International Journal of Industrial Ergonomics 53 (2016) 157–166

Contents lists available at ScienceDirect

International Journal of Industrial Ergonomics

journal homepage: www.elsevier.com/locate/ergon

Global and local heat transfer analysis for bicycle helmets using thermal head manikins

Natividad Martínez [a, b], Agnes Psikuta [a], René Michel Rossi [a], José Miguel Corberán [b], Simon Annaheim [a, *]

[a] Empa, Swiss Federal Laboratories for Materials Science and Technology, Lerchenfeldstrasse 5, CH-9014 St. Gallen, Switzerland
[b] Department of Applied Thermodynamics, Polytechnic University of Valencia, Camino de Vera s/n, 46022 Valencia, Spain

ARTICLE INFO

Article history:
Received 24 October 2014
Received in revised form
19 November 2015
Accepted 28 November 2015
Available online 22 December 2015

Keywords:
Thermal comfort
Thermal insulation
Convective heat loss
Radiant heat gain

ABSTRACT

Predicting thermal comfort of protective headgear is of particular interest since the head is one of the most heat-sensitive body parts. Thermal head manikins enable systematic investigation of heat transfer properties of headgear. Such investigation provides valuable inputs for the development of new helmet concepts to improve thermal comfort.

This study presents a nine-zone thermal head manikin (9zM) to evaluate local heat transfer effects of headgear. Performance of the new manikin and local data were assessed by comparing with data from a two-zone thermal head manikin (2zM) published previously. Variation for heat flux data was found to be lower for 9zM than for 2zM in tests including convective and radiative heat transfer. The calculation of radiant heat gain revealed similar variation at cranial section for both manikins but it increased at facial section for 9zM. Classification of helmets based on heat transfer data differed for head manikins likely due to slight differences in head geometries. Moreover, local heat transfer data obtained from the 9zM allowed a more detailed investigation of headgear properties. This knowledge contributes to a better understanding of the thermal interaction of head and headgear and, therefore, to a more justified development of optimised headgear designs.

1. Introduction

The head is a body part showing high heat-sensitivity in order to control the brain and whole body temperature (Arens et al., 2006; Cheung, 2007; Gerrett et al., 2014; Nadel et al., 1973), hence, it holds an important role in the body thermoregulation. Thermoregulation and thermal perception may be affected when wearing different types of headgear as even differences in heat loss as small as 1 W can be felt by helmet wearers in the facial and cranial regions (Brühwiler et al., 2004; Buyan et al., 2006). Headgear usually represents some additional insulation that highly impairs heat dissipation and moisture evaporation from head to the environment. On the other hand, the use of helmets is more and more promoted for different kinds of working and leisure time activities because of their important protective role. However, low wearing rates for bicycle helmets are observed in European countries mainly if the use is not mandatory (Amoros et al., 2012; Uibel et al., 2012). Bicycle users surveys reported thermal discomfort as one of the main factors limiting helmets use acceptance (Finnoff et al., 2001; Rezendes, 2006; Wardle and Iqbal, 1998). To increase wearer's comfort, which most probably contributes to cyclists' willingness to wear a helmet, several modifications to standard helmet designs have been proposed. Inserting vents, changing properties of the outer shell part and increasing clearance between the head and helmet have been demonstrated to increase dry and wet heat transfer through different kinds of helmets using heated headforms (Brühwiler et al., 2006; Fonseca, 1976; Liu and Holmér, 1997;

