

# Development of methods for the digital representation of the thermal wearing comfort of outdoor clothing

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**Abstract** A multi-model pore system, which includes the micro, meso, macro and mega pores, develops between fibers, yarns, fabrics or multilayer fabrics and human body respectively during wearing clothes. This multi-model pore system significantly affects thermodynamic processes of human and consequently the thermal wearing comfort of outdoor and protective clothing. The objectives of the research are to analyze this effect and to develop application-oriented principles and processes for the holistic simulation of outdoor clothing according to geometrical, textile-physical, and thermal parameters. To achieve the required aim clothing samples for five selected test persons are developed and sewed and the textile materials are comprehensively characterized. The size distribution of the mega pores are identified by the fit simulation and the wear trials are conducted in climate chamber to analyze the heat transfer between body and clothing system. In this paper the thermal simulation of the jacket and test person1 is presented. This innovative approach will give the opportunity to analyze the effect of body shape, design of clothing, environmental conditions and level of activity of human.

**Keywords**— microclimate, thermal simulation, thermo physiology, wear trial.

## I. INTRODUCTION

Numerous researchers have focused on wear comfort for humans in the recent past. The researchers have been working intensively to make complex development processes more transparent and efficient. However, there is still need of a comprehensive research, especially in functional textiles. During the design process of functional textiles for outdoor and protective clothing, both constructive (fit, ergonomic wear comfort) as well as functional aspects (weather protection, thermal wear comfort) are very important. Therefore the realization of holistic product design, predominantly based on empirical knowledge is very complex. During the process of pattern making, the body shapes and working postures have been considered by using computer-assisted 3D design/fit simulations. Therefore, today there are a lot of solutions available regarding the assessment of ergonomic comfort by using virtual modeling as well as analytical tools. But currently no computer-assisted solution exists for the realistic prediction of the thermal comfort. Hence, the cross-linking of both approaches requires extensive research.

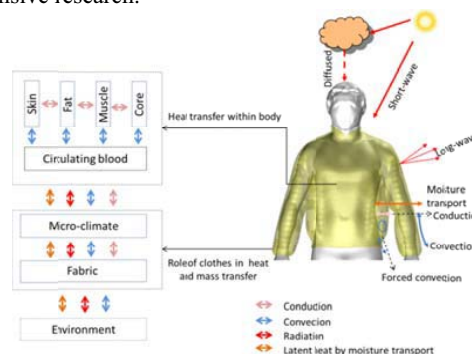


Fig. 1. Thermal regulation between human body, clothing and environment.

Clothes are an integral part of human life, and its main purpose is to protect us against environmental hazards [1]. It is easy to achieve this purpose when clothing comfort is neglected. Thermal comfort is one of the most important and experimentally investigated aspects of clothing comfort, which is affected by many factors, e.g.



environment, characteristics of clothes, microclimate, activity level etc. In addition to other factors, the thermal comfort of clothes considerably depends on the microclimate. A microclimate is the small layer of air between human body and clothing. This air layer is an important factor for thermo-physiological comfort as it is extremely close to the body. The properties of the microclimate (e.g. as insulator in winter and heat exchanger in summer) are affected by several aspects, for example thermal and draping properties of the fabric, garment design, environmental conditions, etc.

The human body constantly interacts with the environment due to convection, conduction, radiation, and sweat evaporation. It is therefore continuously subjected to heat stresses, such as solar radiation, air temperature, humidity, and metabolic heat. A thermal regulation system helps maintain the heat balance between human body and environment in order to achieve a body core temperature of 37°C [2]. The heat exchange between human body and environment during the human thermal regulation can be expressed with the following heat balance equation[3].

$$S = (M - W) - (E + C + R + B) \quad (1)$$

Here, heat storage (S) is the difference between heat production (metabolism (M) corrected for work (W)) and heat loss (evaporation (E), convection and conduction (C), radiation (R) and respiration (B)).

Many experiments have been conducted to understand the heat regulation process of the human body. Moreover, problems associated with clothing thermal comfort have been investigated, yet there is still a great comprehensive need for knowledge and research in order to resolve these problems. The use of thermal manikins or humans is normal practice in the investigation of thermal insulation through clothing and evaporative resistance [4–6]. The only advantage of using thermal manikins is the reproducibility with identical parameters and conditions; however, these tests are very expensive and time-consuming. The manikins have an average shape of a human body and are divided into different sections, which are equipped with heating sources as well as temperature and heat flux sensors. Modern thermal manikins can also sweat, walk, and even exhibit physiological responses similar to humans [7–9].

