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Experimental investigation on the thermal and moisture mapping of cricket helmets using microsensor technology

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Abstract: Based on microsensor technology, a novel test rig was developed for the first time to measure real-time multi-point temperatures and relative humidities inside a cricket helmet worn by a human subject for obtaining the corresponding thermal and moisture mapping. Two types of helmets with and without ventilation openings were investigated to visualise the hot and wet spots clearly inside the helmet. The results show the clear influence of ventilation openings on effective reduction of the temperature as well as the relative humidity inside the helmet. Also, the subjective data were linked to the digital temperature and relative humidity measurements for possible assisting design of helmet with improved thermal comfort. The technology developed is a useful measurement approach to other head gears such as safety, fire fighter and motorcycle helmets, and further to study microclimate environments in close contact with human body.

Keywords: microsensor; thermal and moisture mapping; cricket helmet; thermal comfort; perception

1. Introduction

In daily work and life, a living body generates heat through metabolic reactions. The amount of metabolic heat generated may vary depending on the amount of the activity of the muscle which is exposed to ambient conditions [1, 2]. In order to maintain the optimum temperature inside the human body, the excess heat needs to be dissipated into the surrounding environment [3, 4]. The excess heat generated is dispersed into the surrounding environment through external thermoregulation systems such as clothing [5, 6]. Therefore, to have thermal comfort inside a cricket helmet, the excessive heat generated from the head has to be dissipated into the surrounding environment through the helmet [7, 8]. However, the use of a helmet results in the blockage of heat flow and moisture movement, which limits the heat and moisture transfer from the head to the surroundings. The heat and moisture are trapped in small air pockets between the inner surface of the helmet and the head, also known as the microclimate, which causes discomfort to the user of the helmet [9, 10]. Therefore, efficient transfer of heat and moisture is required to maintain thermal comfort in the helmet.

Thermal comfort in helmets is especially crucial for a physically demanding activity such as batting in cricket [11-13]. In addition to the use of a helmet being compulsory and frequent rehydration not being allowed by the rule, the players may bat for up to 6 hours a day in hot weather which increases the physiological and psychological toll for the players [14-16]. This ultimately leads to reducing player's efficiency in the sport where rapid decision making is required [17].

Generally, there are two ways to regulate the helmet cooling [18-21]. One is to integrate an active head cooling system which consists of heat exchanger, pump, liquid cooling system and sensors [22, 23]. Whether the system is effective in regulating temperature inside the helmet, it is governed by the size of the heat sink installed. Although this type of cooling seems very effective, it is not practical for a cricket helmet because of its cost, size and weight. The other way is through passive ventilation cooling, in which the heat and moisture are allowed in a more effective transfer mode to the surroundings by having ventilation holes on various locations of the helmet [24-28]. The effectiveness of the ventilation holes depends on the shape and size as well as the location.

In dealing with the above challenges, a lot of work has been carried out. To evaluate local heat transfer effects of a headgear, Martinez et al. [29] proposed a nine-zone thermal head manikin. This method gave more clear details of the thermal interaction between the head manikin and a headgear for the design of helmets. Potter et al. [30] used mathematical modeling techniques and sweating thermal manikin to quantify the trade-off between the increased body armor protection, the accompanying mass and thermal effects on human performance. Bogerd et al. [31] utilized a thermal manikin headform to test the effect of full-face motorcycle helmets on convective heat loss under three different interventions (i.e. the wind speed, a head tilt angle and a wig). All helmets were measured in three sessions in which all the vents were opened or closed consecutively in a random order [32]. Flouris [33] studied on the fundamental distinction between thermal (dis)comfort and sensation. He also evaluated the current knowledge on behavioural thermoregulation in order to summarize the present state-of-the-art and give research directions in the future. Foda and Siren [34] proposed a multi-segmental Pierce control mode using the LabVIEW platform, into the control system of a thermal manikin. Hartley et al. [35] examined the direct real-time relationship between thermophysiological afferents and the behavioural response of voluntary exercise intensity. The test results showed that the thermal environment could affect physiological responses and voluntary power. Liu et al. [36] also undertook subjective evaluation on helmets in cold laboratory and warm field conditions. It was found that thermal discomfort existed with helmet wearing in both cold and hot environmental conditions.

However, up to date there is very limited research work on measuring both temperature and relative humidity in multiple positions inside a helmet worn by a subject as well as establishing a relationship between the thermal-moisture mapping and the human perception/sensation, except for the one related to garments and vest [37, 38]. There is a need to provide real-time temperature and moisture distributions inside a helmet tested on a human subject, instead of a thermal manikin headform, in order to provide more realistic data to assist helmet design with necessary thermal comfort. This paper presents a study on developing a novel test rig for the first time to measure multi-point temperatures and relative humidity (RHs) inside a helmet using microsensor technology. Through a series of experiments in relatively comfortable and warm ambient conditions, thermal and moisture mappings of typically ventilated and non-ventilated cricket helmets are obtained, together with a comfort index being linked to the measurements. Based on the mappings, the hot and the wet spots are identified inside the two types of helmets studied, which are further related to human perception/sensation. Such the measurements provide the essential data to assist designing a helmet with necessary thermal comfort and to validate numerical modelling. The technology developed also provides a novel measurement approach to other head gear types, and further to microclimate environments in a close contact with human body.

2. Experimental approach

2.1 Experiment setup

In order to contrast the ventilation opening features, the experimental work was carried out using two helmets with different ventilation settings, i.e. the elite helmet known as NVL (non-ventilated) one, the pro performance helmet known as VL (ventilated) one with a total ventilation area of 4700 mm^2. The difference in ventilation between these two helmets is illustrated in Figures 1(a) and 1(b), respectively. Figure 1(c) shows the microsensor cables led out from the VL helmet and a close view of the sensor embedded in the helmet. Both the NVL and VL helmets are similar in colour (navy), but slightly different weights with wire fixing but without safety guard, i.e. 615 g and 630 g respectively, and sizes as shown in Figure 2.

To study a completely non-ventilated helmet, the ventilation openings on the original NVL helmet were fully sealed. Therefore, the experimental work would compare the two extreme conditions that are ventilated and non-ventilated respectively. The Sensirion SHT75 microsensors (width: 5.08 mm, thickness: 3.1 mm, length: 13.5 mm) were used, which are the capacitive type sensor, with the accuracies being ± 0.3°C (at 25°C) and ± 1.8% RH (in 20-80% RH) and a response time of 8 seconds. This microsensor was chosen due to its ability to measure both temperature and relative humidity using the same probe. It was also chosen because of the sensor being sufficiently small size to be embedded in a cricket helmet at various locations. The sensor locations and its cross sectional diagram are shown in Figure 2. Prior to the measurements, all sensors were calribrated against readings from temperature and relative humidity meter. Based on the total internal surface area of the helmets investigated, 15 microsensors were distributed inside the helmet to ensure that all important areas, such as the frontal, lateral, top and rear regions, were represented to reflect the in-helmet microclimate. Two additional microsensors were attached to the treadmill to record the ambient temperature and RH.

All the sensor probes were placed at the locations (Figure 2) on both types of helmets. The locations 3, 4, 8 and 13 were placed on the ventilation openings of the VL helmet to study the heat and moisture transfer of those locations. Here, a player's activities were simulated by alternately standing and walking at a speed of 5 km/h (or 1.4 m/s) on a flat-bed setting treadmill to study how mild activities affect the microclimate. In order to embed the sensors to the helmets, holes with a diameter of 6 mm were drilled on the helmet shell and the internal fabrics were cut out at the locations where there are no ventilation openings, except for the locations in the VL helmet mentioned the above. The silicone glue was used to seal the helmet after the sensor was inserted. All the sensors were placed at least 5 mm away from the interior surface of the helmet to avoid possible direct contact with the head surface so that the measurements would reflect the true microclimate conditions inside the air pockets corresponding to various regions within a helmet. Therefore, the microsensor interference with the microclimate was minimized.

Although ventilation openings may also lead to possible radiant heat gain, the heat loss from the air exchange through ventilation openings is far more superior. In addition, the measurement system was calibrated against readings from thermometer and humidity meter to ensure the measurements of temperature and relative humidity being complied with the range specified prior to each series of experimental measurements.

