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Latent Heat Loss of a Virtual Thermal Manikin for Evaluating the Thermal Performance of Bicycle Helmets

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Abstract. Thermal performance of three bicycle helmets for latent heat loss was evaluated through a virtual testing methodology using Computational fluid dynamics (CFD) simulations. The virtual thermal manikin was prescribed with a constant sweat rate of 2 g/h and a constant sweat film thickness of 0.3 mm. The simulations were carried out at 6 m/s until convergence was achieved. The results from steady state simulations show heat loss of 158 W from manikin without helmet and approximately 135 W with helmets. However, the thermal performance of helmets with a sweating manikin has been reduced from 89–93% to 84–87%. These results imply that evaporative/latent heat loss plays a significant role in thermal performance of helmets. Therefore, thermal performance tests for helmets should also include testing of helmets for evaporative heat loss.

Keywords: Thermal manikin · Evaporative heat transfer
Convective heat transfer · Cooling efficiency · Turbulence models
CFD · Thermal performance

1 Introduction

Cycling is popular. It is healthy and environmental friendly. Unfortunately, it is also the third most dangerous form of transport resulting in injuries and mortalities. Head injury is reported as the direct cause of death in about 69% of these cycling fatalities [1, 2]. Bicycle helmets reduce the risk of head injuries, caused by accidents. The usefulness of bicycle helmets for reducing risks of head injury has been shown [3–5]. This has resulted in substantial research on improving the safety features of the helmet. However, helmet usage among cyclists is low when compared to other types of protective

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head gear usage. This dislike towards helmets can be attributed to physical and thermal discomfort among users [6–8]. For example, motorcycle helmet usage rates in Italy are reported to be 93% and 60% for Northern Italy and Southern Italy respectively. A difference that can at least be partially explained through headgear induced thermal discomfort in warm environments [9–11]. Though helmets can provide thermal benefits in cold conditions [12] helmets receive an adverse reaction from users in warm conditions. Thermal comfort or discomfort is a product of heat transfer in the volume between head and helmet or lack thereof. This is also influenced by other factors like environmental conditions, body temperature, helmet design etc. Local discomfort on the head in warm conditions is sufficient to cause whole body discomfort [13] and hence this local discomfort resulting from sweating and skin-wettedness needs to be addressed. Headgear increases head insulation which results in heat entrapment and sweating especially in warm conditions and can easily affect comfort perception as heat loss differences of 1 W can be sensed by helmet users [14]. The most common approach to improve comfort is to increase ventilations thereby enhancing convective cooling and sweat evaporation [15, 16] but this cannot be considered as the only solution since the underlying factors that cause thermal discomfort are plentiful.

To understand the influence of thermal comfort on users, it is important to understand the mechanisms and metrics pertaining to thermal comfort. This has paved way for a number of studies on thermal aspects and thermal parameters of headgear. The study of thermal aspects begins with understanding the thermo-physiological processes involving human head and heat transfer. Human head is a part of human body that shows a high heat-sensitivity [17]. Due to high heat sensitivity and unique biology, under forced convection, head can contribute up to one-third of total metabolic body heat dissipation [8]. Heat transfer from head mainly happens through convection (natural and forced), evaporation and radiation. Therefore, it is paramount to understand each mode of heat transfer and its influence on thermal comfort in detail. Studies on convection cooling of head have been carried out by multiple agencies to evaluate and validate helmet designs. These studies use one of the two methodologies namely subject studies and object studies. Subject studies or user trials allow gaining insight into the global or local heat loss of test persons. More specifically, they allow quantifying thermo-physiological parameters such as heat storage, core body temperature, skin temperature and sweat production [18, 19]. Several studies have monitored the effects of sweat on heat transfer and in turn on thermal comfort. Quantification of sweat rates using ventilated capsules [19, 20] and methodologies using absorbent pads [21] have helped in understanding the evaporation mechanism and the existence of a correlation between local and global sweat rate [19, 21]. Taylor and Machado-Moreira [20] developed predictive equations for sweat rate in head at rest or exercising. User trials have also emphasized the importance of insight into latent heat loss for optimizing headgear for thermal performance. Results of user trails are unfortunately not always straightforward for generalization towards helmet improvement due to high individual differences in test subjects.

