A COMPUTER MODEL OF HUMAN THERMOREGULATION EXTENDED WITH AN ACTIVE BODY CLIMATE CONTROL SYSTEM

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ABSTRACT
This paper describes a computer model of human thermoregulation based on the Fiala model that we have extended with a module for active body climate control. The main stimulus for the development of this model is the need to predict the thermal response of the human body to the actual prototype for active body climate control. This prototype supports the heat exchange mechanisms of the body by improving convection and especially evaporation. The model has been validated with experimental data from a field study. As a result, new design recommendations for the enhancement of the prototype and especially the control algorithm, based on vital and environmental parameters, could be identified.

KEY WORDS
Active body climate control, airflow control, dynamic simulation, human thermal response, Fiala model.

1. Introduction
Nowadays, the need for individual textile integrated active body climate control is getting more and more important and essential. In fact, a system that offers such functionality could relieve staff like rescue personnel and special police units that have to wear protective clothing (in this use case ballistic garments). This type of clothing leads, even undesired, to a thermal isolation, which prevents the wearer from dissipating the generated body heat that varies between 80% and 100% of the total metabolic activity of the body \cite{1, 2}. In this way, the thermal load increases very fast with an increase in the metabolic activity and the body can overheat. Consequently, this leads to a decrease in physical performance and thermal comfort and thus to a limitation of the working time.

Another target group for individual body climate control are the elderly with cardiovascular problems. There are cases, when excessive heat leads to a collapse of these patients' cardiovascular system, because their physiological thermoregulation cannot adjust properly. Active body climate control would offer many advantages over conventional air conditioning systems in terms of individual control, effectiveness and efficiency. This could be achieved by the variation of the amount of circulating air in the vicinity of their skin surface with a textile integrated active body climate control system. Such a system could be primarily regarded as a cooling system that is meant to support the heat exchange mechanisms of the body by improving convection and especially evaporation. The climate control system should therefore get an input from several vital and environmental parameters in order to identify the cooling needs of the user.

In fact, an appropriate control algorithm, which could determine the released body heat related to the environmental conditions and the metabolic activity of the person and thus calculate the necessary airflow, needs to be implemented and optimized. In this context, a thorough understanding of the human thermoregulation and its interaction with a realized prototype for active body climate control plays a major role. Therefore, an appropriate model with a reliable transient response is needed.

Regarding models describing the human thermoregulation, several mathematical models of human thermoregulation have been proposed over the past years \cite{1, 3, 4, 5, 6}.

Some of these models define only central and mean skin temperatures, while others attempt to provide a detailed description of the temperature field within the body. The Fiala model \cite{1, 7} can be considered as one of the most advanced models since it has a response able to predict the transient state and thus has better predictive abilities and better modelling of the heat exchange with the environment. This model needs to be extended with a module for active body climate control, which interacts with the body and influences its thermoregulatory behaviour, in the same way as the actual prototype for active body climate control in the reality does.

2. Methods and Materials

2.1 Prototype for Active Body Climate Control

As Figure 1 shows, the realized prototype for active body climate control comprises three main components: a sensor shirt, a cooling vest (worn over the sensor shirt) and a user feedback interface (in this case a PDA). These
components build up a wireless body area network (WBAN).

The sensor shirt is made of an elastic material permeable to moisture, which fits the body contour and allows the generated evaporation heat of the body to diffuse towards the ventilation layer of the cooling vest. Two sensors have been used in order to determine the actual body climate by measuring the skin temperature and relative humidity in the area of the chest and the upper back due to the non uniform distribution of the skin temperature [8]. The relative humidity at the skin surface is a good parameter to determine the amount of heat loss in form of evaporation. The latter represents the largest part of the body heat given up to the surroundings and especially at high surroundings temperature and/or metabolic activity.

Two additional sensors have been integrated into the sensor shirt in order to approximate the energy expenditure due to physical activity: a heart rate sensor and a 3D accelerometer.

Two ventilation parts for separate control of the body climate at the chest and the back area. These are attached to each other via velcro fasteners. As Figure 2 shows, each ventilation part has an air inlet in the top left corner and an air outlet in the opposite bottom right corner, where a ventilator is placed in order to aspirate the air and thus lead to air circulation over the upper part of the body. This way, the air blown out at the outlet becomes warmer and more humid due to the released body heat via evaporation and convection.

Figure 1. The actual prototype for active body climate control

The cooling vest is worn over the sensor shirt and integrates a 7 mm thick space holder material, through which fresh air can circulate. It has two different ventilation parts for separate control of the body climate at the chest and the back area. These are attached to each other via velcro fasteners. As Figure 2 shows, each ventilation part has an air inlet in the top left corner and an air outlet in the opposite bottom right corner, where a ventilator is placed in order to aspirate the air and thus lead to air circulation over the upper part of the body. This way, the air blown out at the outlet becomes warmer and more humid due to the released body heat via evaporation and convection.

