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Numerical Study of the Effect of a Natural Convective Boundary Layer around the Human Body on the Transfer of Heat through a Textile Structure

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Abstract
Heat losses from the human body occur through a barrier of one or more textile layers with particular permeability, thermal insulation, water absorption abilities, etc. The convective boundary layer (CBL) around the clothed body is disturbed during body movement, and the air layer between the body and the textile layer(s) is broken up, thus changing the heat transfer through the textile layer and its insulation abilities. The purpose of the present study was to evaluate the effect of the convective boundary layer around the human body on the heat transfer through a textile layer by numerical simulation, using Computational Fluid Dynamics and a commercial CFD software package, by means of the Finite Volume Method. A new approach for modeling a textile surface was applied based on the theory of jet systems. The results of the study indicated that heat transfer trough the textile barrier is strongly influenced by the speed of the convective layer around the human body and the textile layer placed in between the body and the environment.

Key words: *convective boundary layer, computational fluid dynamics, convective heat transfer, textiles, human body.*

Introduction

In an indoor environment, convective heat transfer from the human body to the surrounding air occurs mainly by natural convection, depending on the gradient between the temperature of the environment and that of the body's surface (in the case of a necked body or uncovered parts of the body) or clothing surface. The convective boundary layer (CBL) surrounds the whole body and interacts with both the skin (or the outer clothing layer) and environment. Cooney [1] estimated that the heat losses from the human body are due to radiation (60%), evaporation (25%), convection (12%) and conduction (3%). Later on Murakami et al. [2] assessed the proportions of heat transfer modes as radiation (38.1%), convection (29%), evaporation (24.2%) and respiration (8.7%). Obviously these figures vary significantly with the activity and environmental conditions.

Actually CBL in an indoor environment depends not only on the temperature gradient between the body and surrounding air, but also on the room air flow, activity, clothing insulation, body posture, etc. Natural convection flow around the human head, which forms a thermal plume above the head, was studied in [3]. It was found that the flow speed of the plume was over 0.3 m/s, being 0.15 – 0.20 m thick. The study did not establish a difference between the CBL for standing and sitting postures, but reported that the flow speed in the case of a lying person was 0.05 m/s, with a maximum thickness of the CBL of 0.01 m.

In general, heat losses from the human body occur through a barrier of one or more textile layers, with particular performance properties: permeability, thermal insulation, water absorption abilities, etc. The well known pumping effect of clothing is related not only to the breaking up of the air layer between the body and inner textile layer or between the textile layers in the clothing ensemble, but also to the disturbance of the convective boundary layer around the clothed body. The thinner the CBL, the higher the heat losses from the body, because of the steep temperature gradient [3]. On the other hand a thicker CBL helps the temperature drop from the clothing surface to the surroundings in a horizontal plane, thus decreasing the heat losses.

Several studies concerned the ability of textiles to serve as a protective barrier between the body and environment. The influence of the fabric structure on air permeability has been studied in [4 - 6]. The relationship between textile permeability and their porosity was investigated in [7, 8]. Other studies dealt with modelling air-permeability [9 - 12]. The heat transfer through textiles has received the attention of several studies as well, where the effect of a single layer fabric, fabric systems or clothing ensembles on their heat transfer capacity in both indoor and outdoor conditions was investigated [13 - 19].

The convective flow from a human body was numerically studied in [20 - 23]. Research with a thermophysiological model showed that the presence of a textile layer over the body strongly influences the skin temperature due to the textile's insulation properties [24, 25]. It was also found that the temperature of the upper textile layer was affected by the total clothing insulation value.

It can be easily presumed that the lower temperature gradient between the clothing temperature and surrounding air in a quiescent indoor environment will affect the properties of the convective flow, wrapping the body. At the same time, it can be expected that the CBL will have a rebound influence upon the textile layer. However, the effect of CBL around the human body on the abilities of textiles to transmit heat from the human skin to the environment has not been studied.

The main aim of the present study was to numerically investigate the effect of the convective boundary layer around the human body on the transfer of heat through a single textile layer. A new approach of presenting the numerical model of a textile surface transmitting heat by convection to the surroundings was presented. CFD simulations were used to study the influence of the speed of CBL and its size on the ability of the textile structure to transfer heat in the through -thickness direction of the sample.

Design of numerical simulation

Theoretical background of the modeling of a woven macrostructure

A plain weave woven macrostructure was chosen to perform the simulation, with a thickness of 0.39 mm and weight of a 133 g/m2. Different approaches exist in the literature used for modelling woven textiles based on the description of:

- a "unit cell", built of two warp and two weft threads,
- one repeat of the weave,
- the woven macrostructure as a perforated plate or a net of an infinite number of openings,
- the woven macrostructure as a continuum of fibres;
- the fibres in the macrostructure as bodies flowed by fluid.