Hence object studies or bio-physical methods have gained importance. Biophysical methods have focused on thermal manikin head studies. Thermal manikin studies induce a heat source onto the surface of a manikin head. Then, the applied heat is kept constant and surface temperatures are recorded or controlled and the applied heat load is recorded in different segments of the manikin head. Different thermal manikin heads have already been developed and investigations on dry heat loss in headgear with the use of a physical thermal manikin head were performed [15, 22]. Additionally, the effect of solar radiation [23] and hair [24] was also investigated. Studies on thermal perception resulting from ventilation changes in motorcycle helmets using thermal manikin was analyzed. None of the above-mentioned studies have analyzed the efficiency of helmets with respect to removal of sweat and heat loss through evaporation. Therefore, analyzing the latent heat loss or heat transfer through evaporation is important to evaluate the helmet design. Evaluation of helmet performance for thermal comfort can be performed using numerical models which have been used to evaluate aerodynamic performance [25] and ventilation performance [26] previously. These numerical models used in evaluating thermal performance of helmets can also be coupled with thermo-physiological models. Several thermo-physiological mathematical models [27, 28] have been developed with different levels of accuracy and complexity to provide the numerical models with realistic values to model thermoregulatory response of the human head and play a crucial role in helmet evaluation. Each of the studies allows gaining insight into the complex phenomenon of local heat loss on the human head, but fail to provide a concrete methodology that allows optimizing bicycle helmets for sensible and latent heat loss. In this research, analysis of heat transfer through evaporation is carried out using virtual models. This paper describes the work carried out to evaluate the ventilation efficiency of three helmet designs with a commercial computational fluid dynamics (CFD) program using Eulerian wall film methodology to simulate sweat production and skin-wettedness on the virtual thermal manikin head. The helmet efficiency values obtained from the virtual experiments will be compared with the efficiency values obtained from sensible heat loss (convection cooling) tests [29].

2 Heat Transfer Between User and Environment

To understand thermal comfort in detail, the thermo-physiological response of human body must be understood. The core temperature of human body is maintained approximately around 37 °C and from this phenomenon we can infer that there exists a heat transfer mechanism between body and environment such that heat is dissipated when in surplus and retained when in deficit. This relationship between heat generation in the body and transfer to environment is dynamic resulting in a heat balance which is given by heat balance equation [30]:

$$S = M - W - (E_{res} + C_{res} + E_{sk} + C_{sk} + K + R) \tag{1}$$

where M is metabolic rate and W is work rate, quantifying the rate of heat production. Heat loss/gain is defined by evaporation (E), convection (C), conduction (K) and radiation (R). Evaporation and convection occurs through respiration (res) and skin (sk) and S is heat storage in the human body which is expressed in kJ/h or W or W/m^2. The human head exhibits unique heat transfer properties owing to its lack of vasoconstriction responses. In addition to this, lack of clothing or insulation that protects other parts of the body results in high transfer of heat from the head. Heat transfer from the head is non-homogenous and results in different parts of the head exhibiting different heat transfer characteristics. For example, the nose exhibits higher cooling rate than the face and cheeks [31]. The opposite of this is also true resulting in an increase in temperature when core temperature of the body increases [31]. Thus, modelling and testing of multiple modes of heat transfer can be a complicated task. For bicycle helmets, having a layer of insulating expanded polystyrene, heat loss is predominantly defined by convective heat loss and evaporative heat loss. Convective heat transfer is defined by:

$$\dot{Q}_{cs} = h_c A (T_h - T_a) \tag{2}$$

where, $\dot{Q}_{cs}$ is convection heat transfer per unit time, A is surface area of the object, h_c is convective heat transfer coefficient, T_h is Temperature of head surface, T_a is Temperature of air/fluid. Thermal performance of bicycle helmets is quantified using cooling efficiency. The evaporation heat dissipation is given by

$$\dot{Q}_{ls} = h_e A (P_{sk} - P_a) \tag{3}$$

where, $\dot{Q}_{ls}$ is evaporation heat transfer per unit time, A is surface area of the object, h_e is evaporative heat transfer coefficient, P_{sk} is vapour pressure of skin, P_a is vapour pressure of air/fluid.

