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A lining for the Thermal Comfort of Trekking Boots – Experimental and Numerical Studies

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ABSTRACT

In this paper, a study on the design and development of functional shoe linings that are thermally comfortable is presented. The comfort of foot wear, in this case, trekking boots, that is perceived by the user greatly depends on the ability of the boot to maintain the foot surface in an equilibrium state in terms of thermo-physiological comfort (Schols et al., 2004). This is related to the capacity of removing the moisture that results from transpiration away from the foot surface. With these premises in mind, a study on the development of new lining constructions using different raw materials has been conducted.

As far as methodology is concerned, this study involves two different stages. The first stage includes an objective evaluation of the thermal comfort of the boots. This stage involves several tasks, including the conception and development of the fabrics to be used in the inner layer of the boots and the development of a thermo-physiological model of the human foot, in order to simulate the temperature and moisture behavior in the developed fabrics. The second stage consists of a subjective evaluation of thermal comfort using prototypes of the developed boots. A subjective evaluation assessment was done through a questionnaire, in which the study subjects are able to indicate where they experience thermal discomfort in the foot, as well as a laboratory physical task used to simulate the “real” use of the boots.

Keywords: Thermal Comfort, Subjective Evaluation, Material Design, Functional Textiles

1. Introduction

Shoe comfort is easily perceived by people. However, understanding the way people develop their comfort perception is a very complex task. This complexity is mainly due to the fact that their perception is based on several parameters, such as the pressure on the foot, vertical impact and shock absorption, foot shape, foot sensibility and interior shoe climate (Schols et al., 2004; Havenith & Heus, 2004; Au & Goonetilleke, 2007).

Thermal comfort perception is related to heat and moisture transport properties, as well as the ability of the materials to maintain human thermal balance in a state of equilibrium. For a significant number of individuals, one of the most important aspects of comfort is related to the issue of

transpiration during long periods of time. If sweat is not transferred from the skin to the surrounding air, or to the external shoe layers, the resulting sensation is interpreted as discomfort.

Various studies have shown that feet are one of the most sensitive parts of the human body when referring to body comfort. The feet are consistently cooler than other parts and their protection and comfort become an important aspect in terms of human comfort.

The study of shoe thermal comfort is of great importance to sport and leisure footwear manufacturers, because in these applications, moisture disposal over a number of hours is the main issue.

Shoe comfort has been the focus of many studies, but what concerns shoe design are the inner

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fabrics used as linings which play an important role because they have a significant effect on the sensation of wetness, and thus on the overall comfort of the shoe (Au & Goonetilleke, 2007)

When muscular activity ceases, the interior of the shoe starts to cool down very rapidly, particularly in the wetter areas, thus leading to a cold sensation in the affected foot area. Both states of sweating or coldness can be perceived as discomfort conditions

The design and development of shoe linings aim to contribute to the reduction of heat exchanges with the environment and at taking away the moisture produced by sweating. This can only be achieved through the combination of materials and fabric structure.

Simultaneously, the design of a functional double knit will, hopefully, address the problems of moisture transport and maintenance of optimum feet temperature. This knit performance will be achieved through the knit structure design in combination with the used materials

2. Methodology

As far as methodology is concerned, this study has involved two different stages. The first stage includes the design and development of fabrics to be used in the inner layer of the boots and an objective evaluation in terms of their thermal comfort.

To complement the methodology, some numerical work took place. Starting from an existing thermal-physiological human model which includes only temperature distributions, a few steps were taken in order to incorporate mass transfer phenomena.

The second stage consisted of an ergonomic evaluation of the thermal comfort using prototypes of the developed boots.

2.1 Design and Development of the Fabrics

For the design and development of the fabrics, research on raw materials was performed in order to identify fibers that could better respond to the previously mentioned needs of a trekking boot

Then, a study was conducted on double knit structures that would enable the desired outcome to take place. Finally, the materials developed were subjected to laboratory tests in order to evaluate their performance in terms of heat and moisture transfer/transport properties, air permeability, surface properties, and thermal insulation.

The air permeability of the samples was evaluated using an air permeability tester, TEXTEST FX3300, in accordance with standard EN ISO 9237 (ISO, 1995) at a pressure of 100 Pa.

The water vapour permeability tests were performed in a PERMETEST apparatus.

