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Improving thermal properties of industrial safety helmets

Yeh-Liang Hsu*, Chi-Yu Tai, Ting-Chin Chen

Department of Mechanical Engineering, Yuan Ze University, Chung Li 320, Taoyuan, Taiwan, ROC

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Abstract

This paper presents the redesign of an industrial safety helmet shell to improve its thermal properties. First an experiment was established to simulate the conditions of a head wearing a helmet. The average temperature beneath the helmet shell, the speed of heat dissipation through convection, and the temperature contour beneath the helmet shell were used to describe the thermal properties of a helmet. Helmets of different types and makes were tested, and various design concepts were examined. Design suggestions for improving thermal properties of industrial safety helmets were made. According to these design suggestions, a new design prototype was developed, tested, and further modified. The thermal properties of our final helmet shell design have improved over the commercially available helmets we tested. It also passed the weight, impact, and penetration tests of the Chinese National Standards. Finally a subjective human evaluation showed that the new helmet design has significantly better thermal properties than existing commercial helmets.

Relevance to industry

Industrial safety helmets provide head protection for industrial workers. Thermal discomfort is one of the major reasons that industrial workers do not like to wear safety helmets. This paper presents and verifies ways on improving thermal properties of industrial safety helmets. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Industrial safety helmet; Thermal properties

1. Introduction

Industrial safety helmets provide head protection against small falling objects striking the top of the shell in industrial environments. Most of the tests in the standards (CNS, 1992; ANSI, 1986; ISO, 1977; BSI, 1987) that apply to industrial safety helmets are to measure whether a helmet can provide effective protection to the wearers. Considerable amount of research has also been done on the performance in impact and shock absorbing ability

of the safety helmet (Mills and Gilchrist, 1987,1993; Rowland et al., 1988; Rowland, 1987). However, many workers are not willing to wear helmets simply because they are not comfortable. The “comfort performance”, which may often be overlooked, is obviously another important issue for industrial safety helmet design.

Hickling (1986) discussed 12 factors that affect the acceptability of head protection at work: weather protection, thermal properties, tactile properties, absorptivity/permeability, mass distribution, degree of fit, size and shape, retention performance and fit, helmet volume, visual factors, speech and sound factors, and helmet compatibility.

* Corresponding author.

Among these 12 factors, the one of importance for the workers in a tropical or subtropical climate, such as that of Taiwan, are the thermal properties of industrial safety helmets. Liu and Holmer (1995) evaluated experimentally the evaporative heat transfer characteristics of industrial safety helmets. The effects of ambient humidity, solar radiation, and wind on heat loss were investigated.

This paper presents a project on how to redesign the shell of the industrial safety helmet to improve its thermal properties. In this project, first an experiment was established to simulate the conditions of a head wearing a helmet. Helmets of different types and makes were then tested. The average temperature beneath the helmet shell, the speed of heat dissipation through convection, and the temperature contour beneath the helmet shell were used to describe the thermal properties of a helmet. Various design concepts, e.g., adding ventilation holes, increasing clearance between the helmet shell and the head, covering the shell with reflective materials, were also tested. Finally, some design suggestions for improving the thermal properties of industrial safety helmet shells were made.

According to these design suggestions, a new design prototype was developed, tested, and further modified. At this stage, attentions were also paid to structural safety, appearance, manufacturability, and other practical issues. Finally, we developed our final helmet shell design. The thermal properties of this final design have significantly improved over other commercially available helmets we tested. It also passed the weight, impact, and penetration tests of the Chinese National Standards (CNS). A human description evaluation showed that the new helmet design has significantly better thermal properties than existing commercial helmets.

2. An experiment to measure the thermal properties of a helmet

Heat may be gained or lost from the head wearing a helmet by conduction, convection, and radiation. Conduction to the air is typically low, while convection and radiant heat transfer can be impeded by the presence of the helmet. There can be three heat sources that affect the temperature

beneath the helmet shell: radiation from the sun, body heat from the wearer's head, and heat exchange with the surrounding air through convection.

Fig. 1 shows an experiment designed to simulate the conditions of a head wearing a helmet. The helmet being tested was resting on a headform. The headform was made of rubber and covered with hair. A set of four halogen lamps were positioned above the headform, so as to evenly distribute their radiant heat over the whole test region. A heat source (a light bulb) was put inside the headform to simulate body heat from the head. The temperature of the headform was controlled to maintain at body temperature 37.6°C.