For the purpose of highly realistic investigations, subjective studies/tests involving humans can be conducted, which are however expensive and include ethical restrictions. In addition, suchlike tests can exhibit widely varying test results due to intra- and inter-subjective variations [10].

Some efforts have also been directed towards simulating the thermoregulation during the interaction of the human body or a cylinder (which has the same temperature as the surface of the human body) with the environment. The researchers have used computational fluid dynamics and investigated the thermal interaction of the nude human body in a naturally ventilated building [11], the heat transfer phenomena within the microclimate [12], and the effect of slits in garment on air flow and temperature distributions [13]. Within these research projects, the influence of different body shapes (body surface, volume), clothing design and fit have not been considered. 3D scanning techniques and an infrared thermal camera have also been used for investigating thermal insulation processes [14]; it has been reported that, if the microclimate is thicker than about 8 mm, internal convection will take place.

To avoid errors by simulation of thermal regulation of the human body, researchers have employed human thermo-physiological models with varying accuracies. There are a large number of human thermoregulation models that were developed based on the first model of 1948 [15]. A multi-node model by Fiala et al [16] is the best performing model among others [17]. This model comprises 15 idealized spherical or cylindrical body elements: head, face, neck, shoulders, arms, hands, thorax, abdomen, legs, and feet. In accordance with former studies, a division was therefore made whenever a significant change of body tissue properties occurred. As a result, the present multilayer model consists of annular concentric tissue layers and seven different tissue materials: brain, lung, bone, muscle, viscera, fat, and skin.

The main focus of this research project is to introduce a method for the application of simulation techniques, which can not only simulate the thermal regulation of the human body in terms of microclimate, clothing, and environment, but also consider the fit of the clothing influencing the ergonomic comfort of outdoor clothing. This simulation process offers an enormous potential to sectors involving outdoor, working, and protective clothing as well as sportswear.

## II. METHODS AND PROCEDURES

### A. Selection of Test Persons and 3D Scanning

Five test persons were selected for investigations and wear trials. These test persons were scanned by using the 3D-bodyscanner VITUS in two standing positions (standard and relaxed) as shown in fig. 2. The data were further used for determination of the body measurements according to the ISO 8559 and DIN EN ISO 7250. With the help of the software *Geomagic*, the data of all test persons were prepared according to the requirements for further simulations.

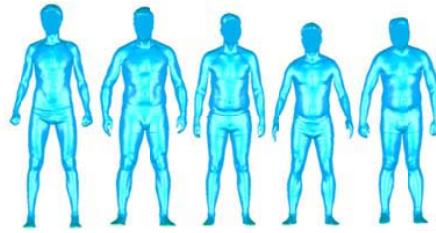


Fig. 2. 3D CAD data of all test persons (standard position).

### B. Selection of Material and Clothing

Four different types of fabrics T1 (material: PES, Fabric type: R/L Knit), T1H (material: PES, Fabric type: R/R Knit), T2 (material: PA6, fabric type: plain weave) and T3 (material: PES, Fabric type: fleece) were selected to construct a long sleeve shirt, long underpants, a trekking trousers and a jacket respectively. In the further process the physical, mechanical, and thermal characteristics of all the materials were tested (Table I).

Furthermore two different clothing systems for two environment conditions were defined. Clothing system-I for warm climate consists on long sleeve shirt and long trekking trousers. Clothing system-II for cool climate consists on long sleeve shirt, long underpants, trekking trousers, and jacket.