The mentioned PERMETEST instrument enables the determination of relative water vapour permeability, wvp (%), and evaporation resistance, Ret (m^2Pa/W), of dry and wet fabrics within 3-5 minutes

The measuring head of this small skin model was covered by a water resistant semi-permeable foil, which avoids liquid water transport from the measuring system into the sample. The cooling heat flow caused by water evaporation from the thin porous layer was quickly recorded by a special computer evaluated sensing system. The instrument provides all kinds of measurements similar to the ISO Standard 11092 (ISO, 1993), with very good measurement reproducibility (CV often under 3%). The correlation coefficient of measurements related to the ISO Standard skin model exceeds 0.9. The results were statistically treated, displayed and recorded for the next use (Hes & Dolezal, 2006).

We also measured the mass of absorbed water by the different knits (horizontal and vertical wicking) using an in-plane wicking tester developed at the Indian Institute of Technology, Delhi (IITD), India (Brojeswari et al., 2006).

The total thermal insulation was determined with a thermal manikin according to the standard procedure ISO 15831 (ISO, 2004) using the serial model. This manikin was dressed with a two-piece jogging suit, and socks produced with the knits under study were tested. All tests were conducted in the steady state.

2.2 Development of a Thermo-Physiological Model

To develop the human thermal comfort model, some steps were taken in order to incorporate heat and mass transfer mechanisms between the human body and the environment through clothing.

Published models of simultaneous heat and mass transfer in fabric were reviewed in order to identify and select the most appropriate assumptions

Some simplifications have been made to the Gibson and Carmachi model (Gibson & Chamarchi, 1997)

The code was implemented with Fortran.

Different boundary conditions were tested and the model sensitivity on the physical properties was studied

Based on previous work (Teixeira et al., 2005), a thermoregulatory model of the human body was coupled with the fabric model. The model allowed transient heat transfer across the body, as well as sweat production and mass transfer to the air and fabric. In this way, the boundary conditions on temperature and water vapour density for the fabric model were calculated at each time step

2.3 Objective / Subjective Evaluation of Prototypes

The development of a product should take into consideration both the physical properties of the materials to be used, and the perception of users, i.e., their psychological assessment of the materials properties. However, the relationship between the physical properties of the fabrics and the subjective assessment, or the psychological sensory responses, is not straightforward (Li, 1994; Au et al., 2002).

To assess the objective and subjective data with regards to the thermal (dis)comfort in the use of the prototypes of the developed boots, a study sample composed of 33 subjects was used. The sample had a mean age of 28.9 (± 8.5) yrs, mean weight of 64.8 (± 9.6) kg, an average height of 170.2 (± 6.5) centimeters, and a foot size mean of 25.2 (± 1.3) centimeters.

The subjective evaluation assessment was done through a laboratory controlled physical task used to simulate the "real" use of the boots. In this physical task, all subjects are requested to walk on a treadmill located in a room with controlled temperature, for 10 min at a speed of 130 cm/s, which is equivalent to a metabolic rate of 150 W/m² activity, according to ISO 8996 (ISO, 2004). This speed is used because subjects are not to undergo very strenuous activity from the viewpoint of feet use, but active enough to detect increases in hypothetical temperature and moisture.

For the implemented tests, some equipment was used, namely:

- 10 pairs of boots (within the foot size range of the subjects) produced with 2 types of inner layers for testing, together with the use of 100% cotton socks;
- a precision balance from Mettler Instruments AG Type AE 200-S, which allows the weight of the socks to be defined before and after walking, and consequently, the accumulated humidity;
- a mechanical treadmill from ProMaster, which allows simulation of "real" walking; and
- a Bruel & Kjaer Type 1213 indoor climate analyser, which allows temperature measurement on the surface of the foot skin in 2 locations, the metatarsal/toes and foot plantar areas.

3. Results and Discussion

3.1 Thermal Comfort Tests with the Developed Knits

A double faced weft knit structure was designed with a focus on foot moisture transport and temperature maintenance problems, as well as the possibility of avoiding the formation of microorganisms/fungus on the foot and in the lining material. The performance of the weft knit will be achieved through the structure and raw materials used in its production (Brojeswari et al., 2006).

Research on materials was performed which aimed to identify fibres that could be used in this project. The guideline for this research is to select materials that would enable the combination of the following properties: humidity transport, anti bacteria resistance, hypo allergic ability and low thermal conduction. Two different sets of fibres were selected, according to their moisture absorbing properties.