To model the woven sample, a transformation method was used which was described, applied and verified in detail in our previous work [12]. A tube-like porous structure of a woven textile – ***Figure 1.a***, permits to consider each pore as a jet opening, and the fabric as an in-corridor ordered jet system – ***Figure 1.b***. Thus a system of 3×3 jets (4×4 threads) is enough to present the whole woven structure and to simulate the heat and mass transfer process in a through-thickness direction, as is shown in the scheme of ***Figure 1.c***.

The following simplifications of the physical task were made due to the complexity of the woven macrostructure and approximation of the air flow through the pores as a jet system [12]:

- the linear density of warp and weft threads did not change in length,
- the thickness of the macrostructure, affected by the weave pattern, was measured experimentally, which determined the length of the pore (jet),
- the size of the pores was set as equal for all pores within the virtual model.

Mathematical model

Heat transfer through a thin woven macrostructure involves combined modes of dry and evaporative heat transfer. In the present study a simplified model that did not involved evaporative heat transfer was applied. The FLUENT CFD software package was used for the numerical study. The simulations were based on Reynolds averaged Navier-Stokes equations (RANS) plus the continuity ***Equation 1 - 4***.

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=$$
$$=X-\frac{1}{\rho}\frac{\partial p}{\partial x}+\nu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)+ \qquad (1)$$
$$-\rho\left(\frac{\partial \overline{u'}^2}{\partial x}+\frac{\partial \overline{u'v'}}{\partial y}+\frac{\partial \overline{u'w'}}{\partial z}\right)$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=$$
$$=Y-\frac{1}{\rho}\frac{\partial p}{\partial y}+\nu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)+ \qquad (2)$$
$$-\rho\left(\frac{\partial \overline{u'v'}}{\partial x}+\frac{\partial \overline{v'}^2}{\partial y}+\frac{\partial \overline{v'w'}}{\partial z}\right)$$

$$\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=$$
$$=Z-\frac{1}{\rho}\frac{\partial p}{\partial z}+\nu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)+ \qquad (3)$$
$$-\rho\left(\frac{\partial \overline{u'w'}}{\partial x}+\frac{\partial \overline{v'w'}}{\partial y}+\frac{\partial \overline{w'}^2}{\partial z}\right)$$

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \qquad (4)$$

where, u, v & w are the speed components in the directions of x, y and z ordinates, respectively; u', v'& w' are the fluctuation velocities in the directions of x, y and z ordinates; X, Y, Z are the components of the intensity of the body's force field acting on the fluid in the directions of x, y and z ordinates, respectively; t is time in s, ρ is the density in kg/m3, P is the pressure in Pa, and ν is the kinematic viscosity in m2/s.

To solve the thermal problem, energy ***Equation 5*** was added to the RANS system. The general form of the equation, implemented in FLUENT, is:

$$\frac{\partial}{\partial t}(\rho E)+\nabla\left[\vec{v}(\rho E+p)\right]=$$
$$=\nabla\left[k_{eff}\nabla T-\sum_j h_j\vec{J}_j+\left(\overline{\overline{\tau}}_{eff}\vec{v}\right)\right]+S_h \qquad (5)$$

where, ρ is the density of the fluid in kg/m3, E is the energy, $\vec{v}$ is the speed vector, p is the pressure in Pa, T is the temperature in K, k_{eff} is the effective conductivity, defined as $k_{eff} = k + k_t$ for k – the thermal conductivity of the material and k_t – turbulent thermal conductivity, h_j is the sensible enthalpy, $\vec{J}_j$ is the diffusion flux of the species j, $\overline{\overline{\tau}}_{eff}$ is

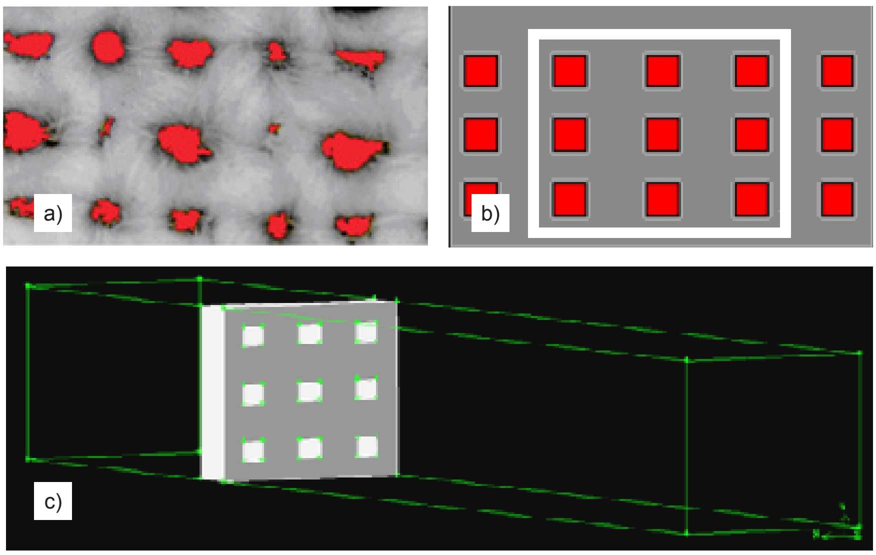


Figure 1. *Presentation of the woven textile structure as a jet system: a) microscopic picture of the woven structure; b) in-corridor ordered jet system; c) computational domain with the textile layer.*