TABLE I  
PHYSICAL, THERMAL, AND MECHANICAL PROPERTIES OF FABRICS

| Properties |                                                                                    | Fabric |       |       |       |      |
|------------|------------------------------------------------------------------------------------|--------|-------|-------|-------|------|
|            |                                                                                    | T1     | T1H   | T2    | T3    |      |
| Physical   | Fabric thickness [mm]                                                              | 0,46   | 0,56  | 0,29  | 1,55  |      |
|            | Average mass per unit area of the fabrics [g m <sup>-2</sup> ]                     | 161    | 184   | 125   | 168   |      |
|            | Absolute water vapor permeability [Pam <sup>2</sup> W <sup>-1</sup> ]              | 2,82   | 3,14  | 4,42  | 6,41  |      |
|            | Air permeability [mm sec <sup>-1</sup> ]                                           | 1077   | 221   | 75    | 1057  |      |
| Thermal    | Thermal conductivity [10 <sup>-3</sup> W m <sup>-1</sup> K <sup>-1</sup> ]         | 46,24  | 55,10 | 36,58 | 42,18 |      |
|            | Thermal diffusivity coefficient [10 <sup>-6</sup> m <sup>2</sup> s <sup>-1</sup> ] | 0,23   | 0,092 | 0,25  | 0,25  |      |
|            | Thermal absorptivity [W m <sup>-2</sup> s <sup>1/2</sup> K <sup>-1</sup> ]         | 161,2  | 186,8 | 230,6 | 84,48 |      |
|            | Specific heat [Jkg <sup>-1</sup> K <sup>-1</sup> ]                                 | 493    | 1643  | 295   | 1640  |      |
|            | Thermal resistivity [10 <sup>-3</sup> K m <sup>2</sup> .W <sup>-1</sup> ]          | 8,50   | 8,62  | 7,00  | 39,38 |      |
| Mechanical | Bending stiffness [mN cm]                                                          | warp   | 0,12  | 0,21  | 0,32  | 0,29 |
|            |                                                                                    | weft   | 0,07  | 0,10  | 1,03  | 0,29 |
|            | Tensile stiffness (E=1%) [kPa]                                                     | warp   | 761   | 577   | 6445  | 646  |
|            |                                                                                    | weft   | 448   | 513   | 38766 | 289  |

### C. 2D Pattern Development

According to the defined clothing systems and the body measurements of five test persons, 2D patterns developed by using the 2D CAD software *Grafis*, as shown in fig. 3. *Grafis* is an user-friendly software that offer an easy opportunity to consider the individual body measurements during pattern making. Then, 2D pattern cuts were sewn together and made the clothing's ready for the wear trial. It was taken into account that the pattern pieces for the different test persons were produced in the same sequence and with the same sewing techniques to avoid design variations (fig. 4).

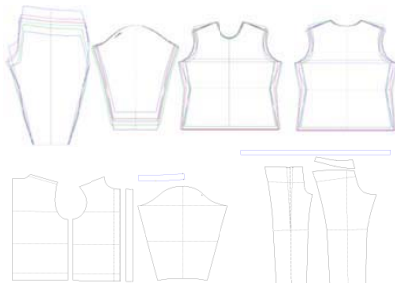


Fig. 3. 2D patterns for long underpants, long sleeve shirt, trekking trousers and jacket for test person 1



Fig. 4. Fit test of the clothing for the test person 1; Clothing system-I (left); Clothing system-II (middle + right)

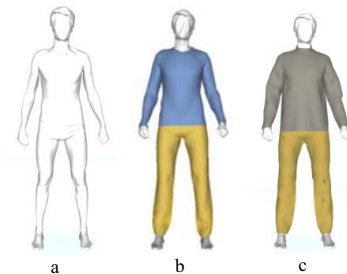


Fig. 5. 3D fit modeling of clothing's on test person 1. a) CAD model, b) Clothing system-I, c) Clothing system-II.

### D. 3D Fit Simulation of Clothings

The 3D fit simulation of clothings was completed by using the software *Modaris V8*, which gives the opportunity of a digital 3D visualization of garments by virtual sewing and also considering the mechanical properties of the textile materials. The developed 2D patterns (*Grafis*) were exported as an AAMA/DXF file and

then imported into *Modaris V8* for 3D fit simulation. After assigning the sewing information and the fabric properties (Table I), the pattern cuts were simulated on the virtual test person 1 (fig. 5). As a result an uneven space is observed between the body and the clothing's. The shape and the thickness of the space depend on the draping properties of the fabric. This space is quite important for the development of the microclimate.

#### E. Wear Trial

Wear trials were conducted to investigate the thermo-physiological response of the five selected test persons by the Hohenstein Institut für Textilinnovation GmbH. For this purpose each of the test persons has performed two trials in the selected climate; warm (23°C, 50% RH) and cool (15°C, 40% RH), in a climatic chamber. The test procedure, lasted for a total 125 minutes, was carried out by each test person on a motor driven treadmill (Kettler Track Experience, Ense-Parsit). The total duration of wear trial consisted on five phases of sitting and walking. In phase 1, 3 & 5, the test person must be seated for 15 min. Whereas in phase 2 and 4, test person walked on treadmill for 40 min with 4km/h and 6km/h respectively.