2.2 Experimental methodology

In this work, the digital measurements were undertaken in two different ambient conditions, i.e. the relatively comfortable ambient conditions (20°C with 50% RH) and the warm conditions (35°C with 30% RH). During the experimental measurements, limiting the factors that influence the heat and moisture transfer in the microclimate is vital. Therefore, the tests were carried out in a relatively controlled indoor environment. Firstly, the tests under the former conditions were carried out in the Sports Centre Gymnasium of the University of Liverpool. In order to limit the unexpected air flow, the treadmill was located far away from the entrance door and the testing time was selected to avoid rush hour. The moving speed in the walking phase under both conditions was set to a slow pace of 1.4 m/s, which is unlikely causing an air flow surrounding the human subject faster than this speed. However, the tests under the latter conditions were carried out in an environmental chamber (12 m (L) x 4m (W) x 5m (H)) at the Sport Science laboratory of Liverpool John Moores University. Both the environmental conditions were monitored using the microsensors until the desired temperature and relative humidity stabilized before initiate the test. Here, fifteen healthy male students with the similar short hair style were recruited from School of Engineering at the University of Liverpool to participate in experiments. Their head sizes (length, breadth and circumference) were measured beforehand to ensure that the helmet would fit. Six of them were randomly chosen from the subject pool to carry out each set of tests, with their average personal data being shown in Table 1. The subjects were asked to wear cotton trousers, t-shirt and trainers during the test. Also, six subjects were fixed to fulfil the measurements for individual experimental approach to maintain consistence. The subjects were released by the University of Liverpool Ethics committee for the tests, a consent form being signed.

In experiments, the data were divided into two categories, i.e. objective data and subjective data. The former were the digital data collected from the microsensors, which would be used to produce the in-helmet thermal and moisture mapping. The digital temperature and RH readings from individual sensors were processed in two formats, i.e. the chart plot by using the OriginPro8 (OriginLab Corporation, Northampton MA USA) and the 2D contour plot by using the Surfer7 software (Golden Software Inc., Colorado USA). It was necessary to observe how mild activities affect the in-helmet microclimate. Therefore, the subjects were requested to alternately standing and walking for 10 minutes at the speed specified on a flatbed setting treadmill. It took 60 minutes to complete with data recording at every 10 seconds in each set of test. The body temperature was also measured using a tympanic thermometer every 10 minutes, i.e. at the beginning and the end of every walking and standing phase. A preconditioning period of about 10 minutes was applied to the test rig and the human subject to ensure that the temperature and the RH readings inside the helmet almost matched with the readings from the ambient sensors before place the helmet on head.

The subjective data were collected by measuring psychological dimensions of human thermal comfort such as thermal, moisture and comfort sensations, which were also recorded every 10 minutes, i.e. at the beginning and end of every walking and standing phase. Simple bipolar scales were used when quantifying such psychological parameters, as shown in Table 2.

In order to establish the relationship between objective data and subjective data, those data need to be processed and analysed, as described below. First of all, the objective data were presented in two formats, which are chart plots and 2D contour plots for two ambient conditions respectively, i.e. 20°C with 50% RH and 35°C with 30% RH. The chart plots were firstly based on the averaged regional readings of temperature and relative humidity from the simplified areas, i.e. the frontal: sensor 1, 2, 6, 11; the lateral: sensor 7, 8, 9, 12, 13, 14; the top: sensor 2, 3, 4, 7, 9, 12, 14; the rear: sensor 4, 5, 10, 15, as shown in Figure 2, for giving comparable data of both types of helmets studied. Then charts are presented to link the measured temperature and relative humidity in various perception scales with respect to the NVL and the VL helmets. There are error bars in the measured temperature and RH to show variation of the objective data. Although the subject number of six is limited, a consistent and meaningful trend of the measured data can be still obtained. However, the contour plots show an aerial view of the contours of the temperature and RH readings from fifteen individual probes inside the helmet. Clearly, the contour plots give the distribution patterns of the measured temperatures and RHs, which reveal the hot spots and wet spots inside the helmet. In addition, the comfort indices are linked to all measured temperature and RH data for both ambient conditions. It would allow the measured microclimate conditions to be evaluated in terms of subjective comfort index to help design a helmet with better thermal comfort.

3. Results and discussion

3.1 The relatively comfortable conditions (20 °C with 50 % RH)

The comparisons of the temperature and relative humidity in the relatively comfortable conditions at the each simplified microclimate region between the non-ventilated and ventilated helmets are shown in Figures 3(a), (b), (c) and (d). Here, error bars are shown in the figure to give the variation of the measurements. From the figure, it can be seen that the NVL helmet has the higher temperature and RH readings than the VL helmet at the frontal, the lateral and the top regions, however with the minimal difference between the two helmets at the rear region likely due to the less effective opening setting there. The largest difference in temperature is in the frontal region and the lateral region, which is between 1.5 °C and 2.5 °C, whereas such the difference in the top region is 1-2 °C. The RH readings on the NVL helmet are 10-15% higher than that on the VL helmet at the frontal, lateral and top regions. The global average RH value in the NVL helmet is 8 % RH higher than that in the VL helmet, which is attributable to the ventilation openings aided the escape of water vapour from the microclimate regions. Due to the ventilation, the VL helmet produced a similar RH values across the regions with the wettest region being the rear region at 78 % RH. Those different micro climate conditions inside the NVL and VL helmets are caused by the difference in ventilation openings on the helmets, as the presence of ventilation openings aids the transfer of heat and moisture from the microclimate into the surroundings.

The temperature and RH variation in the four regions for both the NVL and VL helmets (Figure 3) can be expressed in a logarithmic relationship as follows.

$$T_{region} = T_0^m + A_r^m \ln(t) + B_r^m, \; t \geq 1\text{s} \tag{1}$$

$$RH_{region} = (RH)_0^m + C_r^m \ln(t) + D_r^m, \; t \geq 1\text{s} \tag{2}$$

where A_r^m , B_r^m, C_r^m, D_r^m are constants corresponding to regional temperature and relative humidity in the relativ ely comfortable ambient conditions, which are shown in Table 3. T_0^m and $(RH)_0^m$ are the temperature off-set and relative humidity off-set, with values of 4.8 °C (NVL) and 7.5 °C (VL) for the former, 11.7 % (NVL) and 20.4 % (VL) for the latter. For the relatively comfortable ambient conditions, Eqs. (1) and (2) may be used to estimate temperature and relative humidity inside the similar cricket helmets after a user wears it.

Temperature contour plots corresponding to the relatively comfortable conditions were processed to provide a clearer perspective on the temperature distribution inside the helmet, which are shown in Table 4. It should be noted that the positions of the microsensors on a 3D head are not precisely mapped onto the 2D plots. Clearly, there are similar temperature distributions in the two helmets at the initial stage. This is reasonable as the ambient conditions dominate at start of the measurement. With the test continued, the variation in temperature distribution between the two helmets is increased. As the NVL helmet virtually represents a self-contained microclimate, the variation of the in-helmet temperature is small. The contour lines become increasingly less dense due to the increasingly balanced conditions as the test moves forward, with the exception of the far front and far back regions. At the end of the testing period, the contour plot shows that the hot spots are in the frontal, top and lateral regions, whilst the rear region remains relatively cool throughout the test. The contour plots display that the temperature in the VL helmet is lower than that in the NVL helmet, as expected. The contour plots are also less symmetrical, probably due to the fact that the ventilation openings encourage better heat transfer which could be easily disturbed by movement of the head. The difference of regional temperatures is larger in the VL helmet than the NVL helmet, again due to the presence of ventilation openings. Although the ventilation openings help the transfer of heat, heat still accumulated at different spots (frontal-lateral and rear-lateral) on the VL helmet. This can be improved by addition or a more effective positioning of the ventilation openings.