Figure 2. Design of the ventilation area of the cooling vest

The inner textile separation layer of the cooling vest is, unlike the outer one, permeable to the moisture. In addition, each ventilation part of the cooling vest integrates two combined sensors for measuring temperature and relative humidity at both the inlet and the outlet, which can be used to monitor the ambient air (from the sensor at the inlet) and the thermal exchange between the body surface under the vest and the circulating air in the vest (from the sensor at the outlet). The used ventilators can induce an airflow up to 50 l/min and are controlled by a PWM modulator on the control board. As a result, the ventilation level in the vest can be changed according to the current level of the climate control algorithm.

The conceived control algorithm is based on the measured vital and environmental parameters. Thereby the heart rate \((HR)\) and the activity equivalent for the acceleration \((AEAC)\), described in [9], are fused in order to approximate the actual metabolic activity of the body. Then, the generated body heat can be determined and thus the necessary airflow and the corresponding ventilation level can be calculated. To give the user of the cooling system the possibility to fine tune the ventilation level according to his individual comfort feeling, the feedback interface (PDA) is being used.

2.2 Experimental Database

Furthermore a field study involving nine test persons has been conducted in order to collect data sets, which can be used in the validation of the implemented model. Besides the described sensors of the sensor shirt, a spirometer was used in order to have a reference measurement of the metabolic activity that can be determined from the consumed amount of oxygen. Each test person undertook a load test on a treadmill ergometer wearing the realized prototype and a spirometer. After a baseline phase of 5 minutes, an intensity level of 6 km/h was set at the treadmill ergometer for the period of 5 minutes followed by an increase in the intensity level of 1 km/h every 5 minutes. After the load test phase with the maximum intensity level of 10 km/h, the test person had 10 minutes time for cooling down.
2.3 Fiala Model

Fiala’s model is one of the most recent thermoregulation models available and has shown a reliable transient response. The transient response is fundamental to develop a control algorithm for the cooling system.

Fiala’s mathematical model of the human thermoregulation has two interacting systems: the controlling active system and the controlled passive system. The multi-segmental model of the passive system simulates the physical human body and the heat transfer phenomena occurring inside (blood circulation, metabolic heat-generation, -conduction and -accumulation) and at its surface (free and forced surface convection, long- and shortwave radiation, skin moisture-evaporation, -diffusion and -accumulation) [1].

As shown in Figure 3-a, the body is divided into 15 spherical or cylindrical segments: head, face, neck, shoulders, arms, hands, thorax, abdomen, legs and feet. Each of the body segments is further radially divided into different concentric tissue layers and uses seven different tissue materials: brain, lung, bone, muscle, viscera, fat and skin (e.g. the leg segment has, as Figure 3-b shows, five layers: bone, muscle, fat, inner skin and outer skin). To simplify the model, each layer is assumed to have direct blood heat transfer with the central blood compartment rather than the adjacent body layers. Besides, each of the body segments, except for the face and shoulders, are divided spatially into sectors due to the asymmetric removal of bodily heat. Thereby, most of the segments (like shown in Figure 3-b for the leg segment) are divided into three sectors: anterior, posterior and inferior. The sectors are in addition coupled thermally by a core element around the cylinder axis (see Figure 3-b).

As clothing plays a very important role in determining the human thermal response, it is also described in the Fiala model. Thereby, thermal properties of garments are characterized locally on each segment by two factors; the resistance to sensible heat transfer and the resistance to water transport through the garment.

The active system predicts the regulatory responses of the central nervous system in form of shivering, sweating and peripheral vasomotion of unacclimatized subjects: vasoconstriction for suppression and vasodilatation for elevation of the cutaneous blood flow. The model has been shown to reliably predict skin and body core temperatures, regulatory responses, and the overall thermal sensation for a range of environmental temperatures between 5 and 50°C, and exercise intensities between 0.8 and 10 MET for about 300 different exposures obtained from independent physiological and comfort experiments, as shown in [7]. MET stands for "metabolic equivalent" and is defined as "the ratio of the work metabolic rate to the resting metabolic rate". One MET is the rate of heat consumption at rest and is equal to 58.2 W/m² [7].