For the first set, in addition to hydrophilic fibres, the decision was to use soybean (soybean protein fibre – SPF), corn (polylactic-acid – PLA), bamboo (BAM) and cotton fibres (CO). One of the reasons for choosing soybean, corn and bamboo is the novelty of these fibres and the fact that they are known to have good comfort properties besides being hydrophilic fibres.

Another reason is related to environmental considerations. In an era where environmental considerations are on everyone's agenda, this must also be kept in mind when developing and researching for new solutions. Thus, since SPF, PLA and BAM are biodegradable fibres, they have minor environmental impacts. Cotton is also included due to its good moisture absorbing property, cost effectiveness and also for being a natural material (Farrington et al., 2005; Brooks, 2005).

For the second set, in addition to hydrophobic fibres, the decision was to use polypropylene (PP) and polyester (PES).

As for the particular characteristics of each material selected, SPF fibres are known to have good handle, moisture absorbing and antibacterial properties, present good ventilation properties as well as draping and warmth superior to other high quality fibres (Harvest SPF Textile Co., Ltd; SWICOFIL AG Textile Services), which are the main concerns in the present design concept.

Polylactic-acid (PLA) presents some advantages, such as a cotton appearance, and environmental friendliness as it is based on a natural polymer and therefore, biodegradable. When mixed with other fibres, PLA also presents a good performance; specifically, a natural fibre hand, wickability / breathability of natural fibres, and excellent drapeability (Ingeo™ Fibres).

Finally, the main advantages of BAM include: ecologically and environmentally friendliness, good anti-bacterial properties, good moisture absorption and desorption properties (thus good breathability, good penetrability and coolness), and a soft handle (Harvest SPF Textile Co.).

Table 1 shows the raw materials, their technical designations, and the yarn density of the yarns used in the knits production.

Table 1. Raw Material

Raw Material		Yarn Density tex
100% Cotton	CO	19.6
100% Corn	PLA	19.6
100% Soybean	SPF	19.6
100% Bamboo	BAM	19.6
100% Polypropylene	PP	20.0
85% Polyester, 15% Cotton	PES/CO	19.6

For the design and development of the functional linings, a set of 3 different double faced weft knit structures was designed (Fig 1), in eight different raw material combinations, which led to the production and testing of 24 different knits. The double faced structures were developed in such a way as to place hydrophobic fibre on one face and hydrophilic fibre on the other face. The hydrophobic fibre faces towards the feet. Thus, moisture will not be absorbed by this layer, but will be conducted to the external side, which is formed by the hydrophilic layer.

Structure 1 Structure 2 Structure 3
Fig 1 Weft knit structures

The knits were all produced on the same knitting machine and with the hydrophilic/hydrophobic fibres combinations that are presented in Table 2. The parameters which refer to each of the 24 samples produced are also presented.

Table 2. Knit Characteristics of Structures 1, 2 and 3

	Raw Material	Tightness Factor	Mass g/m ²	Thickness mm
1	PLA/PP	11.901	199.8	1.68
	PLA/PES	11.939	182.6	1.53
	SPF/PP	12.227	199.3	1.39
	SPF/PES	12.043	180.3	1.20
	BAM/PP	13.560	252.5	1.53
	BAM/PES	12.657	190.2	1.22
	CO/PP	13.390	245.4	1.64
	CO/PES	12.718	190.7	1.62
2	PLA/PP	11.949	272.2	1.77
	PLA/PES	11.957	259.9	1.68
	SPF/PP	12.569	281.9	1.27
	SPF/PES	12.300	263.7	1.23
	BAM/PP	12.314	300.3	1.43
	BAM/PES	12.138	256.7	1.22
	CO/PP	12.222	274.9	1.50
	CO/PES	12.175	267.8	1.44
3	PLA/PP	12.071	232.8	1.65
	PLA/PES	11.855	219.7	1.61
	SPF/PP	12.855	258.1	1.31
	SPF/PES	12.624	237.6	1.25
	BAM/PP	12.471	242.8	1.45
	BAM/PES	12.043	218.2	1.18
	CO/PP	12.285	224.6	1.44
	CO/PES	12.078	223.6	1.40

From the test results for air permeability presented in Figure 2, it can be seen that the knits produced with Structure 1 (Fig. 1) present higher values of air permeability, and the PLA/PES combination provides the best results in each structure group

Fig. 2. Air permeability

The water vapour permeability of material is an important property for the maintenance of thermal equilibrium for the user. If this parameter is high, then water vapour is eliminated, and it does not change into a liquid phase which would lead to discomfort.