Table 5 shows contour plots of relative humidity in the NVL and VL helmets corresponding to the relatively comfortable conditions. As it can be seen, although the RH values are initially similar to both helmets, the contour plots evolve as the test continues and are eventually differentiated between the helmets in accordance with their ventilation settings. From Table 5, the contour line density increases as the test continues in all regions, except for the top region in the NVL helmet. This is primarily due to the presence of a large air pocket at the top region as opposed to the other regions. Therefore, the water vapour is distributed more evenly across the region. The lack of ventilation holes can cause the water vapour movement inside the helmet to be restrained and slow, which also contributes to the contour lines being less dense in the top region. The RH readings increase in the frontal- lateral region by 20 % RH over the course of the test. The wettest areas are shown to be the frontal and the frontal-lateral regions for the NVL helmet. Moreover, Table 5 also shows that the RH values generally increase in all regions over the course of the test for the VL helmet. However, the increase in RH readings is within 10 % RH, which is half of that in the NVL helmet. The frontal-lateral and the rear-lateral regions, where there are more sweat glands and no ventilation openings (Figure 1a), are the regions with the highest density of contour lines. It is interesting to see that there is a general reduction in the in-helmet RHs inside the VL helmet from 30 minutes of testing to the end. At the end of the test, the wettest region is the rear-lateral (right) region with 86.5 % RH and the driest region is the top region with 67.5 % RH for the VL helmet. Rear-lateral regions need to be improved through a better ventilation design. For the NVL helmet, the wettest region is on the front.

The warmth, moisture and comfort sensation/perception plotted against the average in-helmet temperature and relative humidity in the relatively comfortable conditions are shown in Figures 4(a) and 4(b) for the non-ventilated and ventilated helmets respectively. Here, the darker grey area shown in the figure indicates the comfort zone. A general observation shows that all the perception values related to the NVL helmet are higher in comparison to the VL helmet. Also, the comfort perception value for the former is slightly above 4 at the end of the test, whereas that for the latter is about 3.5. For both the warmth and moisture perceptions, they have a general upward trend for both of the helmets according to Figures 4(a) and 4(b). The comfort sensation is towards the uncomfortable scale (> 4.0) for the NVL helmet according to Figures 4(a). Overall, the average comfort sensation scale in the NVL helmet was higher than the VL helmet by 0.7. The reason for this small difference may be attributed to such the ambient conditions making it harder for the subjects to differentiate the comfort sensation for each of the regions.

In the relatively comfortable ambient conditions, variation of the measured average in-helmet temperature between subjects seems getting bigger with the time and however, such variation for RH getting smaller for both helmets (Figure 4). In general, the temperature variation inside the VL helmet is greater than that inside the

NVL helmet, which indicates the influence of the ventilation openings. Also, the variation of the comfort index for the former helmet is smaller than that for the latter helmet.

3.2 The warm conditions (35°C with 30% RH)

The regional comparisons of the temperature and RH values between the two helmets in the warm conditions are shown in Figures 5(a), (b), (c) and (d) respectively. Again, the error bars are given to indicate the measurement variation obtained from individual subjects. Clearly, the RH in the VL helmet is about 15 % lower than that in the NVL helmet throughout the test period in almost all regions, except for the rear one where the difference is only 5 %. However, the difference in temperature is minimal between the two helmets for all regions in the whole test period. The reason for such the small difference is likely attributed to that the ambient temperature is not far away from the body temperature. Due to physiological heat balance on body, there was not much room to differentiate the in-helmet temperature between the two types of helmets in the warm conditions. Despite of the minimal difference on the in-helmet temperature, the VL helmet does give a significantly lower RH (about 10-18 % from region to region), which offers a better comfort than the NVL helmet.

Based on Figure 5, the regional temperature and RH both the NVL and VL helmets may be expressed in a logorithmic relationship as follows.

$$T_{region} = T_0^h + A_r^h \ln(t) + B_r^h,\ t \geq 1\text{s} \quad (3)$$

$$RH_{region} = (RH)_0^h + C_r^h \ln(t) + D_r^h,\ t \geq 1\text{s} \quad (4)$$

where A_r^h , B_r^h, C_r^h, D_r^h are constants corresponding to regional temperature and relative humidity in the warm ambient conditions, as shown in Table 6. T_0^h is a temperature off-set, with values of 1.3 ^{o}C (NVL) and 1.7 ^{o}C (VL), and $(RH)_0^h$ is a relative humidity off-set with values of 16.6 % (NVL) and 30.8 % (VL). Eqs. (3) and (4) may be used to estimate temperature and relative humidity inside the similar cricket helmets after a user wears it in warm conditions.

Table 7 shows thermal contour plots in the warm conditions at different time intervals for the NVL and the VL helmets respectively. A small gap of 0.05°C is used between the contour lines due to the small difference between the temperatures inside the helmet and the surrounding environment. According to the table, for the NVL helmet, the resulting contour plots show a less symmetric pattern compared to the contour plots in the relatively comfortable ambient conditions (Table 4). As the test continues, the heat inside the helmet is accumulated at the top region and leads to smaller and smaller difference between the regional temperatures. For the VL helmet, it shows that the contour plot has a more symmetric pattern as opposed to the NVL helmet. Due to the presence of ventilation openings, the contour lines in the VL helmet are not, in general, as dense as that in the NVL helmet. However, the small difference between the two helmets is due to the physiological heat balance related to the high ambient temperature, as mentioned before.

Table 8 shows the experimental relative humidity contour plots in the warm amibent conditions at various time intervals during the test. It indicates that despite having initially a relatively dry area centrally in the NVL helmet, as the test goes on, increasingly higher RH readings are detected as the moisture is being accumulated near the top region without an effective means of escape. At the end of the test, the wettest spots are the frontal-lateral and the lateral regions, and the driest spots are the frontal and the rear region for the NVL helmet. At the same time, for the VL helmet, as shown in the lower half of Table 8, the regions with a ventilation opening, i.e. on the top, frontal, lateral and rear regions, display the reasonably lower RH values in comparison to the counterpart regions in the NVL helmet. The wettest and driest regions are the rear-lateral and the top regions respectively. In the VL helmet, the regional variation on RH is very noticeable due to the ventilation setting, which is reflected by more dense contour lines.

The average in-helmet sensations on warmth, moisture and comfort perception in relation to the temperature and RH readings in the warm conditions throughout the test for both helmets are shown in Figures 6(a) and (b). Here again, the darker grey area shown in the figure indicates the comfort zone. With the exception of small fluctuations after walking phases, the sensation or perception for both helmets are on an up-trend throughout the test. Due to the high ambient temperature, the differences in sensations and perceptions between the two helmets are relatively small, despite of the lower RHs in the VL helmet. This may indicate that the ventilation opening setting on the VL helmet needs to be further improved to introduce a better comfort. As the sensations are towards the very humid and the hot scales (7) for both helmets, the moisture and warmth sensations dominate overall the test. At the end of the test, all the regions are approaching to the very humid range, with a global moisture sensation of 6.7 for the NVL helmet, which is only 0.3 higher than that the VL helmet. The wettest regions were felt at the frontal region for both helmets and the driest region was felt at the top region. In addition, there is no significant difference in the comfort perception between the two helmets, as indicated before. At the end of the test, the overall average comfort perception of both helmets is in the uncomfortable zone. Due to the high ambient condition, the subjects were not able to distinguish effectively the difference in comfort between regions for the helmets with the current ventilation settings.

In the warm conditions, the variation of the in-helmet temperature between subjects is getting smaller for both helmets due to high temperature inside the helmet (Figure 6). Such the variation on the in-helmet RH for the VL helmet has some fluctuation and however, that for the NVL helmet has a trend of reduction. This is likely attributed to the ventilation opening of the former helmet.

3.3 Subjective sensation/perception index

It is necessary to establish a comfort index by linking all objective data with the subjective data for both ambient conditions to provide an overall chart on the relationship between the human perception and the digital measurements on the microclimate inside a helmet. This index is vital to assist helmet design with better thermal comfort backed up with the balanced perception in relation to the in-helmet temperature and relative humidity. The warmth, moisture and comfort sensation indices developed are shown in Figures 7(a), (b) and (c) respectively. Here, the measured digital data are overlain with the subjective data in a single chart. Temperature-relative humidity (T-RH) curves are plotted for both ambient conditions. If the T-RH point is above this curve, the upper perception curve is used, and if the T-RH point is below the curve, the lower perception curve is used, whilst if the T-RH point is on the T-RH curve, the median perception curve is used to derive the resulting perception. There is however, a gap between the two ambient T-RH curves, which means that further experiments are needed in order to complete the index.