the effective viscous stress tensor, and S_h is a term for the heat transfer of chemical reactions and any other heat sources defined.

To close the system of partial differential equations, the RSM turbulent model was used together with the SIMPLE algorithm and a second-order upwind difference scheme.

Simulated cases

The geometry of a single layer woven structure was built with a GAMBIT FLUENT pre-processor. The mean pore area between the threads was 0.039 mm^2, approximated to a square pore with a side of 0.19 mm.

The sample was immersed in a pipe-like domain, in a position which corresponds to a domain cross-section of 3 mm after the inlet and 8 mm before the outlet (***Figure 2***). A cool air inlet with transverse speed (positive-y direction) was introduced to simulate the CBL around a clothed human body. This speed had to be high enough to cool the air, passing in the through-thickness direction (along z axis), and low enough not to generate forced convection. The thickness of the CBL and its speed were changed during the simulation.

The inlet transverse area was collocated with the bottom face of the computational domain as seen in ***Figure 2***. The way this area was measured was not with an area parameter, but with a length one, in particular the z-direction length of the area (z*), because it is always defined for all x-direction coordinates. Thus the values taken for this distance were z* = 1, 2, 3, and 8 mm. This selection was made on the basis of the research in [3], where it was found that the thickness of the CBL around the body is up to 10 mm. On the same basis the values for the speed of convective flow around the body were chosen: v* = 0.01, 0.03, 0.05, and 0.1 m/s.

The grid generated consisted of a total of 159 790 control volumes (CV), with 173 828 nodes and 493 507 faces. The minimum volume of CV was 1.74×10^{-4} mm^3 and the maximum volume was 2.5×10^{-4} mm^3. Sixteen cases were simulated, as presented in ***Table 1***.

Boundary conditions

The temperature before the textile layer was set to 36 °C (skin temperature) for all the simulations. The temperature at the domain outlet was set to 20 °C. The initial temperature of the CBL (at the bottom of the domain) was also set to 20 °C, assuming that this reflects the way of cooling down the body in a real indoor environment with 20 °C ambient temperature. The residuals were set with values of 10^{-6} for all the unknowns, except for the Reynolds stresses, with a 10^{-3} value of residuals.

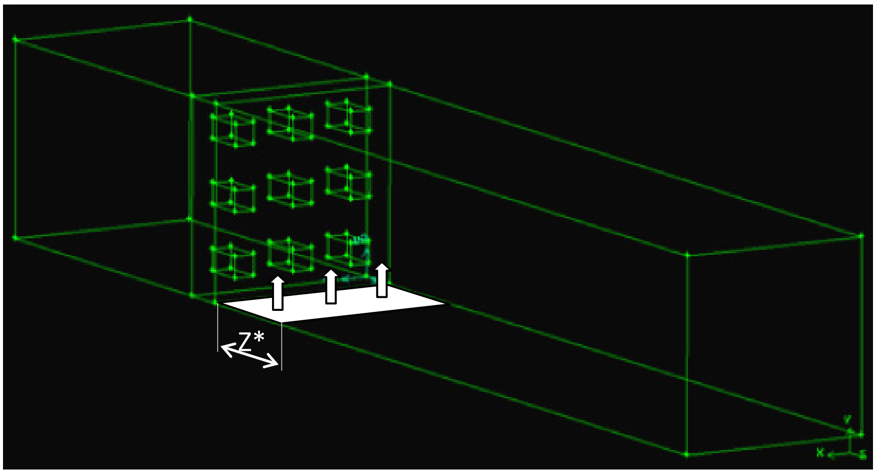


Figure 2. *Numerical domain and the zone of convective boundary flow.*

Table 1. *Simulated cases.*

Case	Thickness of CBL, mm	Speed of CBL, m/s	Case	Thickness of CBL, mm	Speed of CBL, m/s
1	1	0.01	9	3	0.01
2		0.03	10		0.03
3		0.05	11		0.05
4		0.10	12		0.10
5	2	0.01	13	8	0.01
6		0.03	14		0.03
7		0.05	15		0.05
8		0.10	16		0.10