The skin temperature, the humidity of microclimate, and the wetness of the skin were recorded with help of sensors MSR 345 Datalogger (MSR Electronics GmbH, Seuzach, Switzerland). These sensors were attached on the body of the subjects at 10 different points according to ISO 9886 [18]. To calculate the temperature and humidity of the microclimate, the sensor was pointed towards microclimate and with a distance from the body. The calculation of the average skin temperature, the microclimate temperature and the microclimate humidity was performed according to the 8-point method from ISO 9886. A SpotOn system (3M Medica, Neuss, Germany) was used to measure the body core temperature. Furthermore the total amount of sweat that was produced by the subject, was calculated by weighing the nude subject before and after the wear trial. The amount of sweat that was entrapped by the clothing was calculated as the weight difference of the clothing before and after the trial. The clothing were always washed and conditioned for 24 hours before the next trial.

#### F. Thermal Simulation of Test Person and the Clothings

In first step of thermal simulation, there is a need of thermo-physiological virtual model of a human that. For this purpose, already developed CAD models (*Geomagic /Design Concept 3D*) of test persons were used (fig. 2).

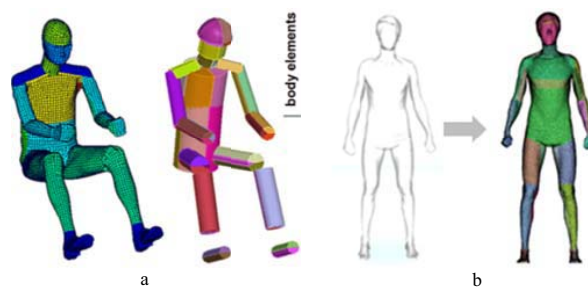


Fig. 6. a) Thermo-physiological model in Theseus-FE, left: surface model, right: body elements [19], b) Thermo-physiological model based on individual data of test person 1.

Subsequently, a thermo-physiological model was developed by means of the Fiala Model (developed at HFT Stuttgart and De Monfort University, UK [20]) and the framework for the software *Theseus FE*. For this purpose, a NASTRAN format of the body model was imported into Theseus FE, and each body part (body division was executed according to the Fiala Model) was assigned to the Fiala thermo-physiological properties. This generated human model (figure 6b), that is based on individual scan data, can now perform active and passive thermoregulation.

The 3D model of the jacket that already developed by 3D fit simulation, was imported into Theseus FE software also via NASTRAN interface. The thermal regulation of body-clothing-environment system is strongly affected by the thermal characteristics of the clothing and the microclimate. As, the microclimate is not uniform across the entire body, so different air zones had to be defined within the microclimate in terms of thickness and their location on the body.

Every air zone has different thickness and also associated with different part of body and jacket surface. Therefore heat transfer because of conduction or convection did not occur constantly across all the air zones. The heat transfer coefficient of each air zone was calculated using the following correlation [21].

$$h = \frac{(Nu_L K)}{L} \quad (2)$$

Here,  $h$  is heat transfer co-efficient,  $L$  is characteristic length (thickness of air zone),  $K$  is conductivity, and  $Nu_L$  is the Nusselt number (which is the function of Prandtl and Rayleigh number). The boundary conditions defined for the thermal simulations follow.

- 1) Thermal and physical properties, specific heat, conductivity, thickness, and mass per unit area were defined to the jacket surface and the air zone.
- 2) An environment was defined with air velocity of 0.3m/sec, which has a temperature of 15°C and 40% relative humidity.
- 3) Metabolic rates (Met) were assigned to the thermal manikin according to the three different levels of activity in the wear trials (Table III), which were calculated against the weight of test person 1.
- 4) The boundary conditions to realize heat transfer between outer surface of jacket & external environment, inner surface of jacket & relevant air zone, and air zone & relevant body segment/surface were defined as linear convection.
- 5) Heat flux due to long wave radiation was considered by defining the view factor cavity. For this purpose, radiation properties were defined to the jacket shell and human model.

### III. RESULTS AND DISCUSSION

#### A. Thermal Simulation

The simulation was run for 7500 seconds (125 min) and following (fig. 7) results were obtained.

