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THERMAL COMFORT EVALUATION USING A CFD STUDY AND A TRANSIENT THERMAL MODEL OF THE HUMAN BODY

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Abstract. *Human thermal modulations are becoming a popular subject when concepts such as, safety and comfort are indispensables in workplaces design. The computational fluid dynamic software have been used and they have been assuming a greater impact in this field due to their higher accuracy. Also, CFD studies can provide detailed information about thermal comfort variables near a human computational manikin, which is difficult and expensive to obtain from experiments in laboratory. The present study is part of a wider project that combines thermal comfort modelling with the design of better and comfortable clothing. The dynamic heat and moisture transfer through the human–clothing–environment system and its effect on the transient physiological response is important and very complex involving several physical phenomena, such as, conduction, convection and radiation for heat transfer and diffusion, desorption, condensation and evaporation for moisture transfer. A CFD study of a room and a thermal manikin, have been developed in the Fluent code from Ansys. The influence of the supply opening conditions, namely air temperature, velocity and humidity has been investigated. A thermal computational manikin with real dimensions divided in 15 different parts has been simulated. Two situations have been compared: a constant temperature and a different temperature in each part. The simulated results have been compared against experimental results from the literature and it was concluded that the computational manikin, divided into different parts with different temperatures seems important to give accurate fluid flow and moisture distributions. In this paper, a new transient human thermal model, which combines a thermoregulatory model and one that describes the dynamic heat and moisture transfer through clothing, is presented. The human body-clothing-environment model developed will provide the transient boundary condition of the computational manikin allowing an accurate prediction of the indoor flow simulation.*

1 INTRODUCTION

The study of thermal environment is becoming popular, because comfort subject is a recent and indispensable subject in designing indoor workplaces. Thermal comfort is generally associated with a neutral or near neutral sensation of whole body temperature, which express satisfaction with the thermal environment[1]. To achieve an acceptable thermal environment, it is useful to be able to predict the effects of a particular combination of thermal parameters in the human thermoregulatory system and, therefore, in the human thermal comfort.

The sensation of thermal comfort is dependent on heat balance between human body and its surrounding environment and, typically, six parameters are used for comfort assessment in indoor environment. First, there are four parameters related to indoor climatic conditions (air temperature, air velocity and relative humidity and mean radiant temperature). Two parameters are related to the human body being evaluated: its metabolic heat production and clothing insulation.

Fanger[2] discussed the existence of optimal thermal comfort, based on the existence of thermal balance, and the magnitude of skin temperature and sweat secretion.

Computational Fluid Dynamics (CFD) techniques, along with human subjects and manikins, have been used in the analysis of human thermal comfort. However, CFD have been greatly developed in recent years, because they can provide detailed information about the thermal environment near a human computational manikin, which is difficult and expensive to obtain from the experiments[3,4,5,6,7].

Because clothing insulation is one of the main parameters in calculating human thermal comfort, the design of better and comfortable clothing is related with the human thermal modelling. The comfortable clothing is an interdisciplinary concept, including objective and subjective aspects[8]. The heat and moisture transfer phenomena between the body and the environment through clothing becomes much more complex, including several phenomena, such as, conduction, convection and radiation for heat transfer and diffusion, desorption, condensation and evaporation for moisture transfer[9].

The present study is part of a wider project that combines thermal analysis using CFD studies, thermo physiological modelling and design of new fabrics for the development of comfortable clothing[10].

A CFD thermal environment analysis has been performed with a simulation of a room and a thermal manikin, in the FLUENT code[11]. The influence of the air supply conditions, namely temperature, velocity and humidity has been investigated. The effect of a thermal computational manikin with real dimensions in the fluid flow has been studied. Two situations have been compared: a constant temperature manikin and one divided in 15 different parts, each one with a different temperature. From the obtained results, it was concluded that the computational manikin, divided into different parts with different temperatures seems important to give accurate fluid flow and moisture distributions.

In order to accurately calculate the real conditions (temperature and humidity) for each part of the thermal computational manikin, a new transient human thermoregulatory model based on previous studies have been developed[12,13]. Some results for temperature and water vapour concentration are presented.

2 CFD MODELLING

The thermal balance between the human body and the surrounding is strongly dependent upon the boundary conditions. These include the surface temperature of the individual, velocity, humidity and temperature of the surrounding air and the temperature of the surrounding surfaces (radiation temperature). This complex interaction demands the accurate knowledge of the local flow field in the vicinity of the individual and also the temperature distribution throughout its body.

The flow is assumed three-dimensional and the corresponding conservation equations for mass, momentum were solved. Energy and other scalar variables, namely for species and turbulence, were then calculated based on the flow field obtained.

The equations were discretized in a finite volume scheme and subsequently solved in the FLUENT code (fluent manual)[14]. In the numerical solution, the second order discretization scheme was used and the SIMPLE algorithm was chosen for pressure velocity coupling. For the turbulence modelling, (RNG) k-ε was chosen due to its stability and precision of numerical results. To study radiation heat transfer, the surface-to-surface radiation type model was used, modeled by a discrete beam approach. Solutions are obtained iteratively and the convergence is accepted when the residuals are below 1E-05.