Results and discussions

Results of the effect of the distance of the convective flow on the temperature distribution after the textile layer in the x = 0.875 mm plane are shown in ***Figure 3*** (for Cases 1, 5, 9 and 13). The temperature flow field clearly shows the effect of the thickness of the convective flow on the temperature distribution after the textile barrier. Obviously the convective flow coming from the

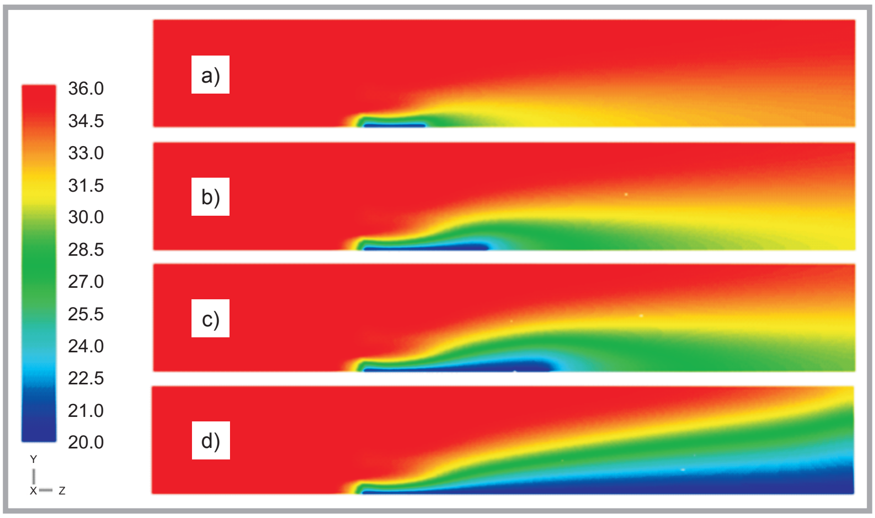


Figure 3. *Temperature field in °C: CBL speed 0.01 m/s, x = 0.875 mm plane; a) Case 1, z* = 1 mm; b) Case 5, z* = 2 mm; c) Case 9, z* = 3 mm; d) Case 13, z* = 8 mm.*

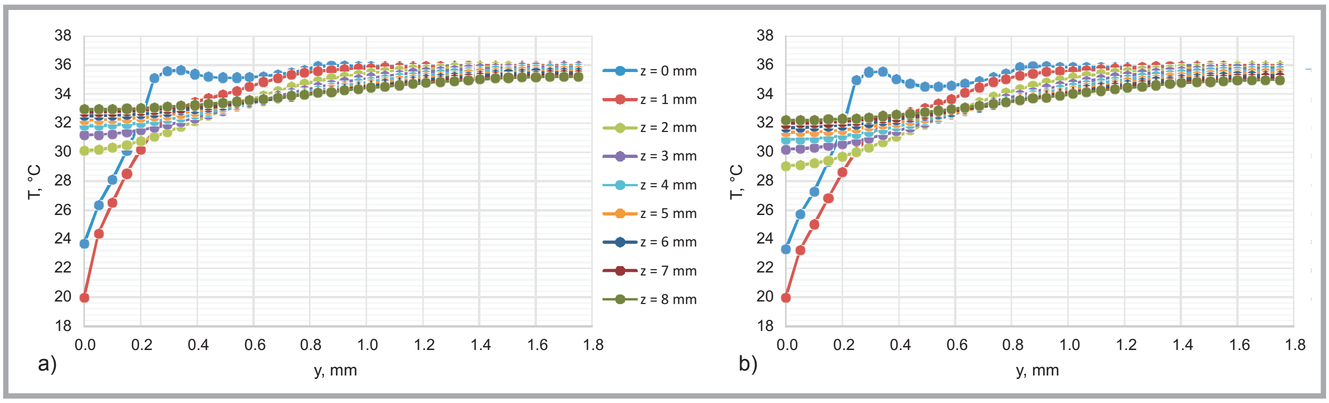


***Figure 4.** y-direction temperature profiles, x = 0.875 mm plane, z* = 1 mm; a) Case 1, v* = 0.01 m/s; b) Case 4, v* = 0.1 m/s.*