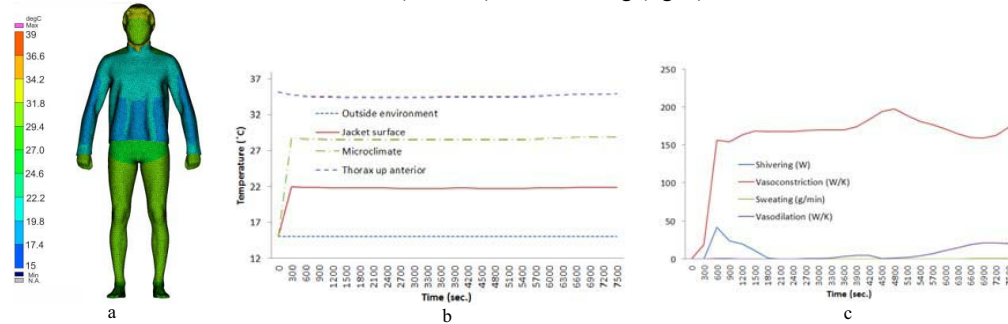


Fig. 7. a) Surface temperature of body and jacket during thermal simulation at time steps 900s, b) Temperature behavior of surface at thorax up anterior during the simulation, c) Response of active system of human model during simulation.

It can be noticed (fig. 7b) that with the start of simulation, the temperatures of jacket surface and microclimate increase to 22°C and 28°C respectively, then maintain almost constant temperature line throughout the simulation. This is because of the influence of two constant temperatures; the body surface temperature (35-36 °C) at thorax up anterior and the outside temperature (15°C). As, microclimate is closer to the body as compare to the jacket surface, therefore it has higher temperature than the jacket surface temperature. Moreover, the trend of the graph shows that jacket surface and microclimate work like an insulator to preserve the body heat. Although, the metabolic rate of test person increases during the wear trial (Table III), the body skin temperature (thorax up anterior) is remain in rang of 34.5-35.5 °C, because of the active system of human body that maintain the core body temperature at 37°C. The active system consists of four processes; shivering, vasoconstriction, sweating, and vasodilation. Shivering and vasoconstriction is activated in the cool environment, but sweating and vasodilation are activated when body feels too warm. The fig. 7c indicates the function of active system during simulation. In phase 1 (sitting, 0 – 900 sec) of wear trial, the metabolic rate of test person is 1 Met. Therefore the body heat is transferred to the microclimate (heat transfer from high to low temperature). Hence, the vasoconstriction and the shivering are activated with the start of simulation to preserve or to produce the body heat. The shivering starts to decrease with the start of phase 2 (900 – 3300 sec; walking with 4km/h) and meets to horizontal line. In this phase, the vasoconstriction stops to increase and maintains constant throughout the phase. This is because of the increasing of the metabolic rate of the test person during walking (3.2 Met). It can also be observed from the fig. 7c, that at the end of phase 2 (3300 sec), the vasodilation activates but soon ended with the end of phase 3 (4200 sec). As, in this phase, metabolic rate is 1 Met, therefore vasoconstriction is further increase so that body heat can be preserved. With the start of phase 4 (4200 – 6600 sec), vasoconstriction decreases and vasodilation starts to release the heat from the body, which is produced due metabolic rate of 4 Met (walking at 6km/h). In phase 5 of wear trial, the metabolic rate is 1 Met, therefore once again the vasoconstriction starts to increase and vasodilation starts to decrease so that body heat can be preserved.

### B. Validation

To validate the simulation results, the wear trials were conducted. At present, the results are still on evaluating stage, so that they cannot yet be presented. A comprehensive report we will published at the end of this project.

### IV. CONCLUSION

This paper presented the simulation of heat regulation between human body, microclimate, clothing and environment. The transportation of heat in the microclimate is a complex phenomenon. The mass flow within the microclimate mainly depends on the surrounding environment temperature, the specific body parts, and the properties of the clothing a person wears. In the past, all thermal simulations involving the human body, its microclimate, clothing, and the environment have been performed based on the assumption that the microclimate is a uniform layer of air underneath the clothing. In reality, the thickness of the microclimate is not consistent all over the body, but it varies and depends on numerous factors, especially the draping properties of the fabric and the shape of the body. To simulate the actual scenario, a fit simulation of the jacket on an individual scanned model was performed by giving the deformation properties of fabric, and the microclimate was subsequently divided into many small air zones according to thickness and location. Moreover, to realize the scanned model as actual human model, it was coupled with the Fiala model.

In order to validate the simulation results, the wear trials of five test persons already conducted by the Hohenstein Institut für Textilinnovation GmbH. The validation will be presented soon in separate research paper.

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