When the measurement results should be expressed in terms of water vapour resistance Ret ($m^2 Pa/W$) according to the ISO 11092 Standard (ISO, 1993), then the following relationship is applied:

$$Ret = (p_{wsat} - p_{w0}) \left(\frac{1}{q_0} - \frac{1}{q_s} \right) \quad (1)$$

Here, q_0 and q_s (W/m^2) mean heat losses of the moist measuring head in the free state and covered by a sample. The variables p_{wsat} and p_{w0} (Pa) represent the water vapour saturation partial pressure that is valid for the air temperature in the measuring laboratory (22-25°C) and the partial water vapour pressure in the laboratory air, respectively. The constant C will be determined by the calibration procedure. Special hydrophobic PP reference fabric for this purpose was delivered with the instrument.

The relative water vapour permeability of the textile sample, wvp , can also be determined by the instrument. This practical parameter is given by Equation (2):

$$wvp = 100 \frac{q_s}{q_0} \quad (2)$$

The measured values for the relative water vapour permeability are presented in Figure 3. The samples produced in Structure 1 and combinations PLA/PES, SPF/PES and BAM/PES present better/higher water vapour permeability.

Fig 3 Water vapour permeability (see legend in Fig. 2)

The wicking property reflects the ability of the material to absorb water, and thus it is related to the ability to remove sweat away from the skin surface. Figure 4 presents the results obtained for the different combinations of double knit Structure 1 on the horizontal position.

Fig. 4. Results of horizontal wicking of Structure 1

As seen by the results, the PLA/PES knit is the combination that better removes the water. The vertical wicking, measured in the wales direction, is shown in Figure 5, where the knits produced with PLA fibers also present the best performance, followed by the BAM/PP knit.

Fig. 5 Results of vertical wicking of Structure 1

Thermal insulation is another property to consider when thermo physiological comfort is studied. If this parameter is high, it means a more difficult heat exchange to the external part of the lining

Figure 6 shows that there is no significant difference between the three knit structures in terms of thermal insulation

Fig 6. Thermal insulation (see legend in Fig. 2)

When only the results obtained for Structure 1 are considered, the PLA/PP and the PLA/PES knits present higher values in thermal insulation while the BAM/PP and BAM/PES knits present the lowest values

After assessing the thermal properties of the 3 knit structures developed at the beginning of the project, it was concluded that Structure 1 (Fig. 1) is a better fit for use as a lining towards the desired end use

From the tested materials (in terms of composition), it was concluded that the combination PLA/PES presents itself as the most suitable for a cold environment, considering its thermal insulation (Fig. 6), while the BAM/PP combination is the most fitting for a warm environment, since in contrast, it presents a low thermal insulation value as well as good capillarity (Figs. 4 and 5)

3.2 Numerical Results of the Thermo-Physiological Model

Mathematical modelling of knits has been reported in the literature (Fan et al., 2000; Chang et al., 2000; Ghaddar, et al., 2003).

These models are a valuable tool to understanding the complex mechanisms of coupled heat and moisture transfer.

In order to simulate the transient behaviour of simultaneous heat and moisture transfer in the boot lining, a simplified version of the Gibson and Carmachi (1997) model has been implemented and described in the present work. The model includes several effects, such as transient heat and mass diffusion through knit thickness and also, the sorption phenomena. One of the governing equations is the energy equation, Equation (3):

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(k_{eff} \frac{\partial T}{\partial x} \right) - (Q_L + \Delta h_{vap}) \dot{m}_{sv} \quad (3)$$

which includes, on the left side, the transient term, and on the right hand side, the diffusion and sorption terms.