Cooling efficiency of a helmet is thus defined as the ability of a helmet to dissipate the heat from the head to the environment, relative to a nude head.

$$\text{Cooling efficiency} = \frac{\text{Heat transfer with helmet}}{\text{Heat transfer (nude head)}} \times 100 \tag{4}$$

3 Materials and Methods

3.1 Computational Domain and Geometry

The methodology used in virtual testing of helmets for latent heat loss follows the same procedure as the previous research paper [29]. Digital models of three helmets to be tested were obtained with high resolution 3D scanning. These three helmets are chosen because the thermal performance values of these helmets for sensible heat loss, determined in the previous study [29] can be compared with the results from this study. The digital model of head was generated using 3D shape modelling of human head. This is achieved using the mathematical model of human head [32] that estimates the 3D shape of an arbitrary human scalp from one dimensional anthropometric measurements on the external surface of a head. 3D scans of human head from multiple subjects were used in developing the mathematical model. The surface details of head and helmet were smoothed to ease grid generation. The digital model of head is split into five measurement zones (scalp, face, forehead, ears and neck) to understand the zonal/local behavior. The assembly between head and helmet is done such that there is realistic contact and no penetration between head and the helmet mesh (Fig. 1). The zones of head and helmet that come in contact were stitched together. The head and the helmet were placed in a computational domain according to practice guidelines.

The size of the computational domain was $6.5 \times 2 \times 2$ m^3. The test object was placed 1.5 m away from the inlet plane to avoid pressure gradients (Fig. 2). Grid sensitivity analysis was carried out for different mesh sizes to determine influence of cell size on the results.

3.2 Resolving Boundary Layer

Prisms were generated in the layer between head and fluid to model the boundary layer in the solid-fluid interface (Fig. 3(b)). Prism layers provide a high resolution for resolving the thin boundary layer at the head using a low-Reynolds number modeling technique. The boundary layer is resolved into three layers depending on the distance from the wall surface. A laminar sublayer near the wall where no slip condition is applied and dominated by viscous forces and characterized by laminar flow. This laminar region is followed by a buffer region where the flow transitions from laminar to turbulent. The final layer of the flow region is the turbulent region where the inertial forces dominate the flow characteristics.

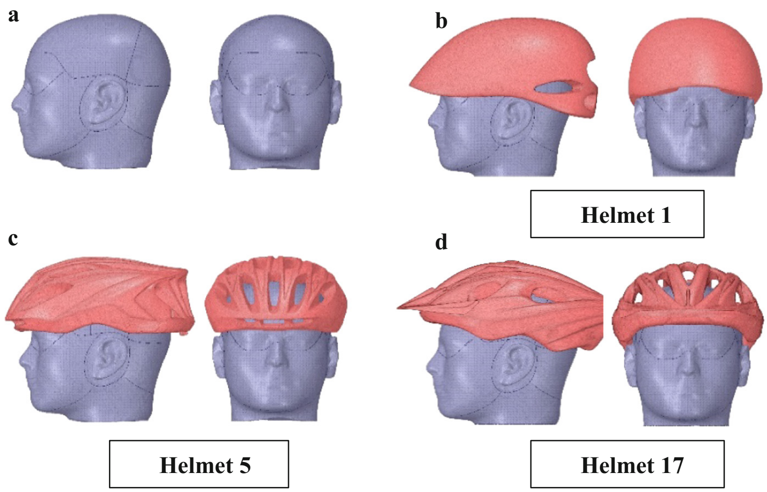

Fig. 1. Digital version of thermal manikin with (a) measurement zones: (b) closed channel helmet (helmet 1): (c) and (d) open channel helmets (helmet 5 and helmet 17)

Resolving the boundary layer is paramount because the flow separation, if not modelled accurately, can result in unrealistic results. The boundary layer that comprises of a viscous layer and a turbulent layer influences the flow on the boundaries and heat transfer. As the velocity of incoming air increases, the Reynolds number (Re) around the object increases resulting in a decrease in viscous sublayer thickness. This necessitates high resolution of the grid close to the walls/test object and is controlled by the dimensionless parameters y* or y^+ for which the condition is $1 \leq y^*/y^+ \leq 5$. The dimensionless quantity y* is used instead of y^+ because y* provides more information on the grid as well as on stagnation and reattachment points. The size of the cell ranges from 0.5 mm near the head surface to 100 mm near the domain walls. Tetrahedral cells (Fig. 3) were used to create the volume mesh with ortho-skewness values and aspect ratio within the allowable limits. The final mesh of the domain contained about 15–23 million cells depending on the helmet geometry and design.