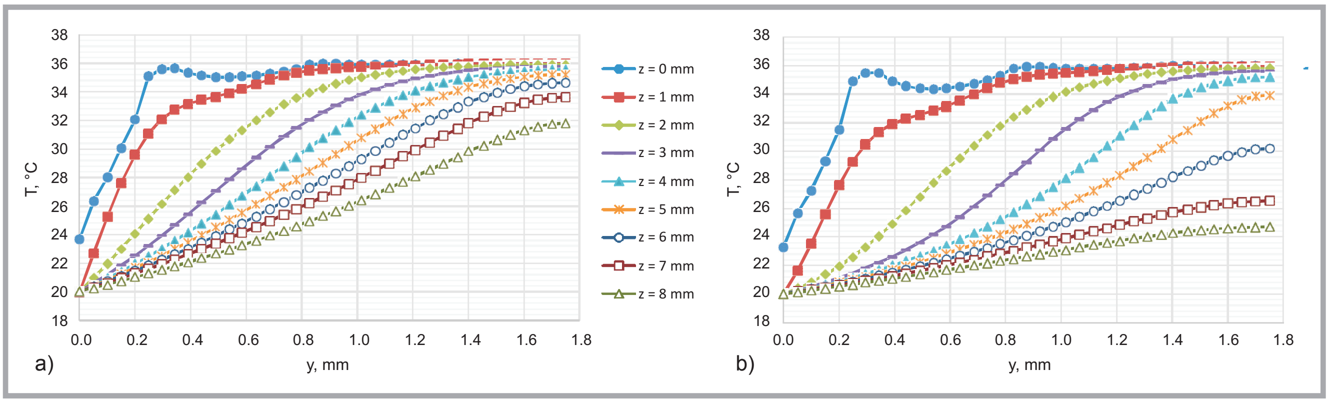


***Figure 5.** y-direction temperature profiles, x = 0.875 mm plane, z* = 8 mm; a) Case 13, v* = 0.01 m/s; b) Case 16, v* = 0.1 m/s.*

bottom of the domain decreased the heat, which was transferred through the textile layer. The bigger the thickness of the CBL, the higher the disturbance of the heat transferred through the textile layer.

To assess the process in detail, temperature profiles were presented for the lowest (v* = 0.01 m/s) and highest speed

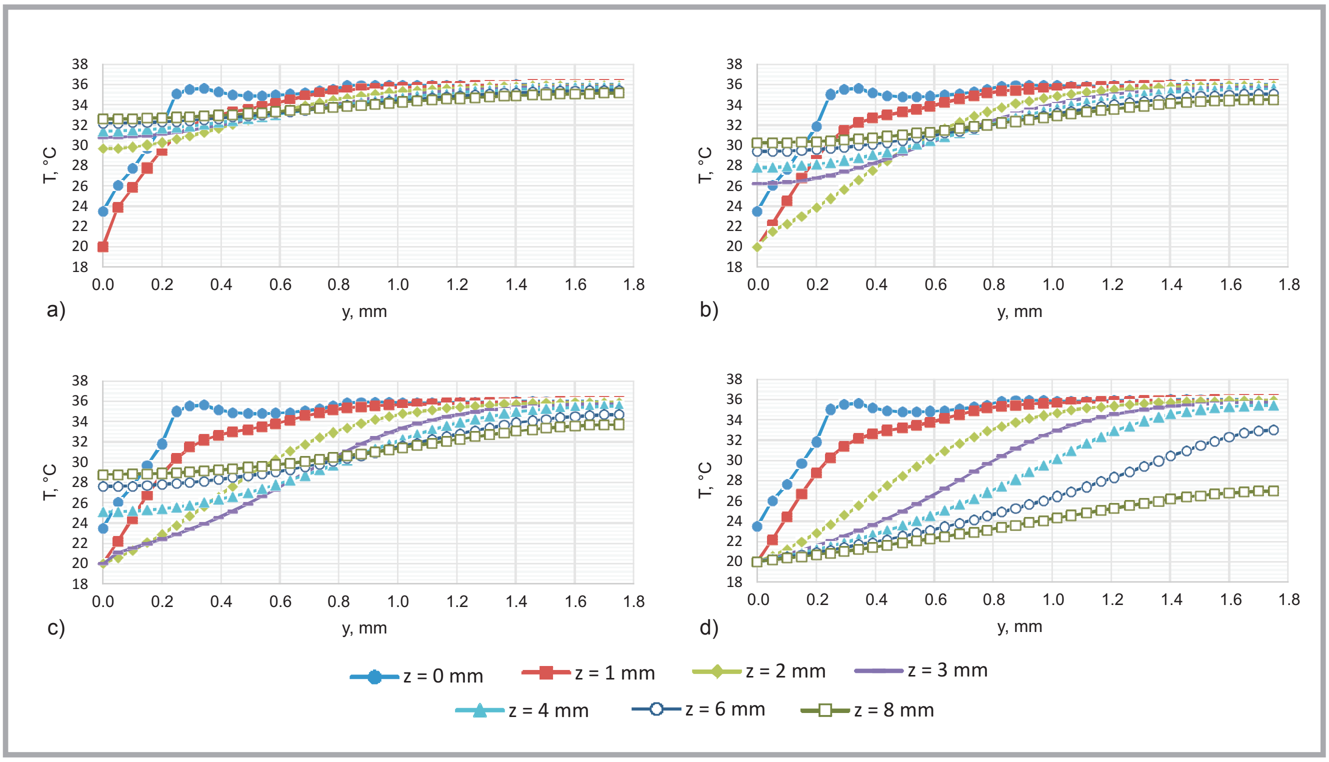


***Figure 6.** y-direction temperature profiles in °C: CBL speed 0.05 m/s, x = 0.875 mm plane, a) Case 3, z* = 1 mm, b) Case 7, z* = 2 mm, c) Case 11, z* = 3 mm, d) Case 15, z* = 8 mm.*