Although all boundary conditions are steady, a transient formulation was implemented which proved more stable. The calculations are repeated at each time step and the results obtained are compared with those of the previous one. A steady solution is always reached.

Figure 1 depicts the physical dimensions of the test room that has an opening air supply and an exhaust opening, of approximately of the same size. The openings were positioned in a way that a symmetry plane could be achieved in the fluid flow calculations.

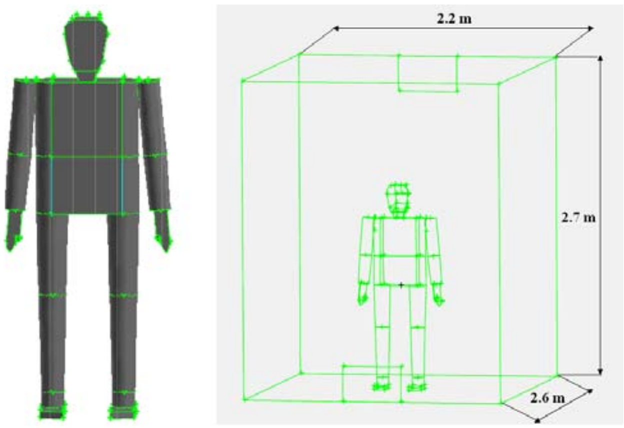

Figure 1: Manikin geometry and room dimensions.

Table 1 summarizes the boundary conditions for the surfaces of the thermal computational manikin, the room walls and for the air supply and exhaust openings. For the air supply opening, two cases have been considered in the simulations: air at temperature (T) of 22ºC and a inlet velocity (V) of 0.15m/s; air (as a combination of three species) with the same properties but with a relative humidity of 65%. A condition of outflow is the most appropriate for the exhaust opening.

The room walls were defined as adiabatic, at a constant temperature of 20ºC. The computational manikin was treated as a wall with different conditions: constant temperature of 33ºC; with a constant relative humidity value of 65% and divided into 15 external parts (figure 2, part 1, that corresponds to lung-heart, due to its nature, is not considered in the manikin geometry), each with a different and constant temperature. The radiation parameters used are also presented in Table 2.

Table 2 summarizes the temperature values for each body part, being: (2) upper torso, (3) lower torso, (4) left forearm, (5) right forearm, (6) left arm, (7) right arm, (8) left hand, (9) right hand, (10) left thigh, (11) right thigh, (12) left leg, (13) right leg, (14) left foot, (15) right foot, and (16) head.

Boundary type	**Physical constants**
Supply opening	V= 0.15m/s ; T=22ºC ; ϕ=65% ; X_{H20}=0.0094 ; X_{O2}=0.2308.
Exhaust opening	outflow
Room Wall	Adiabatic wall; T=20ºC ; ε=0.95
Computational manikin	T=33ºC or Temperature of each part in table 2 ϕ=65%; ε=0.98

Table 1: Boundary conditions.

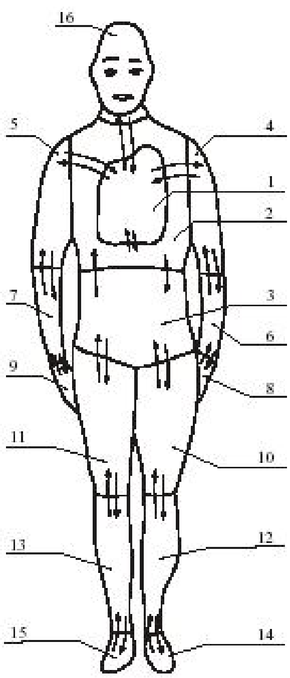

Figure 2: The 16th distinct parts of the human body, where the part 1 is the heart and lungs[12].

The temperature values have been taken from the literature as representative of a thermal comfort situation. Details of the physical parameters of the computational manikin can be found elsewhere[11].

Nº of surface	Temperature (ºC)	Nº of surface	Temperature (ºC)
2	33.62	10	34.10
3	33.62	11	34.10
4	33.25	12	34.10
5	33.25	13	34.10
6	33.25	14	35.04
7	33.25	15	35.04
8	35.22	16	34.58
9	35.22		

Table 2: Temperature of each body part.

The results presented in Figure 3 clearly highlight the influence of the body temperature gradients on the water vapour molar concentration. These are representative results of the importance in modelling the thermal behaviour of the human body in order to compute the thermal interaction with the surroundings.