Abbreviations: 9zM, nine-zone thermal head manikin; 2zM, two-zone head manikin; CCP, convective cooling performance (%); HF Cranial section$_{\text{Helmet i}}$, heat loss observed at cranial section while wearing a specific helmet ($W\cdot m^{-2}$); HF Cranial section$_{\text{Nude head}}$, heat loss observed at cranial section for the nude head manikin ($W\cdot m^{-2}$); RHG, radiant heat gain ($W\cdot m^{-2}$); NV, suffix for helmets without visor; VI, suffix for helmets equipped with visor; HF$_{\text{Light OFF}}$, heat loss corresponding either to facial or cranial section if light source off ($W\cdot m^{-2}$); HF$_{\text{Light ON}}$, heat loss corresponding either to facial or cranial section if light source on ($W\cdot m^{-2}$); RS, radiant shielding (%); RHG$_{\text{Nude head}}$, radiant heat gain for the nude head ($W\cdot m^{-2}$); RHG$_{\text{Helmet i}}$, radiant heat gain for manikin covered with a specific helmet ($W\cdot m^{-2}$).

[*] Corresponding author.
E-mail addresses: natividad.martinez@empa.ch (N. Martínez), agnes.psikuta@empa.ch (A. Psikuta), Rene.Rossi@empa.ch (R.M. Rossi), corberan@ter.upv.es (J.M. Corberán), Simon.Annaheim@empa.ch (S. Annaheim).

http://dx.doi.org/10.1016/j.ergon.2015.11.012
0169-8141/

Reischl, 1986). The characterization of twenty-four different bicycle helmets showed convective heat loss from 65 to 93% compared to nude head condition (Brühwiler et al., 2006). Radiation was shielded by different helmets from 50 up to 85% (Brühwiler, 2008). In case of human participants trials, design modifications on helmets provided lower temperatures and humidity levels under the helmet (Guan et al., 2007; Holland et al., 2002) and reduced hotness perception (Abeysekera and Shahnavaz, 1988; Davis et al., 2001; Dullah et al., 2011).

Numerous studies have substantiated the complexity of the head thermal response. Research on local differences in skin and air temperature, regional variation of sweat rates in the cranial region (De Bruyne et al., 2010, 2008; Machado-Moreira et al., 2008), as well as moisture accumulation under a helmet (De Bruyne et al., 2008; Dullah et al., 2011), have provided some basis for head heat transfer mapping. Dependency of local thermal perception on local temperatures and humidity under a helmet also indicates the importance of knowing spatial differences in microclimates at the head (Bogerd et al., 2010; Dullah et al., 2011). Based on this knowledge, local cooling could be optimised in helmets taking into account spatial differences in thermal sensitivity at head. Observations regarding thermal sensitivity at the scalp revealed site-wise variations in warm thresholds (i.e. 5 °C between the most sensitive location at the temple and the least sensitive at parietal region) (Mehrabyan et al., 2011) and significant variations in thermal thresholds, both cool and warmth sensitivities, in the face as well (Essick et al., 2004).

According to the local differences in thermal sensitivities at the human head, research providing a higher spatial resolution in local heat transfer of helmets has become crucial for fully understanding heat losses mechanism of the head. The application of an adapted tracer gas measurement technique on thirteen and nine sampling locations respectively has evidenced regional differences in ventilation efficiency for bicycle helmets (De Bruyne et al., 2012; Van Brecht et al., 2008). An eight-thermocouple lay-out placed on a thermal headform surface allowed detecting higher temperature increments in lower parietal region (1.7 ± 0.1 °C) than in region just above the ear (0.5 ± 0.1 °C) when wearing different cricket helmets (Pang et al., 2013).