The energy equation is coupled with the gas phase

diffusion equation, Equation (4), which models the phenomena associated with the water vapour component:

$$\varepsilon_v \frac{\partial}{\partial t} (\rho_v) = \frac{\partial}{\partial x} \left(D_{eff} \frac{\partial \rho_v}{\partial x} \right) + \dot{m}_v \quad (4)$$

The transient term appears on the left hand side of Equation (4) and the first term on the right hand side describes the diffusion transfer (D_{eff} is the effective gas phase diffusivity) and the second term accounts for the mass rate of desorption from a solid to a vapour phase. Apart from the gas phase (air and water vapour), the dry solid fibre and the water bounded in the solid phase occupy the remaining part of this volume. Consequently, ρ (density), c_p (heat capacity) and k_{eff} (effective thermal conductivity) are average properties depending on the volume fraction of each component (air, water, vapour and fibre) and they have to be updated at each time step.

The two partial differential equations, Equations (3) and (4), constitute a system of parabolic equations which is solved in time and space to obtain the temperature and water vapour concentration profiles in the knit thickness and along time. The initial and the boundary conditions at both fabric surfaces, for temperature and vapour concentration, are also given. Heat convection to the environment and mass transfer are considered in the knit simulation.

Numerical methods have been used to integrate the system of parabolic equations. The finite volume method (Versteeg & Malalasekera, 1995) has been used for space integration and an implicit scheme was used in time integration.

More details on the mathematical model, algorithm and numerical solution can be found in Correia (1995).

Knits which are made from various natural fibres were tested with the numerical model, and as an example, two different types of fibres can be compared in terms of water retention: a natural hydrophilic fibre (cotton) and a hydrophobic fibre (polyester) (Fig. 7).

Fig 7. Numerical temperature profile across knitting thickness after 10 s

The dry fabrics with an initial temperature of 20°C were placed into contact with a relative humidity of 100% and at an ambient temperature of 20°C. With this test, the temperature change due to the water vapour entrance into the fibres can be observed. Since polyester fibre is hydrophobic, the temperature rise due to the sorption mechanism is smaller.

The amount of water dissolved in the fabric fibres, along time ($\rho_v d\varepsilon_{bw}/dt = -\dot{m}_{sv}$), can also be calculated. The water vapour entrance will continue until equilibrium regain is achieved (Fig. 8).

Fig 8. Volume fraction of water at the centre point of the cotton knitting.

Boundary conditions that are more suitable to the knitting application were tested: on one side, the knitting was usually in contact with human body skin (at 32°C and with some moisture) and on the other side, convection to the environment (an atmosphere of 20° C and a relative humidity of 65%).

The asymmetry of the boundary conditions is well predicted by the numerical model, as shown in Fig. 9, which presents the temperature profile for the three knit structures after a 10 s period

Fig 9. Effect of the boundary conditions on the numerical temperature profile for different fibres after 10 s.

A non-uniform temperature change along the fabric thickness, due to water entrance into the dry fibres, can be observed. Such imbalance yields non symmetry in the water vapour concentration profile (Fig. 10), after a 10 s period.

Some modifications are now being implemented in order to simulate the double knit structure of the produced fabrics.

Fig 10. Water vapour concentration profile across cotton knitting thickness after 10 s

In order to obtain a 'real' boundary condition on the skin, the fabric model was coupled with a human body thermal model which describes the heat transfer across the foot.

It is a one dimensional model which accounts for the conduction and metabolic heat generation, see Equation (5).

$$\rho_B c_{pB} \frac{\partial T}{\partial t} = k_B \left(\frac{\partial^2 T}{\partial x^2} \right) + q_m \quad (5)$$

As an example, in Fig 11, the temperature profiles across the foot (until 0.056 mm), air layer and fabric (the last four points on the right side of the

figure) are presented for three different times: 0 01s, 1 s and 1000 s

After a very short time (1 s), the temperature fabric increases from its initial value (20°C) and at steady state, the external part of the foot is cooler and the fabric is almost body temperature.

Fig 11. Temperature profile in foot, air and knit

In order to simulate the presence of the boots, a new layer was added to the model. The boot material will make it difficult for energy and mass exchange to the environment.

3.3 Temperature and Moisture Accumulation Measurements of Subjective Tests

In terms of the evaluation of the prototype boots, some main variables were considered for statistical purposes, namely:

- temperature increase (in metatarsal and foot plantar areas), computed by the differences between the initial and final temperatures of the skin surface of each foot;
- moisture retention, measured by the obtained differences between the weight of the socks before and after the physical task; and
- identification of the foot areas with discomfort related to both temperature increase and moisture accumulation, obtained through the number of related indications on the questionnaire.