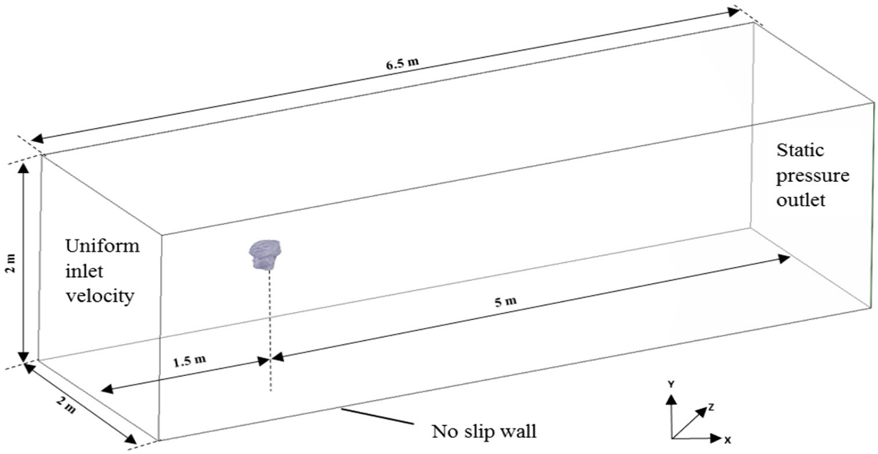

Fig. 2. Computational domain and boundary conditions for thermal manikin with helmet

3.3 Boundary Conditions

The boundary conditions used in the virtual testing of latent heat loss is same as the boundary conditions used in sensible heat loss tests [29]. At the inlet, uniform velocity of 6 m/s (21.6 kph) was imposed with default turbulent intensity value of 5% to assign a median relative air movement while cycling. The outlet of the domain is imposed with ambient static pressure. The surface of the head and helmet was modelled as a no-slip boundary wall with zero roughness. Temperature of incoming air was set to 20 °C (294 K) and the surface temperature of head zones was set to 30 °C (304 K). Each measurement zone was defined with a mass flux value of 0.00033 kg/m^2 s which approximately equals to a sweating rate of 2 g/h on each surface and liquid film (sweat) of constant thickness 0.3 mm was defined on the headform zones.

This research used Eulerian wall film methodology to define and analyze sweat layer that was modelled on the headform surface. This methodology is a built-in module available in Fluent that provide the user with information about thin liquid films on the wall surface. Latent heat transfer that is controlled mainly by the properties of the sweat layer was simulated using Eulerian wall film method for films with minimum thickness and the flow of film was assumed to be parallel to the surface. Mass, Momentum and Energy equations were solved separately for the film using second order discretization. This method also provides extensive details on film parameters and properties which can serve as a tool for identifying regions of low or high heat transfer.

3.4 Turbulence Models and Simulation Settings

The numerical simulations were performed using commercial CFD module Fluent which is based on finite-volume method. The realizable k-ε model with enhanced wall method for boundary layer resolution using one equation Wolfstein model was used to solve Reynolds-averaged Navier-Stokes (RANS) equations.

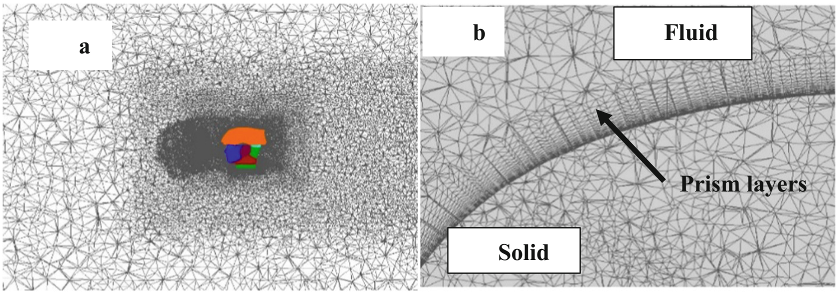

Fig. 3. Computational grid of manikin head and helmet: (a) grid showing different zones with different cell size; (b) prism layers on the surface (solid-fluid interface) to resolve boundary layer