The test environment was surrounded by electric heating coils for controlling the temperature of the surrounding air. According to the Central Weather Bureau of Taiwan, the average temperatures of Taiwan during summer months range from 26.8°C to 28.3°C, and the highest temperatures of the summer months range from 31.5°C to 33.3°C. Therefore, the temperature of the test region was set at 30.0°C. The halogen lamps and electric heating coils were controlled through a temperature controller, so that the temperature of the test environment was maintained at 30.0°C. Also according to the Central Weather Bureau of Taiwan, the average wind speed in Taiwan is about 2.0–2.5 m/s. An electrical fan was adjusted to provide a constant airflow at 2.5 m/s. The room temperature outside the test region was kept at about 25°C.

In summary, the standard test conditions of our experiment simulated a worker wearing a helmet in a 30.0°C sunny day, with wind blowing at 2.5 m/s.

3. Describing thermal properties of a helmet

To the extent of the authors' knowledge, there has not been a universally agreed index that formally defines the thermal properties of industrial safety helmets. Roszkowski (1980) compared the thermal properties of 10 industrial helmets on a resting subject. The results obtained were expressed in terms of dry bulb temperature and relative humidity beneath the helmet. Liu and Holmer (1995) measured the heat loss from a

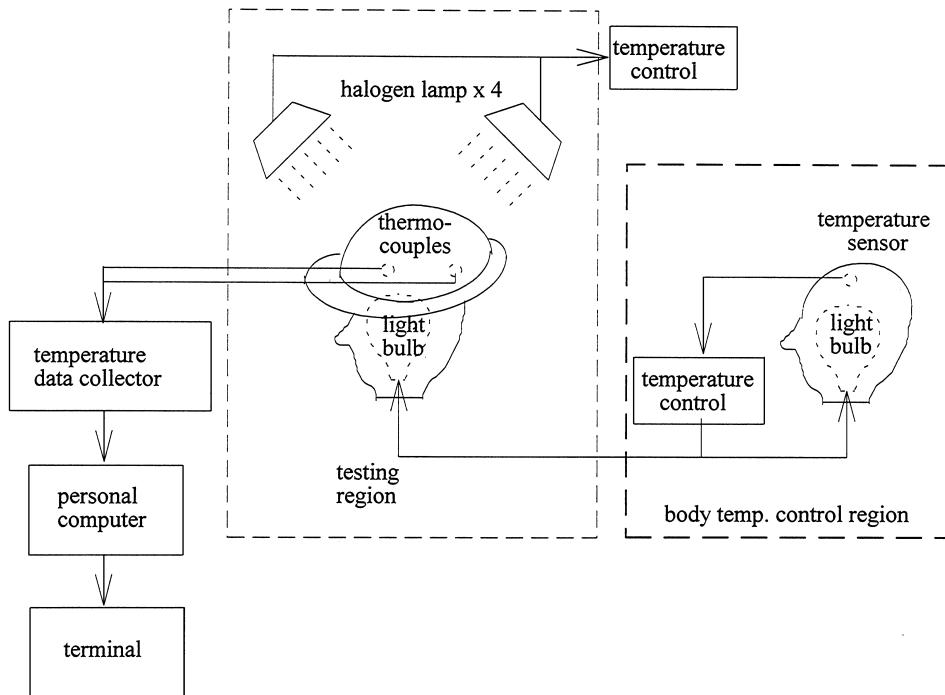


Fig. 1. An experiment to simulate the conditions when wearing a helmet.

wet head mannequin to evaporative heat transfer characteristics of industrial safety helmets. In their experiment, heat loss was directly determined as the power required to maintain the target skin temperature during the last 20 min in each 1 h test for each helmet.

In our project, the major concern is the temperature inside the helmet. We found that in sunny weather with no wind, the temperature inside the helmet often rises over 50°C , which is simply unbearable. Therefore, in our experiment, the average temperature beneath the helmet shell, the speed of heat dissipation through convection, and the temperature contour beneath the helmet shell, were used to describe the thermal properties of the helmets. The relative humidity beneath the helmet was not used because we did not simulate sweating of the head in our experiment. The relative humidity is directly related to the average temperature beneath the helmet shell.