Foot Skin Surface Temperature

An analysis of the foot temperature was carried out by measuring the skin surface temperature of each foot before and after the physical task. The mean values obtained for the 2 types of inner

layers and foot zones are presented and compared in Figs 12 and 13.

Fig 12. Mean temperature increase in the metatarsal/toes zone

Fig 13. Mean temperature increase in the plantar zone

Using the Wilcoxon test (non-parametrical test, related samples), the obtained p value of the test for the metatarsal zone is 0 401 ($p > 0 05$), and thus it can be concluded that there is no statistical significant differences between the temperature

increase in this area for the two types of tested boots.

In the plantar zone, the p value is also higher than 0.05 ($p=0.779$; $z=-0.281$), thus there is no statistical significant difference between the increase in the two temperatures in the plantar zone.

Moisture Accumulation

To test the differences between the two selected materials, the accumulation of moisture in the boots with BAM/PP and PLA/PES inner layers was measured. The mean values obtained for both combinations are presented in Fig 14.

The results of the Wilcoxon test for the differences between the means of the moisture accumulation ($z=-4.280$; $p<0.001$) show a significant value of $p<0.05$, which means that the equal means of the difference hypothesis should be rejected. Therefore, it can be concluded that the moisture accumulation in boots with BAM/PP is higher than the moisture accumulation with PLA/PES and is statistically significant.

Fig 14. Mean value (in grams) of the moisture accumulation in both types of tested boots

Foot Zones with Higher Thermal Discomfort

As pointed out by some authors, such as Au and Goonetilleke (2007), a comfortable shoe does not necessarily have the same perceived fit in every region. Therefore, it is also important to evaluate comfort in different foot regions or zones.

In a more detailed analysis of thermal discomfort, subjects were asked to indicate where they felt/perceived an evident increase of heat, after performing the requested task.

Figs.15 and 16 present the obtained results of the total number of indications for each type of tested lining and foot zone. It is possible to verify that there is a predominance of discomfort indications with regards to the use of PLA/PES. It is mainly in the mid-part of the foot where subjects seem to perceive a more evident thermal discomfort related to the temperature increase. It is also in the mid-foot zone where subjects seem to differentiate more between the two types of fabrics that were tested.

Fig 15. Number of indications of thermal discomfort by different foot zones with regards to temperature increase

Fig 16. Number of indications of thermal discomfort by different foot zones with regards to moisture accumulation

4. Conclusions

This project has aimed to develop linings for the thermal comfort of shoes. The main functions intended for the materials developed are the ability to take away moisture from the foot skin that results from transpiration, and the maintenance of optimum feet temperature.

The final results obtained for moisture accumulation in the boots, as well as for the temperature of the foot skin surface, seem to be consistent with the conclusions relatively obtained in stage 1 to the water vapour permeability, wickability and thermal insulation of the selected lining materials.

The numerical model implemented seems to correctly simulate the main mechanisms of heat and mass transfer that occur through the fabric as well as on the foot. Further work has to be undertaken in order to simulate double faced knits. The results obtained in the subjective evaluation of comfort in different foot zones also tend to support the conclusions drawn in the first stage of the study.

BAM/PP seems to be the combination with the least amount of reported discomfort and this result is, most likely, related to its low thermal insulation, as well as good capillarity.

Finally, it seems that the identification of thermal discomfort on specific foot zones will allow shoes

to be planned and constructed with such differences taken into consideration, and thus with differentiated areas and using inner fabrics with differentiated thermal behavior.