The choice of realizable k-ε model was made based on experiments and existing literature which showed that realizable k-ε model was more accurate when compared to other models like standard k-ε, RNG k-ε, SST k-ω model or one equation model like Spalart-Allmaras model. SIMPLE algorithm was used to couple pressure and velocity. Second order discretization schemes were used for pressure, energy and liquid film. The convection terms and the viscous terms of the governing equations were solved using second order equations. The gradients used in discretizing convection and diffusion terms were computed using least square cell based method since it is computationally inexpensive and provides comparable results to other node-based methods. A steady state calculation was carried out with convergence of residuals monitored every iteration. The change in residual values determined the number of iterations and as the residual values of continuity (10^{-4}), momentum (10^{-6}), energy (10^{-6}), turbulence dissipation rate (10^{-4}) reach their specified values, the simulation was terminated. In addition to residual values, heat flux values on each measurement zone on the head were recorded for every iteration and change in these values for subsequent iterations was verified. The change in total heat transfer rate and film heat transfer rate for every iteration was also recorded and used as a parameter for deciding the number of iterations.

4 Numerical Simulations: Results

4.1 Thermal Manikin Without Helmet

Thermal manikin used in this latent heat loss testing is similar to that of the thermal manikin used in sensible heat loss testing [29] in terms of size and geometry. This is confirmed by comparing the surface area of measurement zones used in both tests as shown below in Table 1. This comparison of surface area proves that the results from the two tests can be compared. The surface area of neck region of both the manikins differ. However, this will not influence the final results since the neck region is not included in heat transfer calculations as it serves as a buffer zone between the headform and the base on which it is placed.

Table 1. Surface area of thermal manikins used in convective and evaporative heat loss virtual testing

Zone	Surface area (m²)	
	Latent heat loss manikin	Sensible heat loss manikin
Scalp	0.0638	0.0676
Forehead	0.0096	0.0141
Face	0.0258	0.0324
Ear-right	0.0068	0.0052
Ear-left	0.0069	0.0051
Neck	0.0392	0.0208

Table 2. Latent/evaporative heat loss from thermal manikin at 6 m/s

Zone	Area (m²)	Latent heat loss (W)
Scalp	0.0638	83.3
Forehead	0.0096	15.8
Face	0.0258	40.7
Ear-right	0.0068	9.3
Ear-left	0.0069	9.4
Total		**158.5**

Table 3. Latent/evaporative heat loss from manikin at 6 m/s with helmets

V = 6 m/s	Surface area (m²)	Nude head	Helmet 5	Helmet 17	Helmet 1
Scalp	0.064	83.3	69.2	71.6	73.0
Forehead	0.010	15.8	13.9	13.7	13.5
Face	0.026	40.7	34.2	34.2	34.2
Ear-right	0.007	9.3	8.4	8.5	8.4
Ear-left	0.007	9.4	8.6	8.8	8.6
Total (W)		**158.5**	**134.3**	**136.8**	**137.6**
Cooling efficiency (%)			**84.7**	**86.3**	**86.8**

Heat transfer values from virtual thermal manikin with the surface temperature maintained at 30 °C and prescribed with a constant sweat rate of 2 g/h on each measurement zone is shown in Table 2. Heat transfer from headform at 6 m/s prescribed with a constant sweat rate is 158.5 W. Heat transfer from scalp region with the largest surface area is 83 W followed by face with 41 W.

This is in direct correlation with sensible heat loss study where the heat loss from scalp and face regions were maximum [29].

4.2 Thermal Manikin with Helmets

The heat transfer values from individual measurement zones of manikin are tabulated in Table 3. The cooling efficiency which is a metric used to evaluate the thermal performance of helmets is also tabulated. The results from the simulations show a decrease in heat transfer from the headform with a helmet. This is as expected since helmets hinder the heat transfer by acting as an insulating layer. The scalp region of head which is covered by the helmet shows a decrease in heat transfer in the order of 12–16%. The forehead and face also shows decrease in heat transfer in the order of 14% and 16% respectively.

