Current Development of Thermal Sweating Manikins at Empa

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Abstract

Over the past two decades, Empa has developed heated sweating body parts and a whole-body sweating thermal manikin (Sweating Agile thermal Manikin, SAM). These manikins are used in clothing research to measure the insulation and water vapour resistance of clothing under steady-state conditions as well as to study the effects of clothing, wind, posture, body movement and climate on the local heat flux from different areas of the body.

At present, two sweating manikins are being developed further to enable the thermophysiological behaviour of the human to be simulated. This is being achieved by coupling the control software of each sweating manikin to a multi-node thermophysiological model. The first manikin being coupled is the heated sweating cylinder which is designed to simulate the torso of an adult human. Good agreement between initial results from the coupled torso and human thermal responses is observed.

Work is now in progress to achieve a similar coupling to the more sophisticated Sweating Agile thermal Manikin SAM using the same physiological model. In order to achieve this goal, further development to optimise and extend the control of SAM is being carried out in parallel.
1. Introduction

Determination of the wear comfort and protective properties of clothing is one of the main focuses of the Laboratory for Protection and Physiology at Empa. This is facilitated by investigating the transport of body heat and sweat through clothing under steady-state and dynamic conditions, which includes determination of the dry and wet thermal insulation and evaporative resistance of individual clothing layers and complete clothing systems. The term wet thermal insulation refers here to the total thermal insulation when sweating. To this end a series of thermal manikins have been developed to simulate the heat and moisture production of the human body and parts of the body. These manikins are listed chronologically in Table 1, according to when they were first taken into operation. Also the number of separately-heated segments, the physical clothing properties measured and references to previous publications are indicated.

<table>
<thead>
<tr>
<th>Manikin</th>
<th>Operation since</th>
<th>Segments</th>
<th>Physical properties measured</th>
<th>References / Standards</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweating guarded hot plate</td>
<td>1985</td>
<td>2</td>
<td>Dry thermal insulation and water vapour resistance of single and multiple horizontal layers</td>
<td>(EN 31092/ISO 11092, 1993)</td>
</tr>
<tr>
<td>Heated hand</td>
<td>1989</td>
<td>1</td>
<td>Dry thermal insulation of gloves</td>
<td></td>
</tr>
<tr>
<td>Sweating arm (with 90° movement of lower arm)</td>
<td>1993</td>
<td>5</td>
<td>Dry thermal insulation and water vapour resistance of sleeves without / with lower arm movement</td>
<td>(Weder et al., 1995)</td>
</tr>
<tr>
<td>Torso (Cylinder representing a ¼ of the total adult body surface)</td>
<td>1995</td>
<td>3</td>
<td>Dry and wet thermal insulation of bedding and upper body garments</td>
<td>(Zimmerli and Weder, 1996)</td>
</tr>
<tr>
<td>Sweating head ALEX</td>
<td>1999</td>
<td>3</td>
<td>Dry and wet thermal insulation of helmets</td>
<td>(Brühwiler, 2003)</td>
</tr>
<tr>
<td>SAM (Sweating Agile thermal whole-body Manikin)</td>
<td>2001</td>
<td>30</td>
<td>Dry and wet thermal insulation and evaporative resistance of complete clothing systems without / with body movement</td>
<td>e.g. (Richards and Mattle, 2001a) / (ISO/FDIS 1 5831, 2003; ASTM F 18 68-02, 2005)</td>
</tr>
</tbody>
</table>

Table 1: Development of heated sweating body parts and a whole-body manikin
All of these systems have been in operation for five or more years. They have proven to be reliable instruments with little need for maintenance. During a series of measurements each manikin is left on, heated at a controlled temperature between experiments to enable steady-state conditions to be regained quickly following change of clothing and/or conditions.

This paper presents an overview of some of the work presently being undertaken to advance two of the above manikins, namely Torso and SAM. Presently the control software for these two systems is being coupled to a multi-node model of the human thermal system. Conceptually similar work led to the development of a manikin specifically designed with thermo-physiological control in mind (Burke and McGuffin, 2001). The present work presents the results of an alternative strategy of modifying existing thermal manikins to gain such control.

2. Modelling Work

Heat loss and thermal comfort of the human body are dependent on many factors, including the clothing being worn. The evaporation of sweat is an important means of body heat loss when a person is physically active or in a hot environment. Consequently, most heat budget models and thermal comfort indices require values of the thermal insulation and evaporative resistance of clothing. To determine these values accurately for manufactured clothing ensembles, life-sized thermal manikins must be used (Richards and McCullough, 2005).

An alternative approach, which can enable the thermo-physiological response of the human to be predicted more accurately under defined conditions, is to use a multi-node model of the human thermal system (Fiala et al., 2001; Huizenga et al., 2001; Stolwijk, 1971; Tanabe et al., 2002; Wissler, 1985).