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REFERENCES

- [1] Au, E.Y. & Goonetilleke, R.S. 2007, 'A qualitative study on the comfort and fit of ladies' dress shoes', *Applied Ergonomics*, vol. 38, pp. 687-696.
- [2] Au, K.F., Chan C.N.Y. & Ho, Y.M.H., 2002, 'An assessment of softness property of knitted golf fabrics', *Research Journal of Textile and Apparel*, vol. 6, no. 2, pp. 37-49.
- [3] Brojeswari D., Das, A., Kothari, V.K., Figueiro, R. & Araujo, M. 2006, 'Effect of Fibre Parameters on Liquid Moisture Transmission Through Fabrics', *Aplimatec '06 Congress, Valencia*, pp. 23-25.
- [4] Brooks, M.M. 2005, 'Biodegradable and sustainable fibres', in R.S. Blackburn (ed.), *Soya bean protein fibres – past, present and future*, Cap. 13, Woodhead Publishing Limited in association with The Textile Institute, U.K.
- [5] Chang, W. & Weng, C. 2000, 'An analytical solution to coupled heat and moisture diffusion transfer in porous materials', *International Journal of Heat and Mass Transfer*, vol. 43, pp. 3621-3632.
- [6] Correia E.L. 1995, 'Modelo Térmico Aplicado à Caracterização do Conforto Proporcionado pelo Vestuário', MSc Thesis, University of Minho, Guimarães, Portugal (in portuguese).
- [7] Fan, J., Luo, Z. & Li, Y. 2000, 'Heat and moisture transfer with sorption and condensation in porous clothing assemblies and numerical simulation', *International Journal of Heat and Mass Transfer*, vol. 43, pp. 2989-3000.
- [8] Farrington, D.W., Lunt, J., Davies, S. & Blackburn, R.S. 2005, 'Biodegradable and sustainable fibres', in R.S. Blackburn (ed.), *Poly(lactic acid) fibers*, Cap. 6, Woodhead.

- Publishing Limited in association with The Textile Institute, U.K
- [9] Ghaddar, N., Ghali, K. & Jones, B. 2003, 'Integrated human-clothing system model for estimating the effect of walking on clothing insulation', *International Journal Thermal Sciences*, vol. 42, pp. 605-619
- [10] Gibson, P.W. & Chamarchi, M. 1997 'Modelling Convection/Diffusion Processes in Porous Textiles with Inclusion of Humidity-Dependent Air Permeability', *Int Comm. Heat Mass Transfer*, vol. 24, no. 5, pp 709-724.
- [11] [11] Harvest SPF TextileCo., Ltd., accessed in March 2008, <<http://www.spftex.com>>.
- [12] Havenith, G. & Heus, R. 2004, 'A test battery related to ergonomics of protective clothing', *Applied Ergonomics*, vol. 35, pp. 3-20.
- [13] Hes, L., Dolezal I. & Hesova L. 2006, 'Simulated objective evaluation of warm-cool feeling of baby diapers', *Proceedings of the International Fiber Conference (IFC)*, Seoul
- [14] Ingeo™ Fibres, accessed in March 2008, <<http://www.ingeofibres.com>>.
- [15] International Organization for Standardization 1993, *Textiles - Determination of physiological properties - Measurement of thermal and water vapour resistance under steady-state conditions (sweating guarded-hotplate test, ISO 11092:1993*, International Organization for Standardization, Geneva, Switzerland
- [16] International Organization for Standardization 1995, *Textiles Determination of the permeability of fabrics to air, ISO 9237:1995*, International Organization for Standardization, Geneva, Switzerland.
- [17] International Organization for Standardization 2004, *Ergonomics of the thermal environment - Determination of metabolic rate, ISO 8996:2004*, International Organization for Standardization, Geneva, Switzerland.
- [18] International Organization for Standardization 2004, *Clothing - Physiological effects - Measurement of thermal insulation by means of a thermal manikin, ISO 15831:2004*, International Organization for Standardization, Geneva, Switzerland.
- [19] Li, Y. 1997, 'Sensory Comfort: Fabric Transport Properties and Subjective Responses During Exercise Under Cool and Hot Environmental Conditions', *Research Journal of Textile and Apparel*, vol. 1, no. 1, pp. 84-93
- [20] Schols, E.H.M., Van Den Eijnde, W.A. & Heus, R. 2004, 'A method for assessing thermal comfort of shoes using a "sweating" foot', *Journal European J of Applied Physiology*, vol. 92, no. 6, pp- 706-709.
- [21] Teixeira, S.F.C.F., Ferreira, M.L., Costa, L.G. 2005, 'A Computer Interface for Human Comfort Calculations', *Proceedings of IMC22*, Irlanda, pp 131-137.
- [22] SWICOFIL AG Textile Services, accessed in March 2008, <<http://www.swicofil.com/soybeanproteinfibre.html>>.
- [23] Versteeg, H.K. & Malalasekera, W.1995, *An Introduction to Computational Fluid Dynamics, the Finite Volume Method*, Longman Scientific & Technical, U.K.
- [24] Weder, M. 2004, 'Physiological Properties of Sportswear', *Proceedings of International Textile Congress*, UPC, Spain, pp. 266-274.