The thermal performance of the helmets with and without sweat can be evaluated by comparing the cooling efficiency values of the helmets with and without sweat as shown in Table 4. The efficiency values of helmets without sweat were obtained from a study on the similar topic [29].

Table 4. Comparison of cooling efficiency of helmets with and without sweat

V = 6 m/s	Cooling efficiency (%)	
Helmet	Convective cooling (no sweat)	Evaporative cooling (with sweat)
5	91.9	84.7
17	89.3	86.3
1	92.4	86.8

5 Discussion

5.1 Thermal Manikin Without Helmet

The heat transfer from headform measurement zones with a prescribed sweat rate is higher than heat transfer from the head tested without sweat layer (dry heat loss). This is as expected because the sweat layer which is modelled as a liquid water film with the same surface temperature (304 K) facilitates high heat transfer. These values of heat transfer are comparable to the values predicted by a study [31], which is in the order of 200–250 W. The difference in total heat loss value between this virtual test and the study by Rasch et al. [33] can be attributed to the following reasons. The sweat rate defined in this testing is of a constant value whereas in the study, the heat loss was measured from a human subject where there is a possibility of sweat rate varying considerably at different measurement regions. Another major influence on the results would be the thickness of sweat film. The thickness of the sweat film which was set to 0.3 mm for this virtual testing was obtained from running multiple simulations with varying film thickness (0.1 mm, 0.2 mm, 0.3 mm, 0.5 mm) and arriving upon the thickness value that matched best with the results of physical tests. This film thickness values can also be defined specific to a particular zone for more accurate results.

Presence of hair on the head in the test subjects from the study can also influence the heat transfer between the user and environment. However, this difference in heat transfer values between the physical testing of real subjects and virtual testing using thermal manikin will not influence the goal of this study, since this study focusses mainly on the thermal performance of helmets for evaporative heat loss using the same thermal manikin.

5.2 Thermal Manikin with Helmets

From the results (Table 3), it is evident that the helmets tested virtually are capable of removing the heat through evaporation to certain extent. The decrease in heat transfer from scalp region between 12–16% can be attributed to the insulation provided by the helmet. The flow pattern on front of the forehead shows a flow restriction by the front of helmet and hence a decrease in heat transferred from that region. The face region, in spite of zero interaction with the helmet shows decrease in heat transfer. Flow separation could be considered as one reason. However, the heat transfer from face region is constant (34.2 W) for all three helmets and hence overlooked. Since this study focusses mainly on heat loss through sweating and evaporation, it is important to establish the impact of the presence of a sweat layer of constant thickness (0.3 mm) on thermal performance of helmets. This can be achieved by comparing the efficiency of helmet with and without sweat as shown in Table 4. From the results, it is evident that the thermal performance of helmets with sweat decreases marginally when compared with the respective thermal performance values without sweat [29]. Sweat layer of constant thickness on the surface of head acts as an entrapment of heat generated from head during cycling. From this research it can be inferred that the helmet design must be evaluated for evaporation cooling in addition to pure convection cooling during design validation.

5.3 Limitations and Further Research

To the best knowledge of the authors, a CFD study about the influence of latent heat loss/sweating on the thermal performance of helmets has not yet been published. The present study is based on this assumption and hence a new methodology has been proposed to model the effects of sweat on thermal performance of helmets. However, the study is also subjected to some limitations briefly mentioned below.

A main limitation of the study is that the virtual testing performed using commercial CFD codes was not verified experimentally. Experimental verification with a thermal manikin that can simulate sweating will be performed in the near future. Several minute details on the helmet (e.g., visors) were not included in the model to simplify the computational mesh. Such geometrical features like visors, chin straps and straps to control fit should be included in the analysis. The sweat rate and the sweat film thickness can be improved by researching on individual measurement zones' sweat rates and applying zone specific sweat rates at predefined source locations. Furthermore, head sweat rate prediction equations developed by Taylor and Machado-Moreira [20], can be integrated into the model using user defined functions (UDF) to make virtual testing more accurate. This study was carried out for only three helmets due to computation and time constraints. More helmets with different vent profiles and designs should be tested to understand the extent to which this model can be used to validate thermal performance.

