶ they concluded that ventilation holes irrespective of the position produced only a marginal

effect for intensifying ventilation. Subsequently, they developed a new type of helmet with openings on the front and back as well as both the right and left sides of the helmet. The front-back openings and both the right and left side openings were connected by a wind channel in between the openings for their helmet model. They reported that the convective heat dissipation speed of the developed helmet was faster than that of other commercial helmets. In the case of Helmet B, openings on the front, back of the helmet, and between the body and brim of helmet increased ventilation on the Forehead and induced evaporative heat dissipation from Forehead zone. A larger sweating rate in the forehead of humans¹⁷ could induce larger evaporative heat dissipation from the head. Our data showed that the effect of ventilation opening in the front (Helmet B) was confined to Forehead zone and did not spread to Head top zone (Figure 3B, Figure 3C). One of the reasons is that the shock absorbance inner lining inside helmet could interfere with the air flow inside Helmet B. The other reason is the large portion of Head top zone in the head surface area (Figure 1). Since the opening in the back is near the top of Helmet B, the air from the front opening to back opening covers a small portion of Head top zone. Thus, the effect of ventilation opening for Helmet B could be not significant in Head Top zone.

When considering that the area of ventilation opening is limited from a safety point of view, other improvements, such as the position of openings or air passages inside the helmet could help to increase evaporative heat dissipation. Since our results for evaporative heat dissipation from the forehead and head top of SHM showed that the direction of wind also significantly effected the evaporative heat dissipation in about half of tested ISHs, it is also important to consider wind direction when designing the position of openings on an ISH.

The evaporative heat dissipation from SHM with a helmet has increased by the wind at the same rate for Nude. Bruehwiler¹⁸ reported that heat dissipation from a SHM by forced convection was proportional to the function of air velocity of $v^{0.65}$ for a nude head. Here, v is the ambient air velocity. The ratio of heat dissipation by forced convection with wind of 3.0-1.0 m/s from the above equation was 2.04, which was close to the data of evaporative heat dissipation of this study of 1.83 or 1.78 for front or left wind for a nude head. For clothing system, Woodcock¹⁹ introduced the moisture permeability index (im) to compare the resistance of total convective heat dissipation with the resistance of total evaporative heat dissipation. Both convective and evaporative heat dissipation were mediated by air movement, and im value also changes with air movement.¹⁹ According to the prediction equation for the resistance of total convective and evaporative heat dissipation in ISO 7933,²⁰ evaporative heat dissipation is affected more by air velocity than convective heat dissipation for both nude and clothing conditions. Then the ratio of convective

heat dissipation at 3.0-1.0 m/s would be smaller than that of evaporative heat dissipation. However, the ratio of convective heat dissipation calculated by Bruehwiler's result¹⁸ was larger than that of evaporative heat dissipation in this study. The predicted cause of this discrepancy was differences in SHM they tested or the loose contact of sweat skin to the surface of SHM, especially for Face. Loose contact in Face is ascribable to a protruding nose and hollow eyes.

Another method of cooling a head when wearing ISH was investigated by Ghani et al²¹ by using phase change material (PCM) and forced convection inside the helmet from an electric fan. PCM prolonged comfort time and forced convection decreased the temperature of the helmet surface. However, the head skin surface temperature with PCM and forced convection inside the helmet were higher than that from an exterior wind.²¹

In our experiment, hair was not put on the SHM. Previous research⁷ showed that hair decrease convective and evaporative heat dissipation. To simulate realistic situations, it will be necessary to include hair in future experiments.

5 | CONCLUSION

This experiment tested commercial industrial safety helmets (ISHs) with openings on both the right and left sides (Helmet A_O), with openings at the front, back, and between the body and brim (Helmet B), and without openings under the conditions where the ambient temperature and the shell temperature of sweating head manikin (SHM) were at the same temperature of 34.0°C. The heat flux in uncovered zones was not influenced by the helmets. The openings on both the right and left sides of the helmet had little effects on the heat flux averaged over six SHM zones. Helmets with openings at the front and back had a significantly larger heat flux for the Forehead zone compared to the other helmets we tested. However, the effects of front-back openings did not spread to the top of the head. More improvements are needed to ventilate all covered zones.

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DISCLOSURE

Approval of the research protocol: NA. *Informed Consent:* NA. *Registry and the Registration No. of the study/Trial:* NA. *Animal Studies:* NA.

CONFLICT OF INTEREST

No conflicts of interest were declared by any of the authors.

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