An ideal sensation/perception scale range for a cricket helmet would be 4-5 for warmth and moisture and 3 for comfort. Based on these indices, in order to achieve thermal comfort, the T-RH point should be below the T-RH curve so that the lower perception curve can be obtained.

The indices are verified by comparing index derived sensation/perception scales with the index that was measured from the experiment. The comparisons show that for the relatively comfortable ambient conditions, all the derived scales are similar to their counterparts except for the ones that are at the end of the test where the derived scales are lower. However, the comparisons show that for the high ambient conditions, all results are similar except for the ones at t = 30 minutes. These differences may be due to the fact that the indices are developed based on the limited experimental parameters. This can be improved if more subjects are involved and more ambient conditions are considered.

4. Conclusions

A novel test rig has been developed, which is comprised of a helmet with fifteen embedded microsensors, a data logger and a laptop, with the capability of measuring real-time temperature and RH data inside a helmet for producing the related thermal and moisture mapping. Here, two types of cricket helmets have been tested, i.e. a non-ventilated helmet (NVL) and a ventilated helmet (VL), to represent helmets without any ventilation opening and with reasonable ventilation openings, respectively. Two ambient conditions have been considered here, i.e. the relatively comfortable conditions (20 °C / 50 % RH) and the warm conditions (35 °C / 30 % RH). The experimental results show that ventilation openings clearly aid the transfer of heat and moisture from the microclimate into the surroundings, especially under the comfortable ambient conditions. In addition to benefiting from a drier, cooler microclimate, the subjects who wear the ventilated helmet also have a smaller increase in body temperature during the test. Even though the ventilated helmet offers a better performance in heat and moisture managements, there is still a room for improvement, especially concerning the frontal-lateral and the rear-lateral regions in the warm conditions.

The research outputs show that there is reasonable and sensible correlation between the subjective sensations/perceptions on warmth, moisture and thermal comfort and the measured in-helmet temperature and relative humidity, which are essential to establish comfort indices. The comfort indices developed provide an aid for helmet designers to maximise the thermal comfort in given ambient conditions. The thermal and moisture mappings also provide the digital data to validate computer modelling of in-helmet microclimate conditions. In addition, the technology developed provides a novel measurement approach to other head gear types (such as safety helmets, fire fighter helmets, motorcycle helmets, etc.), and further to microclimate environments in close contact with human body (such as bandage, outdoor garments, etc.). The approach can also be used to monitor indoor or in-car temperature and RH distributions to assist designing those environments with better thermal comfort.

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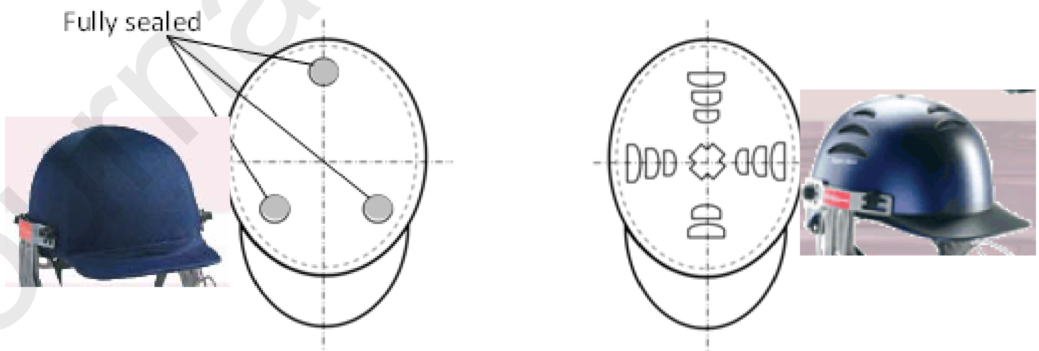
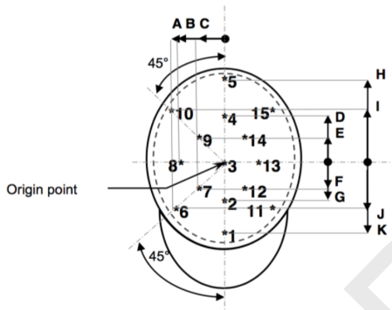


(a) Elite helmet, (b) Pro-performance helmet

(c) The cabling of the micro sensor cables for Pro-performance (VL) helmet

Figure 1. The helmets with different ventilation settings



Dimensions (mm)	A	B	C	D	E	F	G	H	I	J	K
NVL	95	90	75	100	55	55	70	135	65	65	100
VL	85	80	50	90	50	50	70	120	85	85	105

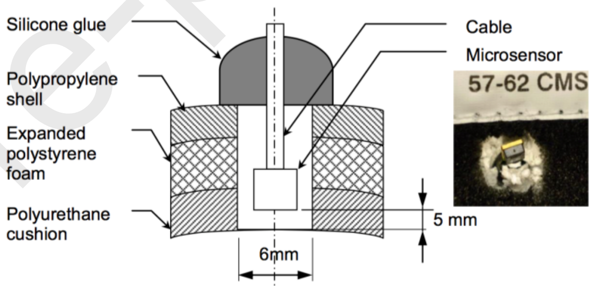


Figure 2. The sensor locations inside the helmet (left) and the cross sectional diagram of the probe (right).

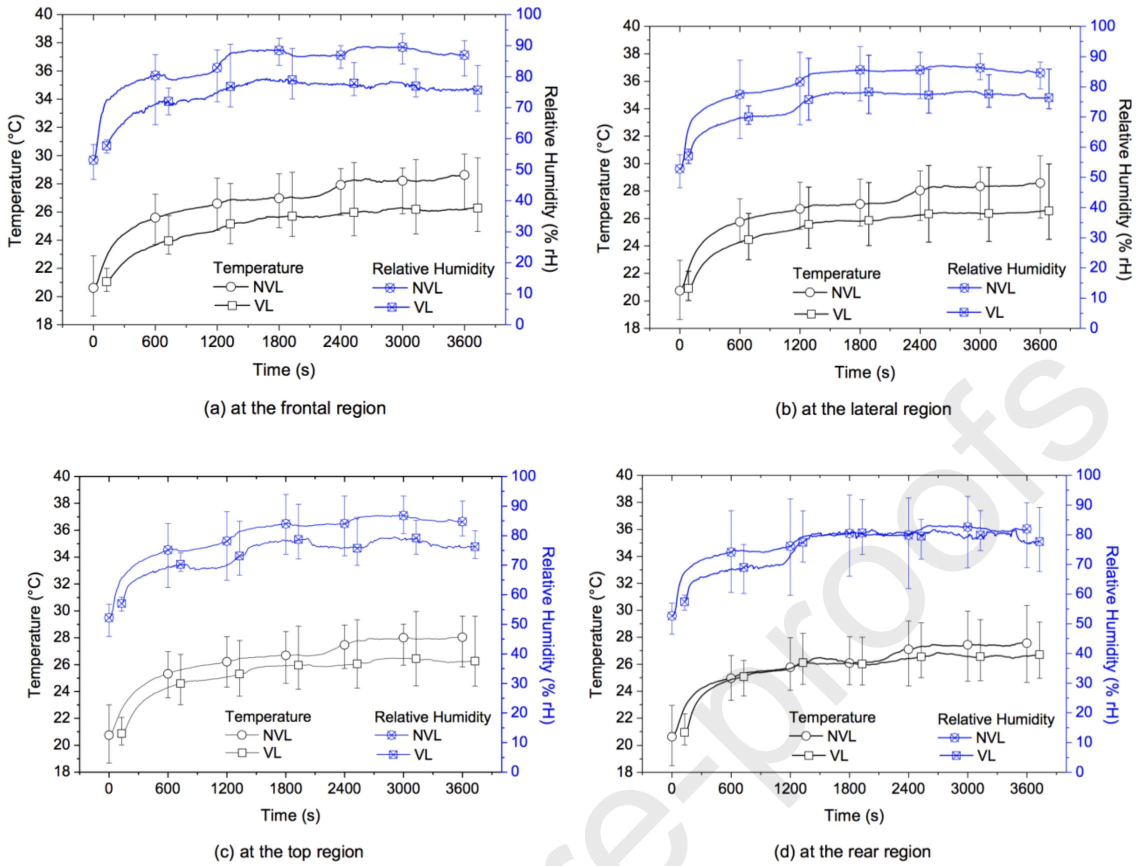


Figure 3. Comparisons of the measured regional temperature and relative humidity between the NVL and the VL helmets in the ambient condition of 20°C and 50%RH.