A total of 16 thermocouples were attached to the inside of the helmet shell in a rectangular pattern,

as shown in Fig. 2, to measure the temperatures beneath the helmet shell. The average temperature was the average of temperatures taken from all 16 thermocouples when a steady-state condition was reached. Repeatability of measuring the average temperature was also examined. The standard deviation of the average temperature measurement was 0.38°C .

To measure the speed of heat dissipation with convection, the average temperature was measured with the electric fan turned off. Then the electric fan was turned on and the time required for the helmet to reach a new steady state temperature was recorded. This time was used to describe the speed of heat dissipation inside the helmet.

Finally the 16 temperatures taken from the thermocouples were further processed to draw a temperature contour plot. From the temperature contour plot, we can observe whether the temperature inside the helmet is evenly distributed and whether any “hot spots” exist beneath the helmet shell.

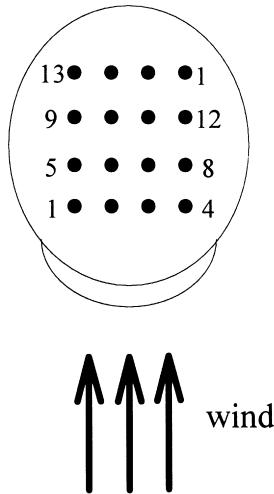


Fig. 2. The arrangement of the 16 thermocouples. The distance between two neighboring thermocouples is 5 cm.

4. Design suggestions

Helmets of different types and makes were then tested. Fig. 3(a) shows the test data of a typical commercially available helmet. When all three heat sources were turned on, the final average temperature beneath the helmet shell was 38.3°C. When the halogen lamps were turned off (no radiant heat), but the test region was still kept at 30.0°C by the heat provided by electric heating coils, the average temperature beneath the helmet shell dropped to 31.0°C. This temperature was just slightly above the temperature of the test region. On the other hand, when the electric heating coils were turned off, and the test region was maintained at 30.0°C by the heat of the halogen lamps, the average temperature rose to 41.0°C. When the heat source inside the headform was turned off (no body heat), the average temperature dropped slightly to 37.2°C. Finally, when all three heat sources were on, but the electric fan was turned off (no convection), the final average temperature rose rapidly to 50.1°C.

From the test results above, we can conclude that radiant heat is the major heat source when wearing a helmet, and the “green house” effect will cause the temperature beneath the helmet shell to rise

rapidly. Convection is the primary way to dissipate heat from beneath the helmet shell. Body heat has only a marginal effect on the temperature beneath the helmet shell. Therefore, to improve thermal properties of an industrial helmet, the helmet shell should be redesigned to provide better insulation against solar radiation, and to provide better ventilation.

4.1. Improving insulation

Adding a layer of close-fitting helmet liner is a way to insulate the head from solar radiation and remove the “green house” effect beneath the helmet shell. But it also adds weight to the helmet. A commercially available helmet with such design was tested and it showed better-than-average thermal properties. However, its weight was 40% more than the weight allowed by CNS.

Therefore, our research to improve insulation against solar heat focused on changing the surface of the helmet shell. The color of the shell is of course an important factor. The helmet tested in Fig. 3(a) was white. The test was repeated on the same helmet in red, and yellow. As shown in Fig. 3(b), the final average temperatures of these color helmets under standard test conditions were 4–7°C higher than that of a white helmet.

Covering reflective materials on the outside of the shell is also effective. When the helmet tested in Fig. 3(a) was covered with various reflective materials on the top portion of the shell, the final average temperature dropped 4–6°C under the standard test conditions. On the other hand, our test results showed that helmets made of different plastic materials, PE, ABS, or PC, do not produce significant difference in thermal properties.