6 Summary and Conclusion

Thermal performance of three helmets for evaporative heat loss through sweating was analyzed using Computational Fluid Dynamics (CFD) simulations. Simulations were carried out at windspeed 6 m/s (21.6 kph) inside a wind tunnel using a thermal manikin modelled from a 50th percentile head shape of a western population that is derived from an anthropometric head shape model with individual measurement zones. The individual zones were maintained at 30 °C at an ambient temperature of 20 °C. The manikin remained vertical and no inclination was applied. The study shows that the helmets evaluated allow removing 84–87% of the heat from the head in the presence of sweat. These values are less as compared to 89–93%, cooling efficiency derived from sensible heat loss only [29]. This study clearly shows that the presence of sweat on the surface of head impacts the thermal performance of helmets.

References

1. Fife, D., Barancik, J.I., Chatterjee, B.F.: North-Eastern Ohio Trauma study: II, injury rates by age, sex, and cause. Am. J. Publ. Health **74**, 473–478 (1984)
2. Wood, T., Milne, P.: Head injuries to pedal cyclists and the promotion of helmet use in Victoria. Aust. Accid. Anal. Prev. **20**, 177–185 (1988)
3. Thompson, R.S., Rivara, F.P., Thompson, D.C.: A case control study of the effectiveness of bicycle safety helmets. N. Engl. J. Med. **320**, 1361–1367 (1989)
4. Attewell, R.G., Glase, K., McFadden, M.: Bicycle helmet efficacy: a meta-analysis. Accid. Anal. Prev. **33**(3), 345–352 (2001)
5. Olivier, J., Creighton, P.: Bicycle injuries and helmet use: a systematic review and meta-analysis. Int. J. Epidemiol. **46**, 278–292 (2017)
6. Sacks, J.J., Kresnow, M., Houston, B., Russell, J.: Bicycle helmet use among American children. Inj. Prev. **2**, 258–262 (1996)
7. Villamor, E., Hammer, S., Martinez-Olaizola, A.: Barriers to bicycle helmet use among Dutch pediatricians. Child Care Health Dev. **34**, 743–747 (2008)
8. Bogerd, C.C., Aerts, J.M., Annaheim, S., Bröde, P., De Bruyne, G., Flouris, A.D., Kuklane, K., Mayor, T.S., Rossi, R.M.: Thermal effects of headgear: state-of-the-art and way forward. Extrem. Physiol. Med. **4**(1), A71 (2015)
9. Servadei, F., Begliomini, C., Gardini, E., Giustini, M., Taggi, F., Kraus, J.: Effect of Italy's motorcycle helmet law on traumatic brain injuries. Inj. Prev. **9**, 257–260 (2003)
10. Orsi, C., Stendardo, A., Marinoni, A., Gilchrist, M.D., Otte, D., Chliaoutakis, J., Lajunen, T., Özkan, T., Pereira, J.D., Tzamalouka, G., Morandi, A.: Motorcycle riders' perception of helmet use: complaints and dissatisfaction. Accid. Anal. Prev. **44**, 111–117 (2012)
11. Papadakaki, M., Tzamalouka, G., Orsi, C.: Barriers and facilitators of helmet use in a Greek sample of motorcycle riders: which evidence? Transp. Res. F Traffic Psychol. Behav. **18**, 189–198 (2013)