One of the most extended techniques for evaluating thermal properties of headgear is thermal manikins. Thermal head manikins have been developed enabling reproducible and systematic analysis of heat transfer properties of headgear. The use of different thermal headforms, mainly to study ventilation and radiant shielding properties of helmets, has been reported for many different applications such as bicycle (Alam et al., 2010; Brühwiler, 2009, 2008; Brühwiler et al., 2006, 2004; Reid and Wang, 2000), motorcycle (Bogerd and Brühwiler, 2008; Bogerd et al., 2010), rowing (Bogerd et al., 2008), cricket (Pang et al., 2013, 2011), firefighting (Reischl, 1986), industrial safety (Abeysekera et al., 1991; Hsu et al., 2000; Liu and Holmér, 1997) and military headgear (Fonseca, 1974; Osczevski, 1996). Thermal head manikins provide an anatomical reproduction of the human head geometry and size with a typical simplification of the face region, where ears and hair are not usually present. The surface of thermal headforms is divided into a diverse number of independent heated zones (Brühwiler, 2003; Liu and Holmér, 1995; Osczevski, 1996; Reid and Wang, 2000; Reischl, 1986). Several heating methods have been applied in different manikins with heating resistance wires being most common (Brühwiler, 2003), and a light bulb inserted into the head or filling the head with warm water (Hsu et al., 2000; Pang et al., 2011; Reischl, 1986). The surface temperature of the manikin is typically measured using a resistance wire evenly wounded on the independent zones and controlled at a fixed set-point temperature corresponding to human skin temperature at thermo-neutral state (e.g. between 34 °C and 36 °C (Brühwiler, 2003; Fonseca, 1974; Liu and Holmér, 1995; Pang et al., 2011; Reischl, 1986)). The power needed to maintain this temperature at stable environmental conditions (air and radiant temperature, relative humidity and wind speed) refers to the net combined heat loss through convection, conduction and radiation.

Despite the high reliability and reproducibility achieved by thermal head manikins, head segmentations described so far are not detailed enough to provide valuable assessment of local heat losses over entire head surface. Therefore, a finer and dedicated segmentation might allow investigating thermal properties of headgear with adequate spatial resolution to be related to local physiology. Combining the reproducibility of thermal head manikins with high spatial resolution in the study of local heat loss might yield to a better understanding of the mechanisms underlying thermal effects of headgear.

The aim of this work is to analyse the performance of a novel nine-zone thermal head manikin providing a dedicated segmentation designed according to our previous experience in headgear testing. First part of the study is aimed at determining the consistency of the nine-zone thermal head manikin data with previously published data of a two-zone thermal head manikin for bicycle helmets testing in two cases of measurements highly related with cycling scenarios: i) Convective heat transfer (Brühwiler et al., 2006) and ii) Combined convective and radiative heat transfer (Brühwiler, 2008). Second part of the work is aimed at determining the additional findings of a local investigation of heat transfer provided by the novel head segmentation into nine independent zones.

2. Material and methods

2.1. Nine-zone thermal head manikin

According to detected testing needs for headgear after our previous experience, a novel segmentation of the head surface have been proposed for building a novel nine-zone thermal head manikin (9zM) (Sweating Thermal Head, Measurement Technology Northwest, Seattle WA, USA, 2012). The 9zM surface is divided into nine independent heated zones able to measure individual heat loss and surface temperature (Fig. 1). The headform is made out carbon fibre-epoxy with thermally conductive reinforcement. Distributed heating wires and wire temperature sensors are wounded on the inner and outer surface for each zone, respectively. Head circumference measured above eyebrow-site is 59 cm. The cranial region of the 9zM was finely segmented into six independent zones typically covered by headgear. The zones included right and left temple as well as a serial fragmentation of the area in-between. This allocation was chosen to investigate differences in heat transfer from anterior to posterior. Face, forehead and neck were the remaining independent zones with the forehead being a zone partially covered by the headgear. Zones surface areas are depicted in Table 1. Additionally, a thermal guard zone exists at the base of the neck to prevent conductive heat loss.

2.2. Two-zone thermal head manikin

A two-zone thermal head manikin (2zM) (Brühwiler, 2003) has been intensively used for investigating heat transfer properties of different kind of headgear (Brühwiler, 2008, 2003; Brühwiler et al., 2006, 2004; Buyan et al., 2006). This headform was adapted from a polyester shop window manikin. It was divided into two measuring sections: cranial section (the upper and rear part of the head) and the facial section (comprising also forehead, ears and a small part of