2.4 Modelling of the Prototype for Active Body Climate Control

The module for active body climate control, modelling the presented prototype or cooling vest, interacts with the passive system in a similar way as the active system does (see Figure 4). Thereby, it takes into consideration the environmental characteristics (ambient air temperature: $T_{air}$, ambient air relative humidity: $RH_{air}$, ambient air velocity: $V_{air}$, and mean surroundings temperature: $T_{srn}$) and the input data from the passive system (heat losses $HL$ in form of evaporation, convection and radiation). Then, it predicts the response of the cooling vest through calculating the temperature $T_{airflow}$ and the relative humidity $RH_{airflow}$ of the airflow circulating inside the cooling vest with the velocity $V_{airflow}$. The latter parameters are then fed back to the passive system and thus influence the new generated body heat losses $HL$. 

Figure 3. Multi-segmental multi-layer model of Fiala [1]: a) Different segments of the body, b) Different layers of a body segment (e.g. the leg)

Figure 4. Block diagram of the different components of the extended thermoregulatory model
The cooling vest model comprises three layers: an inner textile layer permeable to moisture, an outer textile layer with a low permeability to moisture, and an intermediate air layer, in which the controlled airflow circulates and dissipates the body heat losses. In addition, the cooling vest model is split up into four segments (upper front: UF, lower front: LF, upper back: UB, and lower back: LB), as shown in Figure 5. Each of these segments interacts with the corresponding segment of the passive system, which is located underneath (e.g. the segment UF of the active body climate control system interacts with the anterior sector of the abdomen segment in the passive system). Besides, each two segments of the cooling vest (UF and LF, UB and LB) build up a cascade (see Figure 5), so that the airflow circulation inside both parts of the cooling vest is modelled conform to the real situation. In fact, the aspirated ambient air at the front inlet is first being influenced by the heat losses of the anterior thorax segment resulting in changes of the characteristics of the airflow (airflow temperature and relative humidity). Then the air passes the LF segment, where the interaction of the airflow with the heat losses of the anterior abdomen takes place. Finally, the airflow reaches the front outlet.

Figure 5. Cascade-based multi-segmental model of the active body climate control system (cooling vest)

3. Results

In this section, the validation of the extended model with the experimental data from the field study described above is presented. Moreover, some design recommendations, which could be identified from the simulations with the extended model, are illustrated. These could lead to the enhancement of the actual prototype and especially of the control algorithm based on vital and environmental parameters.

From the collected nine data sets, only two data sets (of test person n°4 and n°9) have shown reliable data of the used sensors over the whole measurement cycle and are thus being considered in the validation process. As for the remaining data sets, there has been a malfunction of certain sensors in parts of the measurement cycle and thus these data sets cannot be used to validate the implemented model.

3.1 Validation of the Model

In order to validate the extended model, the simulated mean temperature, mean vapour pressure of the skin in the torso area and the outlet air of the cooling vest, and dissipated body heat loss through the cooling vest have been compared with the measured data for test persons n°4 and n°9. Thereby, the Mean Absolute Percentage Error (MAPE) has been calculated for the parameters mentioned above according to the following equation:

$$MAPE = \frac{1}{n} \sum_{t=1}^{n} \frac{|y_t - x_t|}{y_t} \tag{1}$$

$y_t$ represents the reference value corresponding to the measured value and $x_t$ represents the simulated value by the extended model.

As illustrated in Figure 6-a, the simulated mean skin temperature (continuous blue line) in the torso area has shown a good overall agreement with the measured data (dashed red line). The values for MAPE were 3.4% for test person n°4 and 2% for test person n°9 respectively.

However, the comparison of the measured mean temperature of the outlet air of the cooling vest with the data from the extended model has shown a larger deviation (see Figure 6-b) resulting in a MAPE of 13.5% for test person n°4 and 15.3% for test person n°9. This could be explained by the deviation between the measured and the simulated amount of convection heat loss. In order to compensate this deviation, the local effective heat transfer coefficient $U_{cl}^*$ [1] of the inner layer of the cooling vest needs to be determined more precisely and accordingly adjusted.

In order to validate the results of the relative humidity in the model, the corresponding vapour pressure has been first calculated from the relative humidity according to the following equation:

$$VP = \frac{RH}{100} \cdot VP_{sat} \tag{2}$$

Thereby, $VP_{sat}$ designates the saturation vapour pressure. This way, the validation of the temperature independent vapour pressure would deliver more reliable results.
Figure 6. Comparison of the simulated and the measured mean temperature of a) the skin in the torso area, b) the outlet air of the cooling vest, for test person n°9.