4.2. Improving ventilation

Several different design concepts for improving ventilation of the helmet shell were tested. The most intuitive way is to put ventilation holes or slots on the helmet shell. However, after many tests on different sizes, shapes, and locations of ventilation holes, we concluded that the ventilation holes produced only a marginal effect for intensifying convection. A simple two-dimensional computer

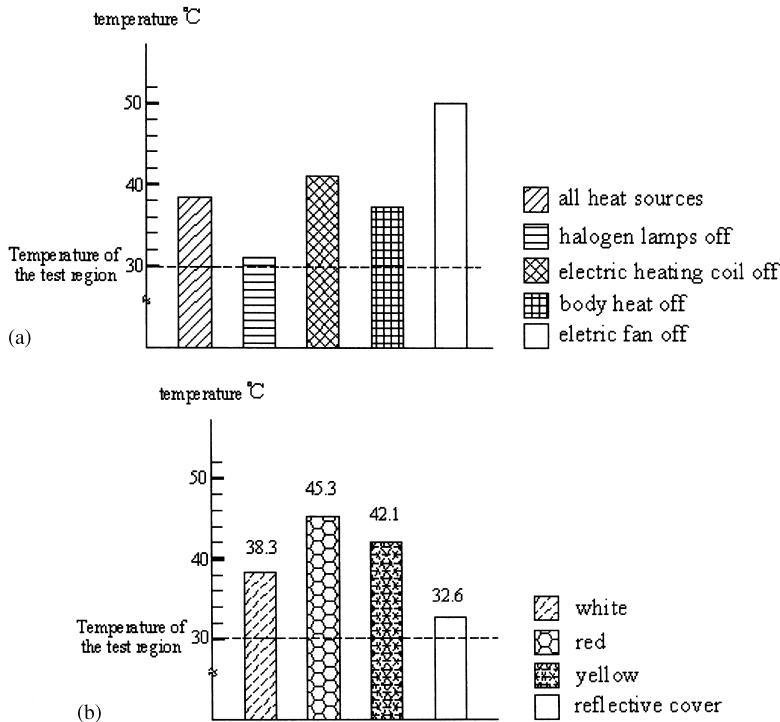


Fig. 3. (a) The effect of all heat sources. (b) The effect of different color and reflection cover.

simulation revealed that, the speed of circulation of the air beneath the helmet shell was very slow compared with the airflow outside (about 1/10 under the assumptions of our computer simulation model). Adding ventilation holes alone does not produce a significant change in the airflow pattern beneath the helmet shell.

Further tests showed that increasing the clearance between the helmet and the head is an effective means to increase air circulation speed, thus to increase heat exchange with the outside air. This also explains the workers' behavior when wearing a helmet in a hot weather: they often wear helmets in a high position to allow more airflow between the helmet and the head. Too much clearance between the head and the shell will affect the shock absorbing ability of harness of the helmet. Actually the vertical clearance is specified in the test standards for impact and penetration tests. Therefore, instead of increasing the clearance, we suggest that "wind channels" on the shell of the helmet have to

be properly designed together with the ventilation holes.

Adding ventilation holes and wind channels should not affect the structural safety of the helmet shell. On the contrary, if properly designed, adding the wind channels on the helmet shell can provide local reinforcement against impact and increase lateral rigidity of the helmet shell.

Another behavior that can be observed from local outdoor workers is that, in a hot weather, the workers often wear helmets in a reverse direction, with the beak at the back of the head. Our test results showed that wearing a helmet this way can also effectively decrease the average temperature beneath the helmet. Wearing the helmet in a reverse direction actually decrease the clearance between the helmet and the front of the head. However, without the beak, the air can flow into the helmet much more smoothly. The beak should also be properly designed so that it will not impede the airflow from the front.

Based on the experiment, our design suggestions are summarized as follows:

1. Radiant heat is the major heat source when wearing a helmet. Using a light color shell (such as a white one) and covering the top portion of the helmet shell with reflective materials are effective for insulating the radiant heat.
2. Convection is the primary way for heat dissipation from beneath the helmet shell. Adding ventilation holes or slots does not produce a significant effect for intensifying convection. “Wind channels” should be designed to provide more clearance between the helmet shell and the head. At the same time, those wind channels should be designed to increase the structural rigidity of the helmet shell.
3. The beak should also be designed so that it will not impede the airflow from the front.