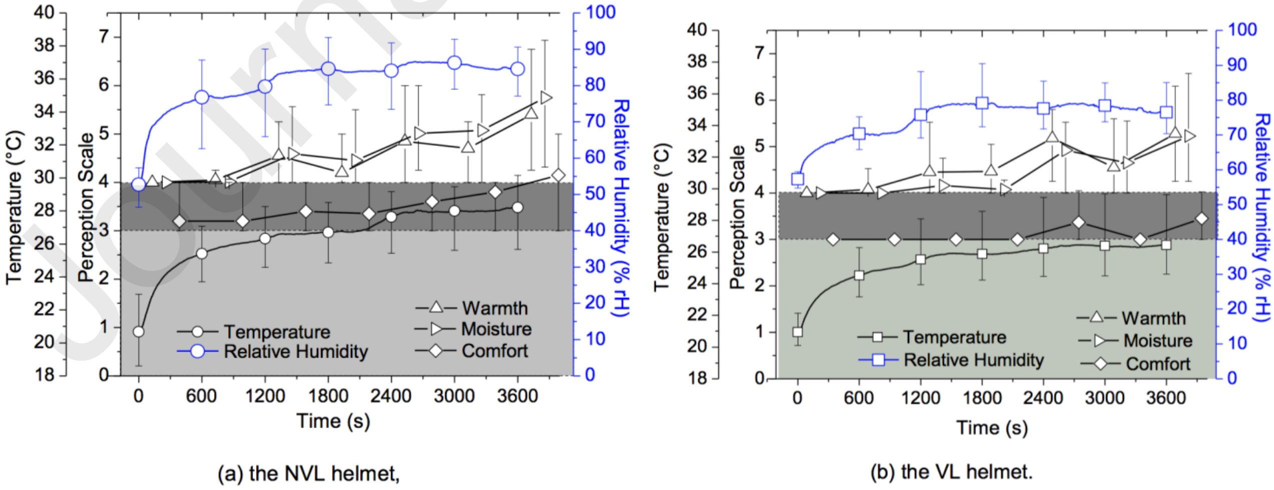


Figure 4. Average in-helmet temperature and relative humidity against subject sensations/perception in the ambient conditions of 20°C and 50%RH (with the darker grey area corresponding to comfort zone).

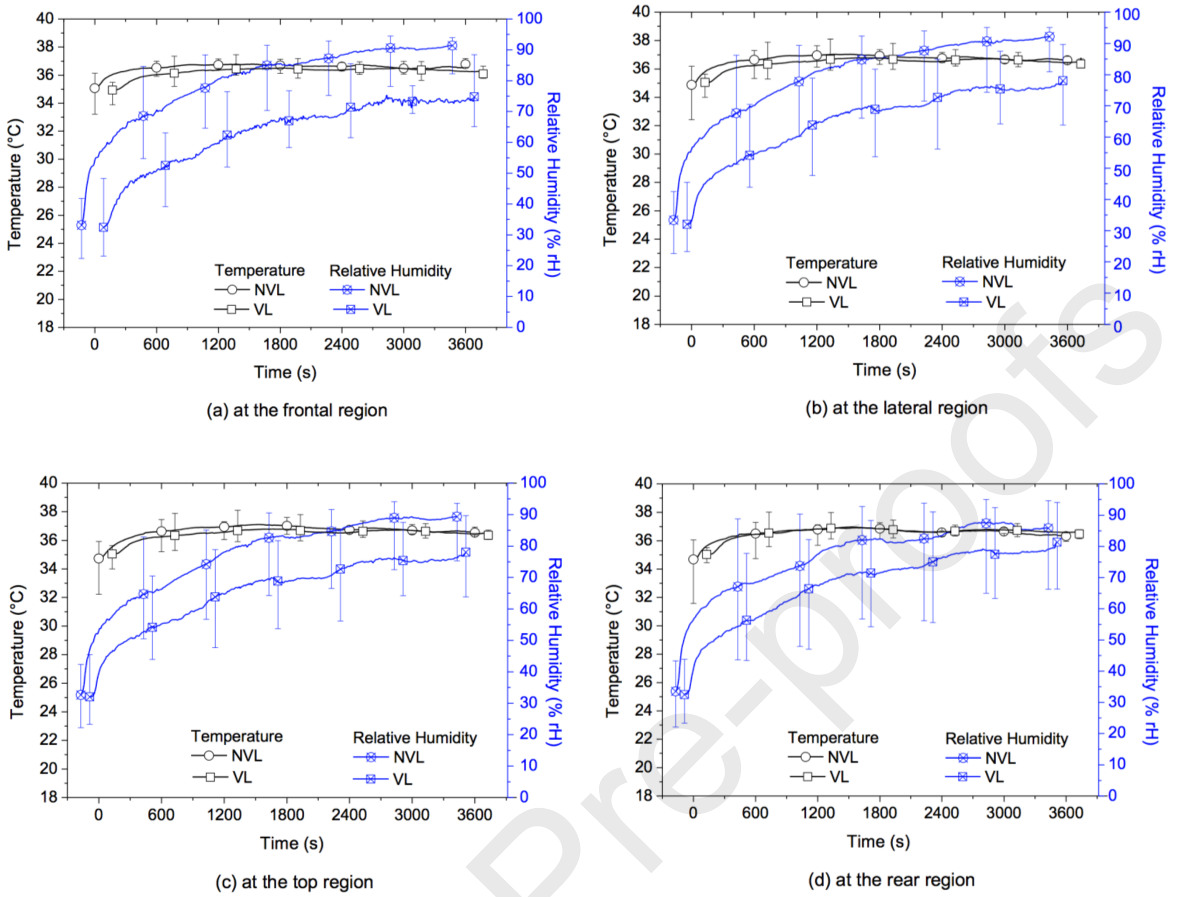


Figure 5. Detailed comparisons of the measured temperature and relative humidity between the NVL and the VL helmets in the four simplified regions subjected to the ambient conditions of 35°C and 30%RH.