(v* = 0.1 m/s) of the simulated CBL. ***Figures 4*** and ***5*** show temperature profiles in the y-direction for z* = 1 mm and z* = 8 mm thickness of the CBL, respectively.

The temperature in the z = 0 mm plane (y = 0) in ***Figure 4*** decreased from 23.68 °C in Case 1 (***Figure 4.a***) to 23.30 °C in Case 4 (***Figure 4.b***). For all other downstream planes (z = 2 to 8 mm), the temperature in Case 1 was a bit higher than in Case 4 (for the same y = 0): 31.19 °C against 30.21 °C (for z = 3 mm) or 32.94 °C against 32.19 °C (for z = 8 mm). An exception appeared for the z = 1 mm plane, where the temperature for the two cases was equal (20 °C), as it was influenced by the CBL temperature.

The same analysis is valid for the results in ***Figure 5***. However, the difference in temperature values were visible not only for y = 0, but for the next cross-sections in the y-direction. The temperature after the textile barrier was higher for a lower speed of the CBL (Case 13, ***Figure 5.a***), as was also observed in ***Figure 4***. The most important difference, compared to ***Figure 4***, was that after the z = 5 mm plane the temperature in Case 16 (***Figure 5.b***) dropped down much faster than in Case 13, due to the influence of the thicker convective layer. For example, in the y = 1.6 mm plane, the temperature was 34.39 °C for the z = 6 mm cross-section (Case 13, ***Figure 4.a***), as compared to 29.71 °C (Case 16, ***Figure 4.b***).

It can be concluded that the transfer of heat trough the textile barrier is strongly influenced by the speed of the convective layer around the human body. The higher the CBL speed, the lower the ability of the textile layer to keep the body warm.

The influence of the thickness of CBL can be further analysed through the temperature graphs in ***Figure 6*** for 4 of the cases investigated. The speed of the CBL is 0.05 m/s and the CBL thickness is z* = 1 – 2 – 3 – 8 mm (Cases 3, 7, 11 & 15).

Two types of lines could be differentiated in each graph. The first one corresponded to the lines in z ≤ z* zone. In these, the temperature in the y = 0 mm plane was 20 °C, as those points belonged to the transverse flow inlet. Following one of these lines, the temperature increased while distancing from y = 0 mm, reaching 36 °C: the temperature of the heat flow through the textile layer. This distance was a useful indication for the penetration effect of the transverse flux temperature into the main flux through the textile barrier: the bigger the z ≤ z* zone was, the longer the penetration distance was.

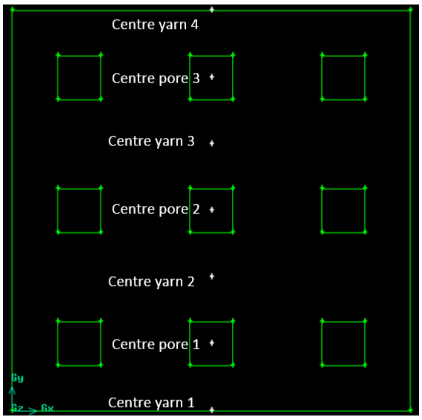


Figure 7. *Scheme of visualization of heat transferred through the textile layer in the z- direction.*

The second type of line was in the z ≥ z* zone. These lines were not directly affected by the CBL, hence the heat flow simply developed freely, stabilising at a constant temperature after a certain z-distance. Contrary to the first group, the lines from the second group cross among them. The zones with lower temperature tended to increase it, while those with higher temperature tended to decrease it.