12. Lehmuskallio, E., Lindholm, H., Koskenvuo, K., Sarna, S., Friberg, O., Viljanen, A.: Frostbite of the face and ears: epidemiological study of risk factors in Finnish conscripts. BMJ **311**, 1661–1663 (1995)
13. Zhang, H., Arens, E., Huizenga, C., Han, T.: Thermal sensation and comfort models for non-uniform and transient environments, part III: whole-body sensation and comfort. Build. Environ. **45**, 399–410 (2010)
14. Brühwiler, P.A., Ducas, C., Huber, R., Bishop, P.A.: Bicycle helmet ventilation and comfort angle dependence. Eur. J. Appl. Physiol. **92**, 698–701 (2004)
15. Liu, X., Holmer, I.: Evaporative heat transfer characteristics of industrial safety helmets. Appl. Ergon. **26**, 135–140 (1995)
16. De Bruyne, G., Aerts, J.M., Vander Sloten, J., Goffin, J., Verpoest, I., Berckmans, D.: Quantification of local ventilation efficiency under bicycle helmets. Int. J. Ind. Ergon. **42**, 278–286 (2012)
17. Nadel, E.R., Mitchell, J.W., Stolwijk, J.A.J.: Control of local and total sweating during exercise transients. Int. J. Biometeorol. **15**, 201–206 (1971)
18. De Bruyne, G., Aerts, J.M., Van der Perre, G., Goffin, J., Verpoest, I., Berckmans, D.: Spatial differences in sensible and latent heat losses under a bicycle helmet. Eur. J. Appl. Physiol. **104**, 719–726 (2008)
19. De Bruyne, G., Aerts, J.M., Vander Sloten, J., Goffin, J., Verpoest, I., Berckmans, D.: Transient sweat response of the human head during cycling. Int. J. Ind. Ergon. **40**, 406–413 (2010)
20. Taylor, N.A.S., Machado-Moreira, C.A.: Regional variations in transepidermal water loss, eccrine sweat gland density, sweat secretion rates and electrolyte composition in resting and exercising humans. Extrem. Physiol. Med. **2**, 4 (2013)
21. Bain, A., Deren, T., Jay, O.: Describing individual variation in local sweating during exercise in a temperate environment. Eur. J. Appl. Physiol. **111**, 1599–1607 (2011)
22. Brühwiler, P.A.: Heated, perspiring manikin headform for the measurement of headgear ventilation characteristics. Meas. Sci. Technol. **14**, 217–227 (2003)
23. Brühwiler, P.A.: Radiant heat transfer of bicycle helmets and visors. J. Sports Sci. **26**, 1025–1031 (2008)
24. Bogerd, C.P., Brühwiler, P.A.: The role of head tilt, hair and wind speed on forced convective heat loss through full-face motorcycle helmets: a thermal manikin study. Int. J. Ind. Ergon. **38**, 346–353 (2008)
25. Blocken, B., Defraeye, T., Koninckx, E., Carmeliet, J., Hespel, P.: CFD simulations of the aerodynamic drag of two drafting cyclists. Comput. Fluids **71**, 435–445 (2013)
26. Pinnoji, P.K., Haider, Z., Mahajan, P.: Design of ventilated helmets: computational fluid and impact dynamics studies. Int. J. Crashworthiness **13**, 265–278 (2008)
27. Stolwijk, J.A.: A Mathematical Model of Physiological Temperature Regulation in Man, Washington, USA (1971)
28. Fiala, D., Psikuta, A., Jendritzky, G., Paulke, S., Nelson, D.A., van Marken Lichtenbelt, W. D., Frijns, A.J.H.: Physiological modeling for technical, clinical and research applications. Front. Biosci. **S2**, 939–968 (2010)
29. Mukunthan, S., Kuklane, K., Huysmans, T., De Bruyne, G.: A comparison between physical and virtual experiments of convective heat transfer between head and bicycle helmet. In: Proceedings of AHFE, pp. 517–527 (2017)
30. Blatteis, C., Boulant, J., Cabanac, M., Cannon, B., Freedman, R., Gordon, C.J., Hales, J.R. S., Horowitz, M., Iriki, M., Janský, L., Jessen, C., Kaciuba-Uscilko, H., Kanosue, K., Kluger, M.J., Laburn, H.P., Nielsen-Johannsen, B., Mercer, J.B., Mitchell, D., Simon, E., Shibata, M., Szekely, M., Szelenyi, Z., Werner, J., Kozyreva, T.: Glossary of terms for thermal physiology. Jpn. J. Physiol. **51**, 245–280 (2001)

31. Gavhed, D., Mäkinen, T., Holmér, I., Rintämaki, H.: Face temperature and cardio-respiratory responses to wind in thermoneutral and cool subjects exposed to −10 °C. Eur. J. Appl. Physiol. **83**, 449–456 (2000)
32. Danckaers, F., Lacko, D., Verwulgen, S., De Bruyne, G., Huysmans, T., Sijbers, J.: A combined statistical shape model of the scalp and skull of the human head. In: Proceedings of AHFE, pp. 538–548 (2017)
33. Rasch, W., Cabanac, M.: Selective brain cooling is affected by wearing headgear during exercise. J. Appl. Physiol. **74**, 1229–1233 (1993)