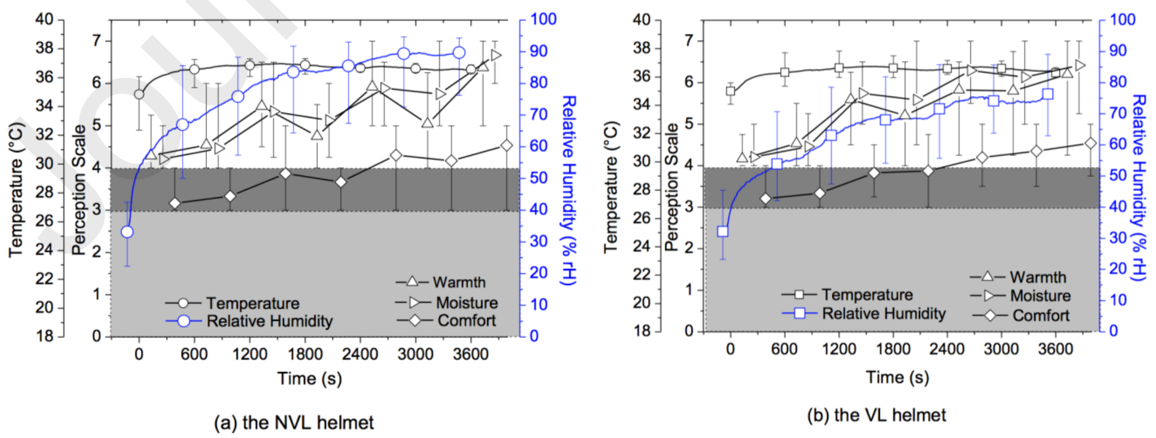
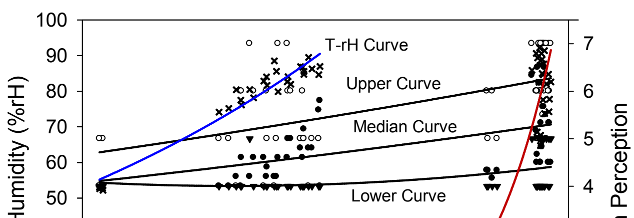
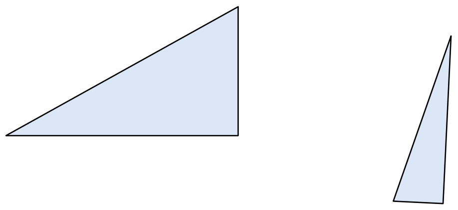
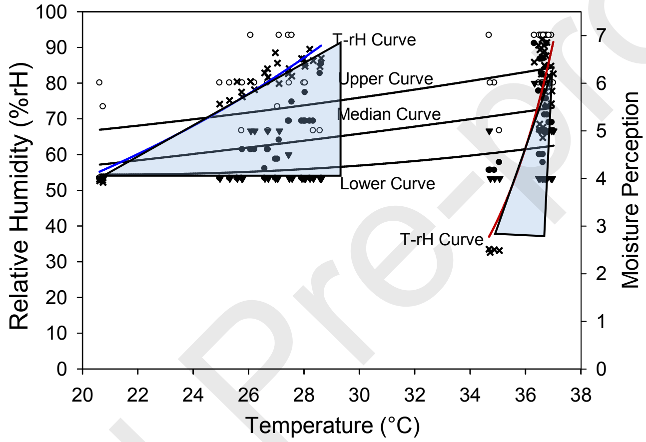


Figure 6. Average warmth sensation, moisture sensation and comfort perception during the test period for the NVL and the VL helmets subjected to the ambient conditions of 35°C and 30%RH (with the darker grey area corresponding to comfort zone).

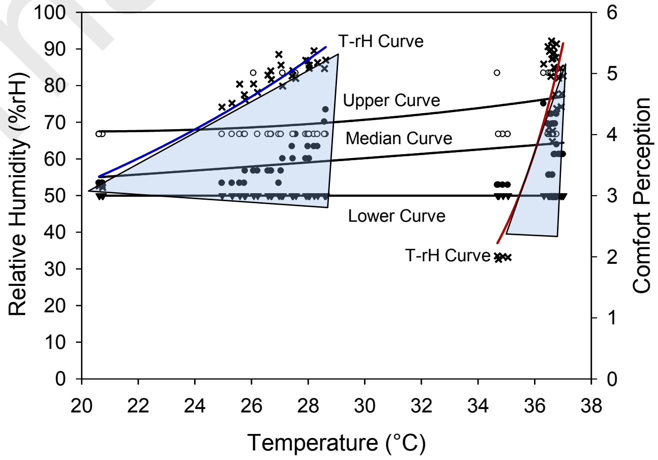




(a) the warmth sensation index



(b) the moisture sensation index



(c) the comfort perception index

Figure 7. Relationships between the sensation/perception and the measured microclimate temperature and RH. [39].

Table 1. The average person data of the male subjects (there are 6 subjects for each test).

t= 5 minutes	t= 30 minutes	t= 60 minutes

Ambient Condition	Helmet	Average subject data: Age (year)	Average subject data: Weight (kg)	Average subject data: Height (cm)	Average head sizes (cm): Length	Average head sizes (cm): Breadth	Average head sizes (cm): Circumference
Moderate (20°C/50% RH)	NVL	31.4±3	70.4±4	166.8±3	17.8±1	16.0±1	55.6±0.5
	VL	29.2±2	66.8±3	171.6±4	17.5±1	15.7±1	54.4±0.5
High (35°C/30% RH)	NVL	35.0±4	69.2±3.5	167.2±2	17.6±1	16.1±1	54.5±0.5
	VL	32.2±3	68.5±3	170.3±4	18.0±1.2	15.8±1	56.2±0.5

Table 2. The warmth, moisture and comfort sensation/perception scales used in the test.

Sensation/ Perception		Warmth	Moisture	Comfort
Reference		Fanger 1972/ Ashrae 1993	Berglund 1998	Arens *et al*. 2006
Scales	7	Hot	Very humid	
	6	Warm	Humid	
	5	Slightly warm	Slightly humid	Very uncomfortable
	4	Neutral	Neutral	Uncomfortable
	3	Slightly cool	Slightly dry	Neutral
	2	Cool	Dry	Comfortable
	1	Cold	Very dry	Very comfortable

Table 3. Coefficients in Eqs. (1) and (2).

Region	A_r^m, B_r^m, R^2		C_r^m, D_r^m, R^2	
	NVL	VL	NVL	VL
Frontal	1.56, 15.64, 0.9868	1.72, 12.58, 0.9956	5.43, 45.29, 0.9623	5.37, 35.16, 0.8649
Lateral	1.53, 15.94, 0.9870	1.58, 13.87, 0.9910	4.88, 46.66, 0.9729	5.19, 36.59, 0.9568
Top	1.58, 15.13, 0.9953	1.52, 14.22,0.9781	5.38, 42.18, 0.9161	5.69, 32.17, 0.9161
Rear	1.37, 16.14, 0.9861	1.43, 15.32, 0.9550	4.63, 44.71, 0.9798	5.57, 34.53, 0.8578

Table 4. The experimental temperature contour plots at various time intervals for the NVL (Top) and VL (bottom) helmet in the ambient conditions of 20 °C and 50 % RH.