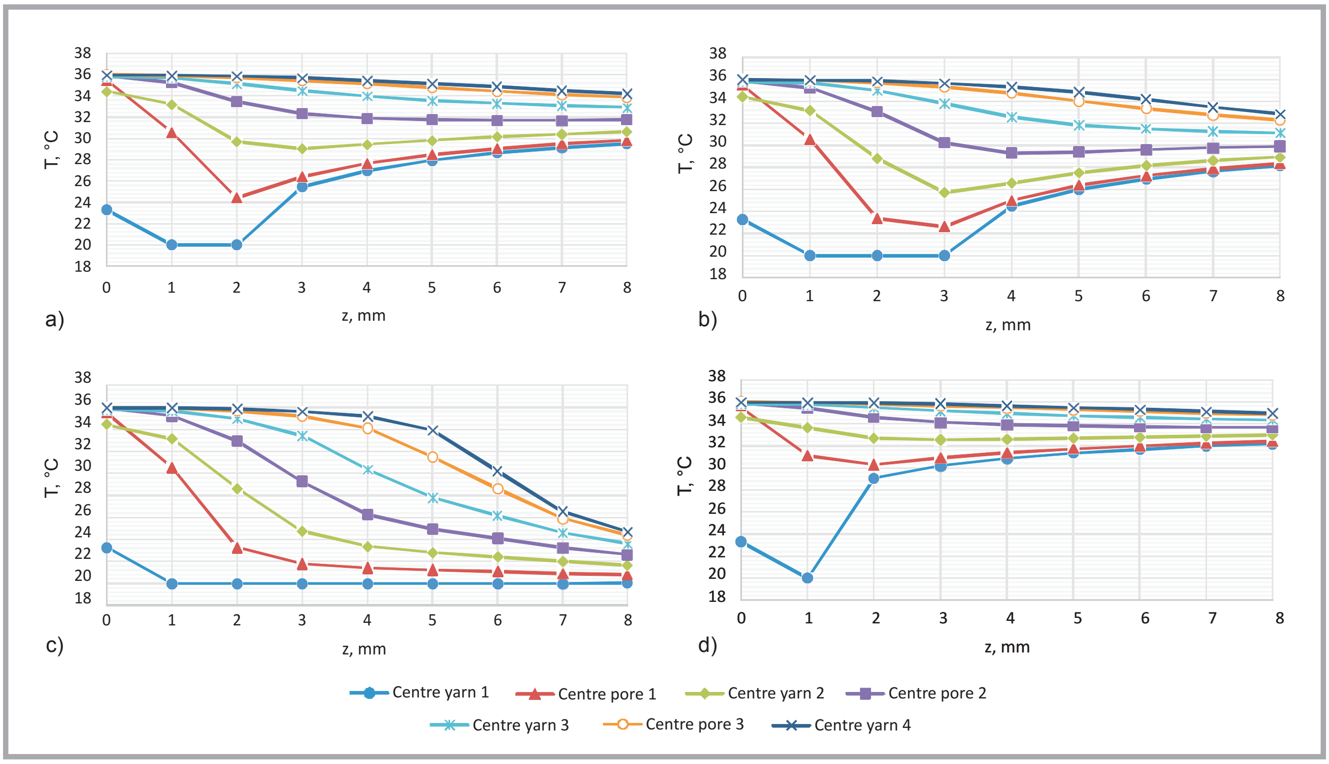
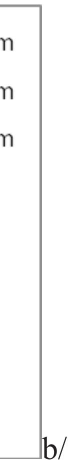


Figure 8. *z-direction temperature profiles, in °C: CBL speed 0.1 m/s, x = 0.875 mm plane; a) Case 4, z* = 1 mm; b) Case 8, z* = 2 mm; c) Case 12, z* = 3 mm; d) Case 16, z* = 8 mm.*