Figure 7-b shows a large deviation between the simulated (continuous blue line) and the measured (dashed red line) mean vapour pressure of the outlet air of the cooling vest in the first 10 minutes. The first baseline phase and the load test phase with the intensity of 6 km/h are included. The low measured mean vapour pressure of the outlet air of the cooling vest in that time interval could be explained by the fact that at low activities the evaporation heat losses do not get to the inner air layer of the cooling vest, but are rather stored by the textile material of the sensor shirt and the air layer between the skin surface and the inner textile layer of the cooling vest. However, the simulated mean vapour pressure of the outlet air of the cooling vest is high since in the extended model only a textile layer permeable to moisture separates the skin surface from the inner air layer of the cooling vest. In addition, a low airflow was set, which led to the high vapour pressure.

Figure 7-a shows the same behaviour of the simulated (continuous blue line) and the measured (dashed red line) mean skin vapour pressure in the torso area in the first 10 minutes because the relative humidity or the vapour pressure of the ventilation air directly influences that of the skin, as shown in Figure 4.

Otherwise, an acceptable qualitative approximation starting from the second intensity phase of the load test can be observed. Thereby, a $MAPE$ of 20% and 18.5% for the mean vapour pressure respectively of the skin in the torso area and the outlet air of the cooling vest have been calculated for test person n°9.

Figure 7. Comparison of the simulated and the measured mean vapour pressure of a) the skin in the torso area, b) the outlet air of the cooling vest, for test person n°9.

Figure 8 shows a comparison of the simulated (continuous blue line) and the measured (dashed red line) dissipated body heat losses through evaporation, convection and radiation for test person n°9. Thereby, a large deviation can be observed in the first 10 minutes. This deviation strongly correlates with the deviation observed for the vapour pressure of the outlet air of the cooling vest, since the latter has, in combination with the airflow inside the cooling vest (continuous green line in Figure 8), an important impact on the amount of dissipated skin heat losses by the cooling vest and especially on the evaporation heat loss that represents the largest part of the total skin heat losses.

Nevertheless, a good approximation starting from the second intensity phase of the load test can be observed. Thereby, a $MAPE$ of 22% and 16% could be obtained for test person n°4 and test person n°9 respectively.
3.2 Design Recommendations obtained from the Model

In this section, some design recommendations obtained from the extended simulation model, which could lead to the enhancement of the actual prototype and especially the control algorithm based on vital and environmental parameters, are presented.

In the current control algorithm for the active body climate control, the workload is being used in order to determine the necessary airflow to be set in the cooling vest. Thereby, the workload has been calculated from the whole body metabolism (metabolic activity) according to the following equation:

\[ \text{Workload} = \text{Metabolism} \times (1 - \eta) \]  

(3)

\( \eta \) designates the mechanical efficiency of the human body and generally varies between 0% at steady state conditions and 20% at high activity intensities. However, the simulations with the extended model have shown (see Figure 9) that the heat losses \( HL \) (continuous green line), which should be considered by the control algorithm rather than the workload, show a different behaviour than the workload. This could be explained by the fact that the metabolic heat production, which directly influences the body heat losses, is more complex. In fact, the metabolic heat production contains, in addition to the basal metabolism (corresponding to neutral thermal conditions) three other components; i.e., changes in the basal metabolism and in an additional metabolism by shivering (primarily in cold environmental conditions) and working (obtained from the workload) [1].

Figure 10 shows a comparison of the heat losses of the skin in the torso area \( HL_{\text{torso,s}} \) with the total skin heat losses. This comparison implies that for the actual climate control system and the used clothing scenario in the field study (sportswear: T-shirt, underpants, shorts, socks and sports shoes) the skin heat losses in the torso area could be approximated to 25% of the total skin heat losses. This approximation can also be considered by the control algorithm for the active body climate control in order to accurately determine the necessary airflow to be set in the cooling vest.

4. Conclusion and Future Work

In this paper, the extension of a Fiala-based human thermoregulation model with an active body climate control system has been described. The Model has been validated against independent experimental data for a range of exercise intensities between 1.5 and 12.5 MET and showed good agreement with the measured transient responses of the cooling vest and the mean skin temperatures.

In addition, new design recommendations for the enhancement of the actual prototype and especially the control algorithm, based on vital and environmental parameters, could be identified. Nevertheless, the extended model needs to be improved in order to better predict the behaviour of the mean vapour pressure of the skin in the torso area and the
cooling vest. Here, the model showed a large deviation in the beginning of the conducted load test and a good approximation in the rest of the test.

Future work will therefore comprise the modelling of the different layers between the skin surface and the inner textile layer of the cooling vest (including a standing air layer). In addition, the different local effective heat transfer coefficients $U^{*}_{cl}$ of the used textile materials need to be determined more precisely. Then, the model needs to be validated for a wide range of environmental conditions in other field studies involving more test persons.

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