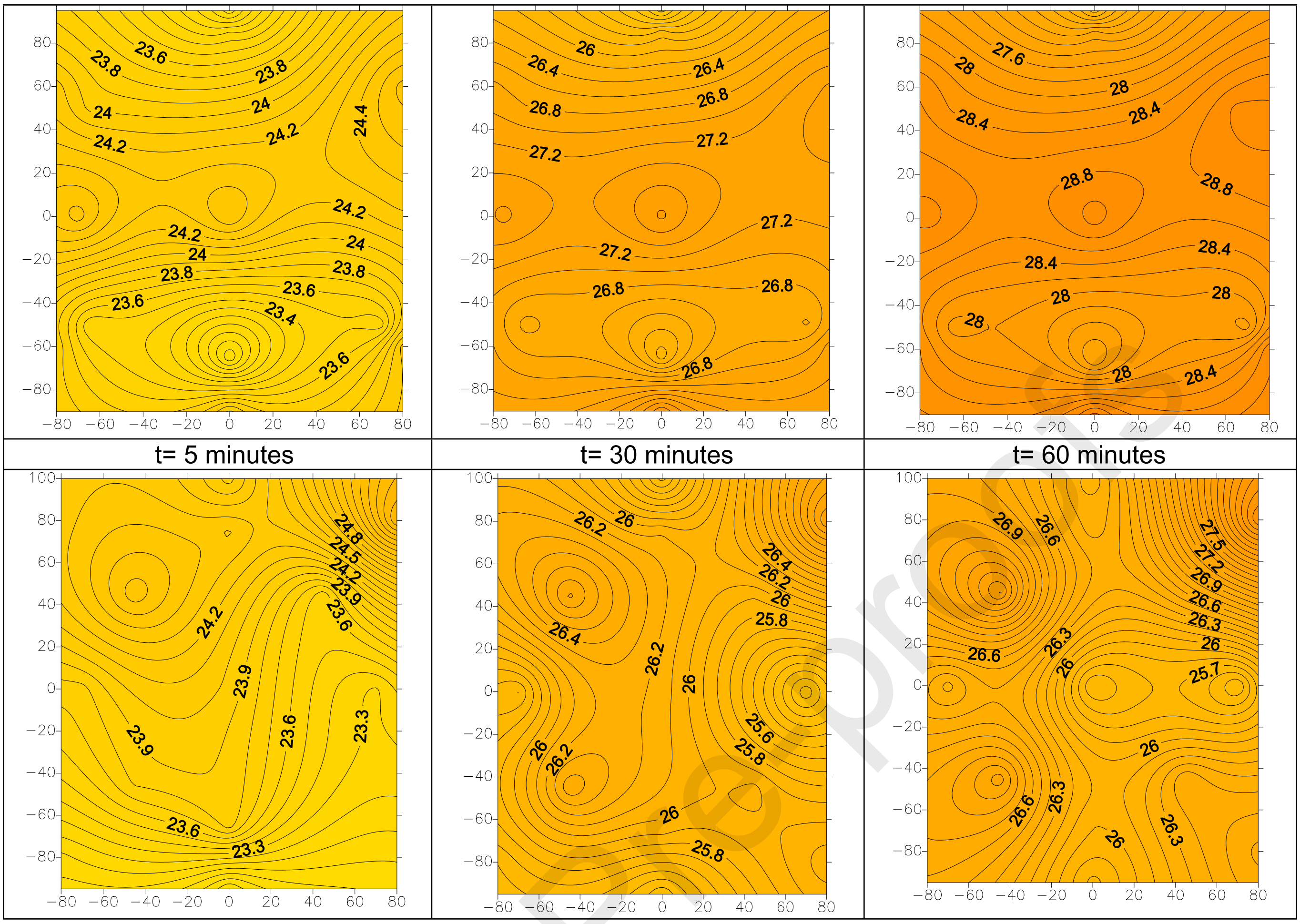


Table 5. The measured RH contour plots at various time intervals for the NVL (Top) and VL (Bottom) helmet in the ambient conditions of 20 °C and 50 % RH.

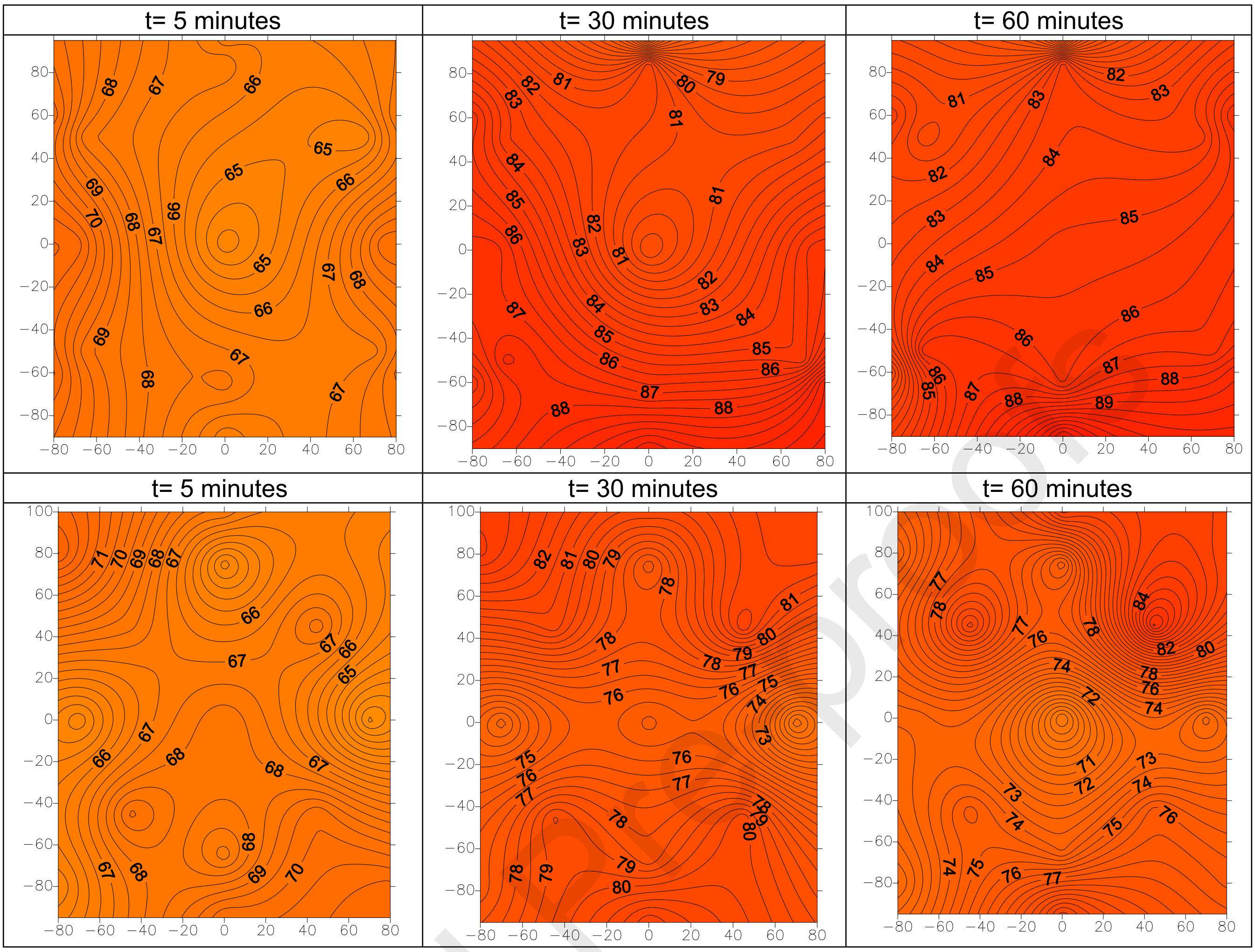

t= 5 minutes
t= 30 minutes
t= 60 minutes
t= 5 minutes
t= 30 minutes
t= 60 minutes

Table 6. Coefficients in Eqs. (3) and (4).

Region	A_r^h, B_r^h, R^2		C_r^h, D_r^h, R^2	
	NVL	VL	NVL	VL
Frontal	0.22, 35.03, 0.5946	0.44, 32.94, 0.6799	9.36, 14.55, 0.9655	9.03, -0.64, 0.9379
Lateral	0.28, 34.78, 0.7204	0.48, 33.01, 0.6951	9.54, 13.78, 0.9649	9.43, -0.82, 0.9615
Top	0.57, 32.48, 0.7944	0.33, 34.02, 0.7577	9.35, 12.39, 0.9362	9.41, -0.81, 0.9623
Rear	0.49, 32.95, 0.6609	0.45, 33.27, 0.6799	9.04, 13.21, 0.9660	9.71, -1.01, 0.9540

Table 7. The experimental temperature contour plots at various time intervals for the NVL (top) and VL (bottom) helmet in the ambient conditions of 35 °C and 30 % RH.