5. Development of a new helmet shell design

According to these design suggestions, a new design prototype was developed, tested, and further modified. At this product development stage, attention was also paid to structural safety, appearance, manufacturability of the helmet shell, and other practical issues. Finally, we developed our final helmet shell design as shown in Fig. 4. Some of the important features of this final design are listed below:

1. There are ventilation holes on the front and back, as well as both sides of the helmet shell.

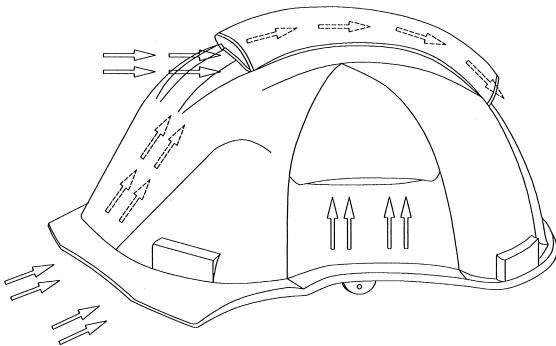


Fig. 4. Our final helmet shell design. The arrows indicate airflow.

2. Together with the ventilation holes, wind channels were designed on the top of the shell and on both sides of the shell, to provide clearance between the shell and the head.
3. The wind channels also provide local reinforcement against impact on the top of the shell, and increase the lateral rigidity of the helmet shell.
4. The beak of the helmet has an arched front tip and a wind channel that integrated smoothly into the front end of the helmet shell.
5. There are arched flanges on both sides and the back end of the helmet shell, to allow more airflow between the helmet shell and the head from different directions.
6. There are flanges around the ventilation holes to prevent water from leaking into the helmet on a rainy day.

We also checked with a few helmet manufacturers about the manufacturability of our helmet, and made slight modifications on the design, mostly around the ventilation slots. With all the features listed above, the estimated production cost of our helmet is about the same as that of other helmets.

Fig. 5 compares the temperature contour plots of our final design with a commercially available helmet (Helmet B). Helmet B was used for this comparison because it is the helmet that has the best thermal properties among the helmets we tested. Fig. 5(a) is the temperature contour plot of this helmet under standard test conditions. The average temperature was 35.1°C. It has two “hot spots” on both sides of the helmet at the front end, with temperatures over 38.5°C. The temperature contour plot also shows steep temperature gradient over the entire helmet.

Fig. 5(b) shows the temperature contour plot of our final design under standard test conditions. The average temperature was 32.6°C, and the temperature was more evenly distributed over the whole helmet. There were still two hot spots on both sides of the front end of the helmet, which indicates that the airflow in those two areas can be further improved. Fig. 5(c) shows the temperature contour plot when the helmet was covered with reflective material on the top portion of the shell (Fig. 6). The average temperature further dropped to 31.6°C, only 1.6°C higher than the temperature of the testing region.