One of the most advanced of these models which Empa has compared with human subject trials is the IESD-Fiala model (Fiala et al., 1999; Fiala et al., 2001). Validation work, presented at the previous manikin meeting 5I3M, demonstrated the predictive accuracy of the IESD-Fiala model for fire-fighters under hot stressful conditions (Richards and Fiala, 2004). For this work, the physiological responses of fire-fighters to exercise and asymmetric infrared-radiation were investigated at Empa (Richards, 2000). SAM was used to measure the thermal insulation and evaporative resistance of the different fire-fighting clothing worn. These values were input into the IESD-Fiala model, and the dynamic thermo-physiological behaviour of the fire-fighters was predicted. The predicted physiological responses generally agreed well with the wear trial data.

As part of the ongoing validation of the IESD-Fiala model, predicted responses are now being compared with a large range of human data under normal and extreme conditions within COST action 730 (www.utci.org) in which a Universal Thermal Climate Index is being developed.
3. Sweating Heated TORSO

The sweating heated TORSO (Zimmerli and Weder, 1996) consists of a cylinder with outer diameter of 30cm, divided into two guard sectors at the ends and a measurement section in the middle. Each sector is controlled with either constant temperature or constant power. Water used to simulate sweat is supplied at a controlled rate through 54 sweat outlets distributed over the surface of the measurement sector. When operated under constant power mode, the surface temperatures of the guards follow the surface temperature of the measurement cylinder to minimise the lateral heat exchange between guards and measurement cylinder.

4. Coupling the TORSO to the IESD-Fiala Model

Our goal in coupling the control software of the TORSO to the IESD-Fiala model is to simulate the thermo-physiological behaviour of the human in real time. At present the Torso surface temperature and sweat rate are controlled with the mean skin temperature and sweat rate of the whole human body, respectively. Forthwith this coupled system is referred to as the Fiala-Torso.

One example of the initial results of coupling the Fiala-Torso system is shown in Fig. 1. The simulated mean skin temperature actually followed by the Fiala-Torso system is compared to that determined under cool exposure using subjects (Wagner and Horvath, 1985). The experimental conditions under both the simulation and the human experiments were an ambient temperature of 20°C, relative humidity (rh) of 40%, air velocity of 0.1m/s and metabolic rate of 55 W/m². For the human experiments, only briefs were worn (0.216 clo) whereas the Fiala-Torso was unclothed.

![Figure 1 Initial results of the Fiala-Torso system response compared to the mean human response](image)

Generally very good agreement is seen between the Fiala-Torso system and human results. During the first half-hour of exposure, the human demonstrates a cooler
mean skin temperature than the Torso. This initial discrepancy is due to the fact that under these conditions, the human skin cools down very rapidly (Wagner and Horvath, 1985) whereas the Torso responds more slowly due to the thermal mass of the shell part materials. Nevertheless, after this initial period the Torso surface temperature catches up with the true average human response. This cooling response is faster than for a human exercising and/or wearing more clothes and the authors expect that under warmer conditions or with more clothing less discrepancy shall be observed.

5. Preparations to couple SAM to the IESD-Fiala model

Work is now in progress to couple the model to SAM. The Sweating Agile thermal Manikin (SAM) has 26 separately-heated body sectors, 125 sweat outlets and is capable of performing realistic body movements (Richards and Mattle, 2001b). This manikin provides detailed information about the clothing worn, dependent on the climate and sweat rate used. The climatic chamber used provides a well-controlled environment with a wide range of temperatures (-30 to 40°C), humidities (20 to 90% rh) and wind speeds (0.2 to 40 m/s). For standard operation, the surface temperature is controlled homogeneously at 34.0 ±0.1°C. With the model coupled to SAM, the local skin temperatures shall be controlled heterogeneously according to the model.

The present 36 internal sweat-distribution valves are to be replaced with 144, so that each sweat outlet shall have its own dedicated valve. Also the hands and feet, which are presently non-sweating and used as heat guards for the limbs, shall gain sweat outlets and thus the ability to sweat. This shall be a significant advancement, as these body parts are very important in the thermal regulation of the human. Furthermore, it is proposed to replace the present shell parts of SAM with new shell parts (under development) better suited to thermo-physiological control.

6. Conclusions

In addition to measurements of physical properties of clothing materials and the possibility of using these properties to simulate the human response indirectly, the thermo-physiological response (mean skin temperature and mean sweat rate) of the human can now be simulated directly using the sweating cylinder Torso. During next year it is planned to be able to simulate the thermo-physiological response of the human directly in more detail (local skin temperature and local sweat rate) using SAM for a given clothing and climate.

Acknowledgements

Our thanks go to Prof. Lomas, IESD, De Montfort University, UK for his support in the PhD work of A. Psikuta. The authors wish to thank WL Gore UK for helping to fund the first part of this work, and the Swiss State Secretariat for Education and
Research (SBF/SER) for funding the latter part of this work as part of COST action 730 under project C06.0023.

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