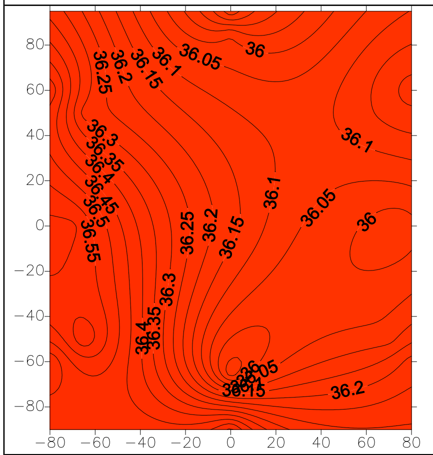
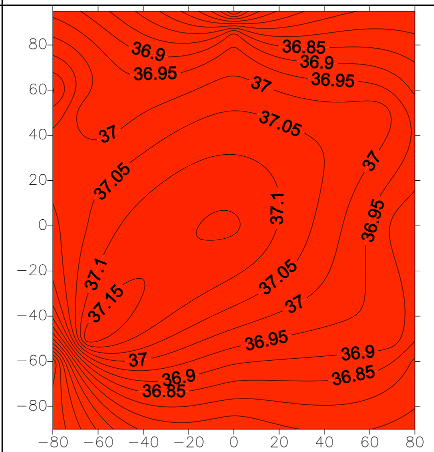
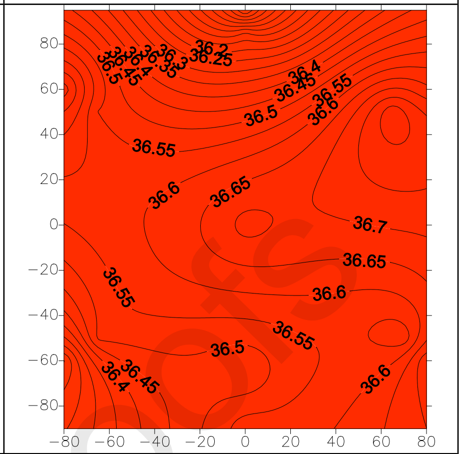
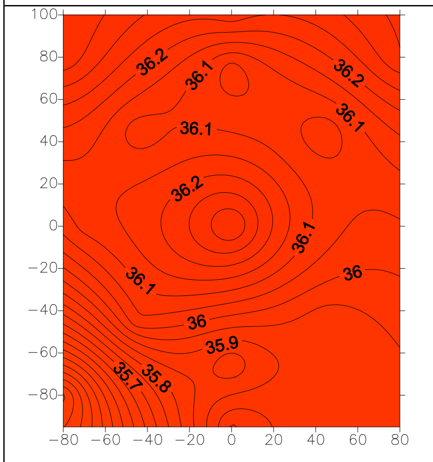
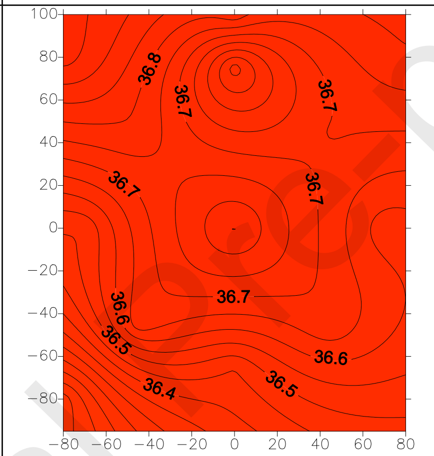
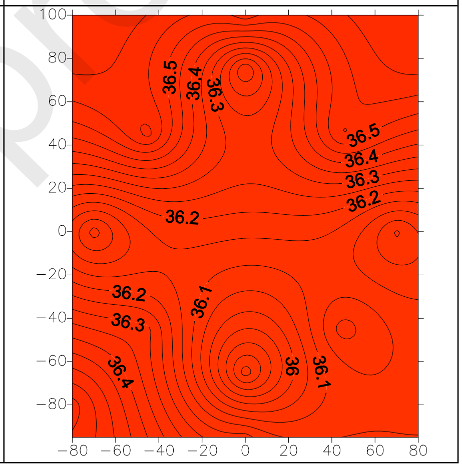
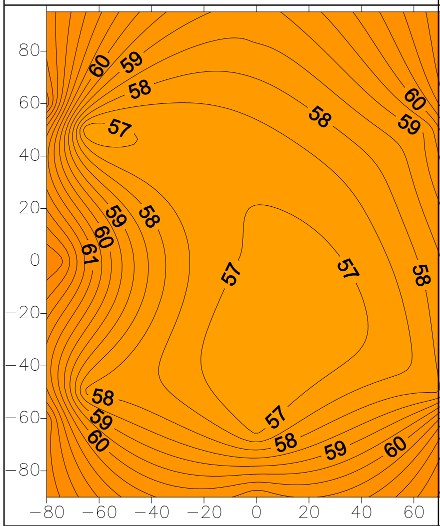
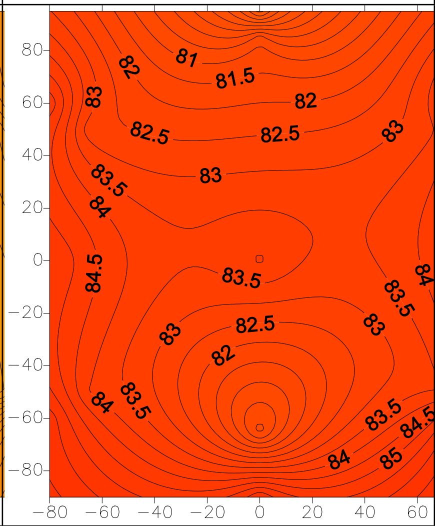
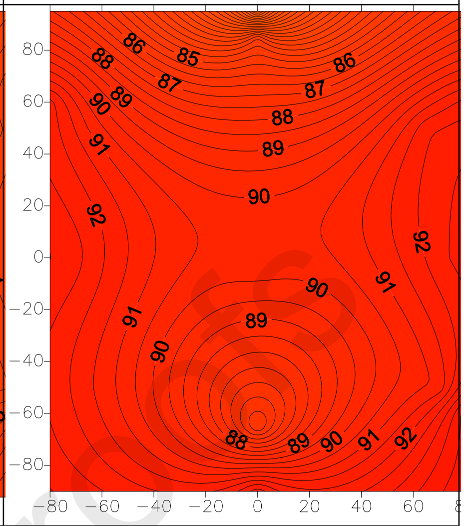
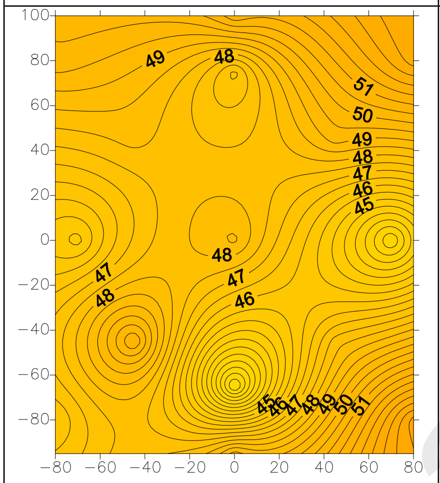
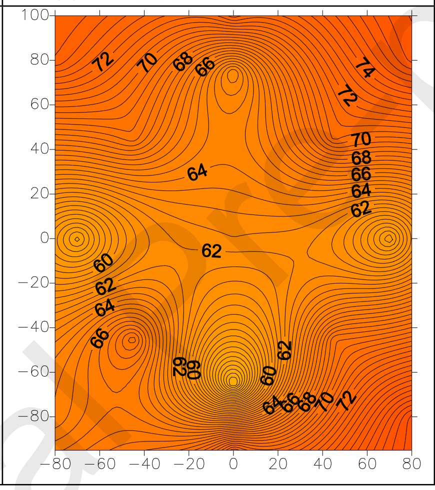
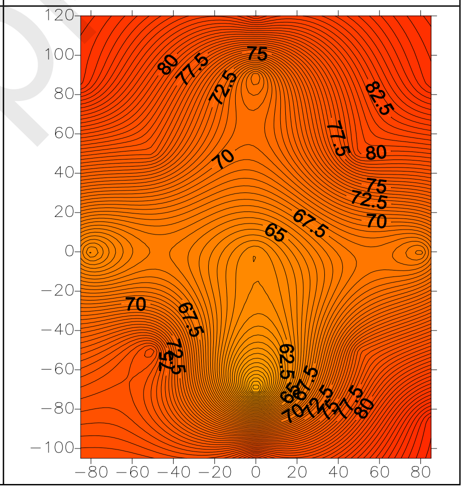
t= 5 minutes	t= 30 minutes	t= 60 minutes
		
t= 5 minutes	t= 30 minutes	t= 60 minutes
		

Table 8. The measured RH contour plots at various time intervals for the NVL (Top) and VL (bottom) helmet in the ambient conditions of 35 °C and 30 % RH.

t= 5 minutes	t= 30 minutes	t= 60 minutes
		
t= 5 minutes	t= 30 minutes	t= 60 minutes
		

[40].

Highlights

- Combined temperature and moisture microsensors are embedded in two types of helmets
- In-helmet thermal and moisture mappings have been obtained for the first time
- Human perceptions on warmth, moisture and thermal comfort have been recorded
- Comfort index is linked to the measured in-helmet temperature and relative humidity

[41].