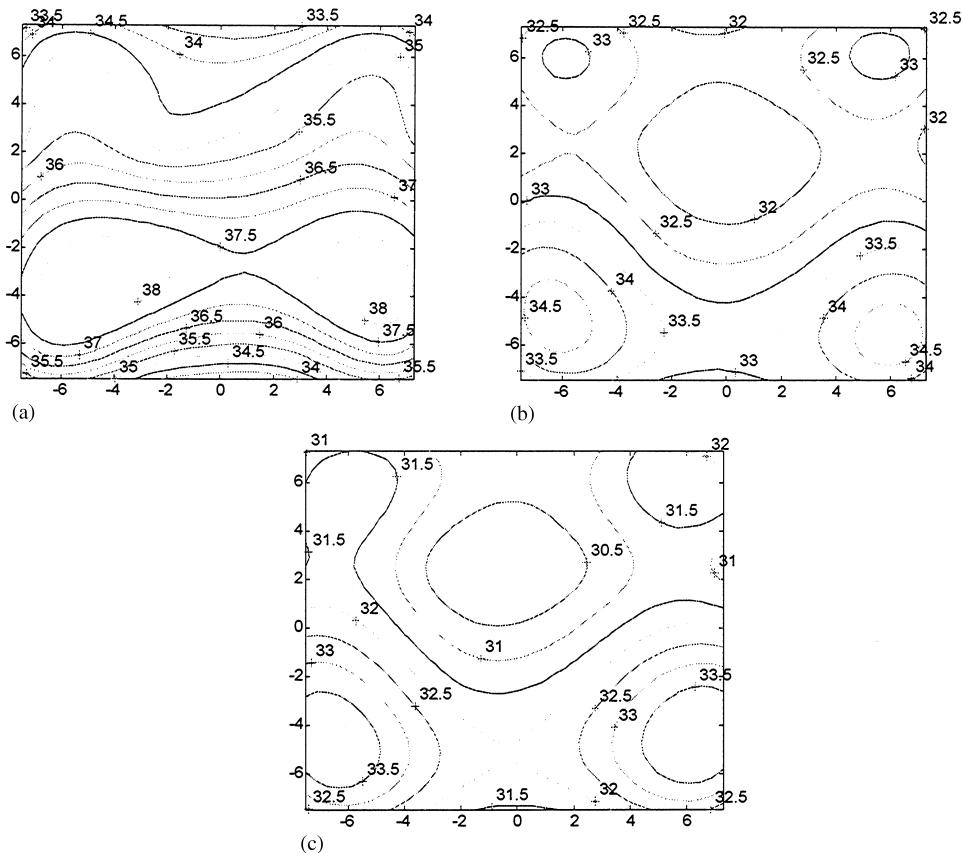


Fig. 5. Temperature contour plots. (a) Temperature contour plot of Helmet B. (b) Temperature contour plot of our final design. (c) Temperature contour plot of our final design, with reflective material covering the top portion of the shell.

Fig. 7 compares the speed of heat dissipation of the helmet tested in Fig. 3 (Helmets A, B, and our new design). When the electric fan was turned off, our design had an initial temperature of 40.4°C (with no reflective materials), comparing with 50.1°C of Helmet A and 52.6°C of Helmet B. When the electric fan was turned on again, it took 220 s for our design to reach the new steady-state temperature 32.6°C , while it took 380 s for Helmet B to reach the new steady-state temperature 34.6°C , and it took 700 s for Helmet A to reach the new steady-state temperature 38.3°C .

The prototype of our final helmet design was made of ABS by vacuum molding. The mass of our helmet with harness and other accessories is 370 g (346 g without harness and other accessories),

which satisfies CNS standard of 425 g. It also passed the CNS impact and penetration tests.

6. A human description evaluation of the new helmet design

Finally a human description evaluation was performed to compare the thermal properties of our new helmet design with those of two commercially available helmets that are popular to the local workers (see Table 1 for a description of the helmets). Helmets 1 and 2 have similar shape shells, the primary difference between them is the color. Note that these helmets are different from Helmets A and B tested in the previous section.

Fourteen healthy young male subjects (average 22.3 years old) who were sensitive to heat volunteered to participate in the study. Before the first measurement, each subject was informed about the experimental procedure and agreed to answer the questions sincerely. All subjects wore different helmets randomly and walk around in a sunny, outdoor environment for 10 min. Then the subjects received a 10-min break before they switched to a different helmet. After wearing each helmet the subjects were asked to answer five questions subjectively on a nine-point scale, and describe their experience about each helmet. The five questions are (1) the subjects' feeling about the temperature within the helmet, (2) whether they feel obvious "hot spots" in the helmet, (3) whether they sweat profusely wearing the helmet, (4) how well does heat dissipate when wind blows, and (5) whether the helmet is comfortable in general.

Fig. 8 shows the sum of total scores of each helmet rated by the 14 testers. There is a significant difference between the the new design helmet and the two commercially available helmets ($p < 0.001$). Fig. 8 also shows that Helmet 2 has significantly higher score than Helmet 1 in thermal properties ($p < 0.1$), which indicates that the light color of safety helmet has a significant effect. Fig. 9 shows

the sum of individual scores rated by the 14 testers on the five thermal property evaluations. Our new industrial safety helmet design has significantly higher scores than the two commercially available helmets on all five questions ($p < 0.01$).

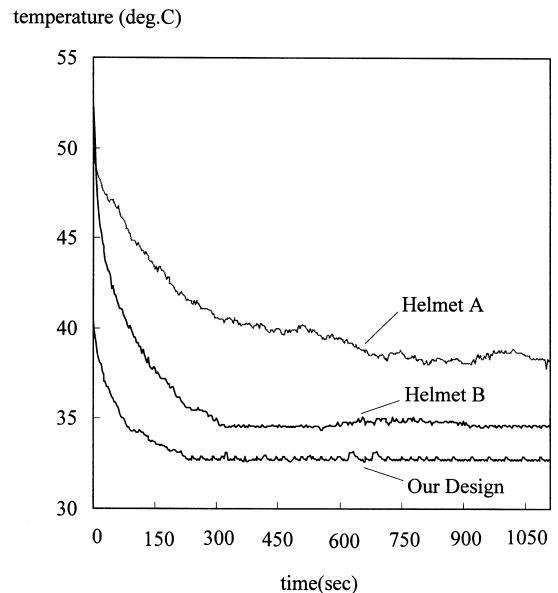


Fig. 7. Heat dissipation speed.