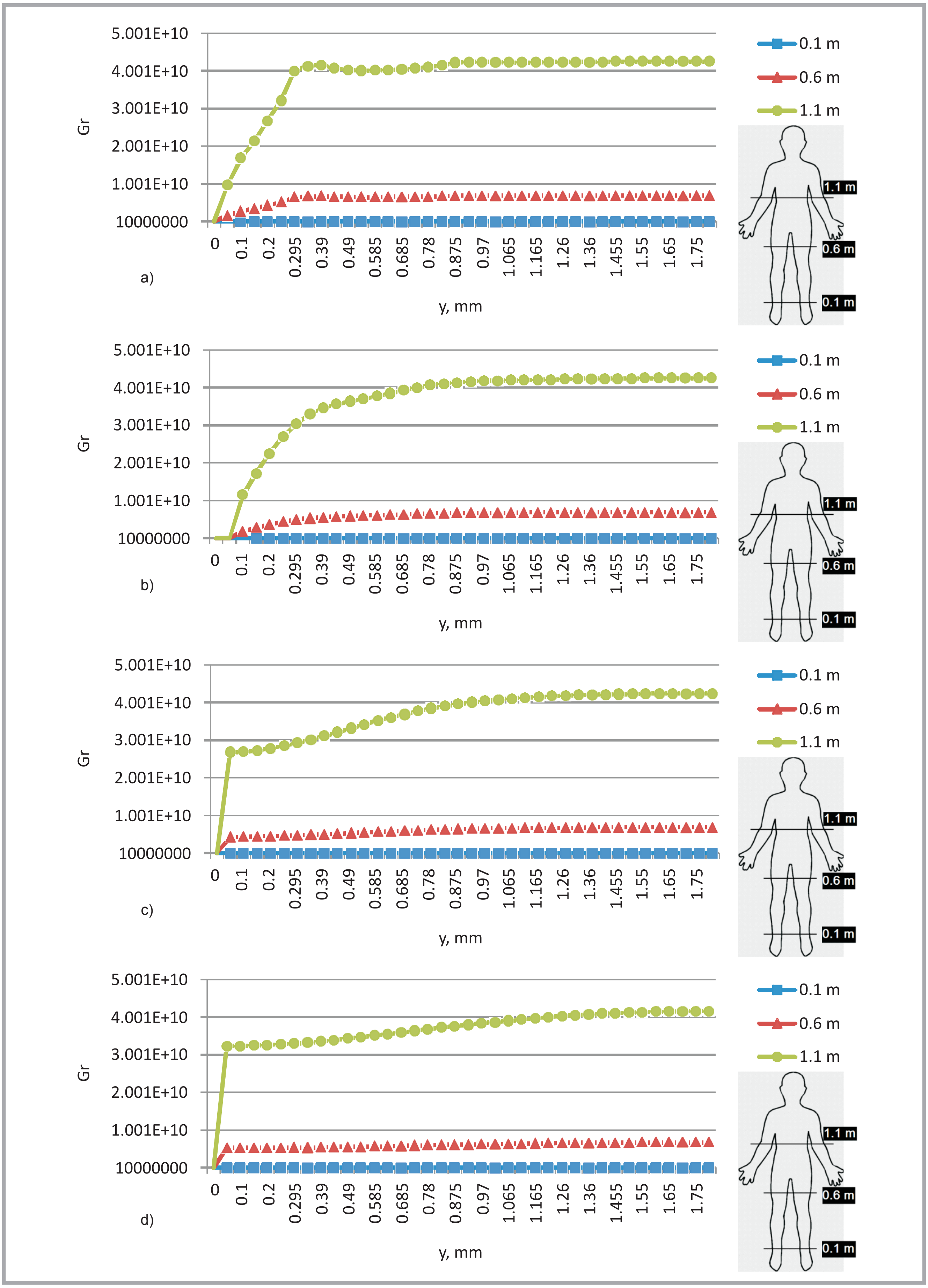


Figure 9. Grashof number for different heights of the human body: CBL speed 0.01 m/s, CBL thickness z = 1 mm x=0.875mm plane; a) z = 0 mm; b) z = 1 mm; c) z = 2 mm; d) z = 5 mm.*

The influence of the CBL on the heat transferred through the textile layer was demonstrated in more detail by the z-direction profiles of the temperature. A scheme of the visualisation of these results is shown in ***Figure 7***.

For the centre of yarn 1 (the line y = 0 mm), the temperature was 20 °C at the inlet, and after it was surpassed the air was heated up. The other profiles showed the dragging effect of the transverse flow by the main one. The lines with low y-values decreased their temperature at lower z-distances than those with high y-values (see ***Figure 8***).

These lines did not usually cross between them because the amount of air and its speed through the pore was much higher than through the transverse inlet, making the cooling effect light.

The Grashof number (Gr) governs flow thickness and speed and determines the type of CBL. It is assumed that when $Gr < 2.10^9$, it is a case of laminar flow, and when $Gr > 10^{10}$, it is a case of turbulent flow. Between these values the flow is considered to be transitional. ***Figure 9*** summarises numerical results for the Grashof number calculated for different heights of the body: 0.1 – 0.6 – 1.1 m. The results presented are for one and the same speed of CBL (0.01 m/s), but for different CBL thicknesses.

It is clearly shown that the convective flow follows the body contours when it is laminar. However, for all cases investigated, the CBL is turbulent at 1.1 m and above, which means that the transfer of heat through the textile layer will be affected by the CBL depending on the clothing item produced from the textile. The insulation abilities of a clothing item from one and the same textile will be different: a cotton shirt, for example, will have lower thermal resistant abilities compared to cotton trousers from the same fabric, due to the interaction of heat flow from the skin to the environment with the speed of the turbulent CBL.

Conclusions

In this study, the effect of the convective boundary layer on the heat transfer abilities of a textile macrostructure was investigated by means of CFD for different velocities of the CBL and different CBL thicknesses. Numerical results for temperature profiles after the textile ”barrier” were obtained, together with a more detailed description of the temperature distribution in the plane of the textile layer.

The results for Grashof number calculation showed the practical importance of the particular influence of the CBL on textile insulation abilities depending on the exact place of the body where the textile layer (clothing item) is used. It was found that one and the same layer of textile will have a higher insulation ability when used on the legs than on the shoulders in steady state conditions and indoor environment.

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