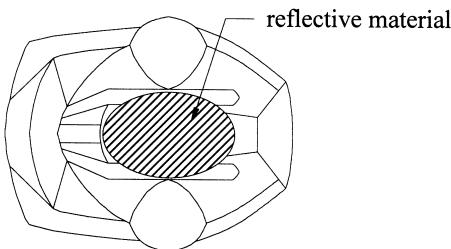


Fig. 6. Covering reflective material on the top portion of the helmet shell.

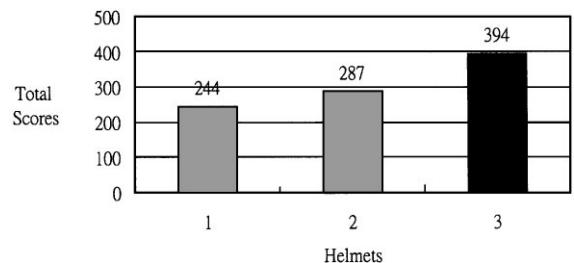


Fig. 8. Total scores of each helmet on the thermal property evaluation.

Table 1
The helmet settings

Helmet	Ventilation holes	Color	Weight (g)	Clearance (cm)	CNS
Helmet 1	No	Yellow	355	5	Pass
Helmet 2	No	White	353	5	Pass
Our new design (Helmet 3)	Yes	White	346	5	Pass

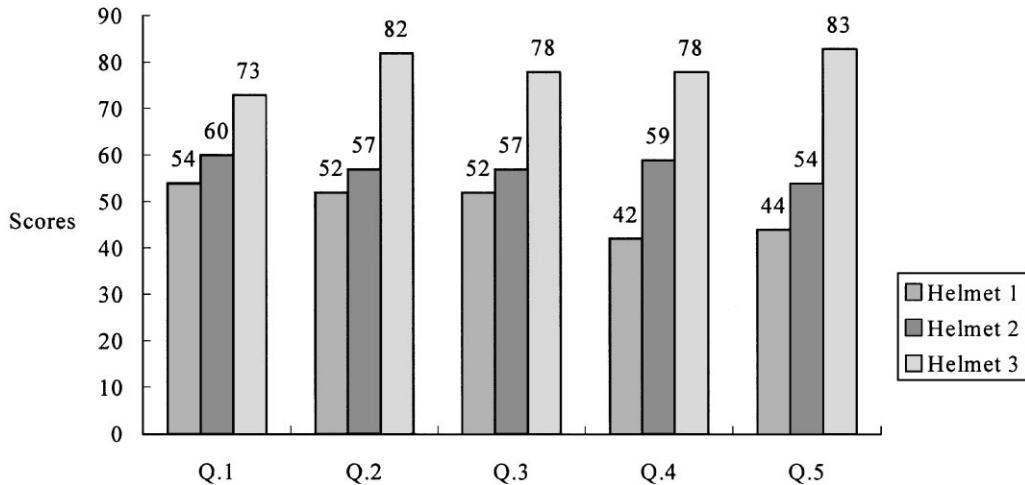


Fig. 9. Scores on the five questions for thermal property evaluation.

7. Conclusion

This paper suggests two basic approaches that can improve thermal properties of industrial safety helmets: (1) to provide better insulation against radiant heat, which is the major heat source when wearing a helmet. For example, using white paint and a reflective covering are very effective. (2) to provide better ventilation to intensify convection, which is the primary way for heat dissipation from beneath the helmet shell.

Several design concepts were found to be effective for improving thermal properties of safety helmets. Using these design concepts, we also developed a new design prototype, which exhibited better thermal properties than the commercially available helmets we tested. With this experience, we believe that there is still much room to further improve industrial safety helmets to provide better thermal comfort for the head, so that safety helmets will be more welcomed by industrial workers.

Acknowledgements

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