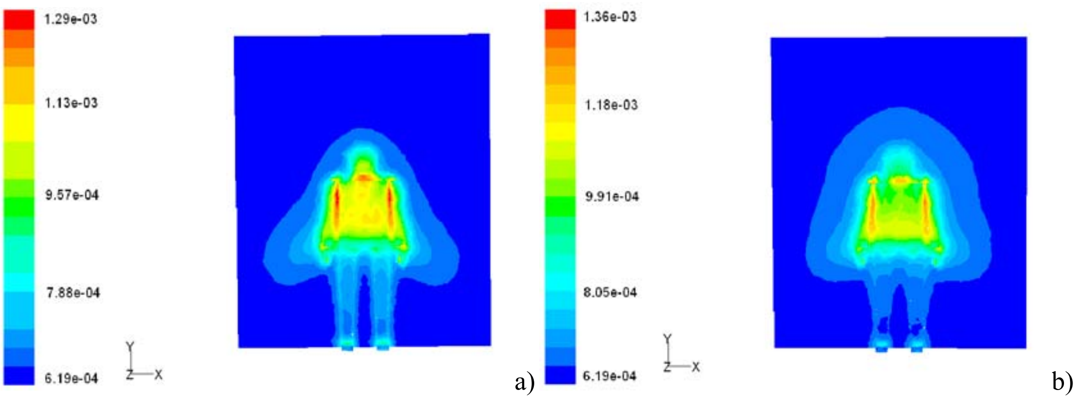

Figure 3: Contours of molar concentration of H_2O in plane XY a) simulation with all manikin at skin temperature of 33ºC b) simulation with manikin divided in parts (kmol/m^3).

3 TRANSIENT THERMAL COMFORT MODEL

3.1 General assumptions

As mentioned before, as in the CFD study, the human body is divided into 16 distinct parts. Part 1, lungs-heart, is considered as a unique system being all the other parts divided into three layers: core, shell and skin (Figure 4).

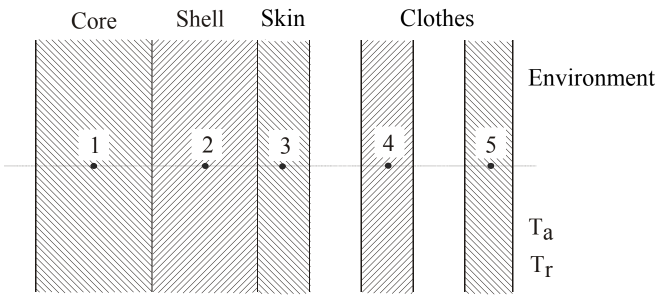

Figure 4: The three layers of each body part and the two layers of clothes, in the dressed case[12].

Each layer is isothermal and within each part exchanges are between the core and the shell and between this and the skin. Each of the 15 parts (2-16) of human body can be covered with layers of clothing. When the body part is naked, heat exchanges to the surrounding air by convection, radiation and evaporation. When the body part is covered, i.e, when the body is clothed, skin exchanges heat with the first layer of clothes and the last layer exchanges by convection and radiation with the air.

3.2 Heat and balance equations

The heat balance equation for the part 1 of the human body (lungs-heart) is given by equation (1):

$$\frac{dT_{11}}{dt} = \frac{1}{C_{11}} * \sum_{i=2}^{16} \left[\dot{C}_{1i} * T_{1i} + \dot{C}_{2i} * T_{2i} \right] - \frac{T_{11}}{C_{11}} * \sum_{i=2}^{16} \left[\dot{C}_{1i} + \dot{C}_{2i} \right] + \frac{\dot{H}_M}{C_{11}} - \frac{\dot{H}_R}{C_{11}} \qquad (1)$$

where C is the heat capacity of the heart and lungs *body node 11* (W/m^2), $\dot{C}$ is the heat capacity blood flow rate (W/K), *T* is the temperature (K), *H* is the internal heat production or heat loss (W) and *t* is the time (s). The subscripts *M* and *R* are related to the metabolism and to the respiration, respectively and *1i* and *2i* are the core and shell of *body part i*, respectively. The first four terms of equation (1) are related to the heat exchange due to the blood flux in the core and shell, in all the 16 parts of the body (i = 1, 2, …, 16). The fifth term is related to the heat change due to the metabolism and the last term to the heat change due to the breading.

The heat balance equation for the first layer, core, for the *part i* (=2, 3, …, 16) of the body is:

$$\frac{dT_{1i}}{dt} = \frac{\dot{C}_{1i}}{C_{1i}} * \left(T_{11} - T_{1i} \right) + \frac{K_{1i}}{C_{1i}} * \left(T_{2i} - T_{1i} \right) + \frac{\dot{H}_{M_{1i}}}{C_{1i}} \qquad (2)$$

where K is the conductive heat transfer coefficient (W/K). The first term represents the heat exchange between the source of heat (part 1, lungs-heart) and the core of the *body part i*. The second term represents the heat exchange by conduction between the shell and the core layers. The last term represents the metabolic heat produced in the interior of each part of the body core.

The heat balance equation for the second layer, shell, for the part i (=2, 3, …, 16) of the body is:

$$\frac{dT_{2i}}{dt} = \frac{\dot{C}_{2i}}{C_{2i}} * \left(T_{11} - T_{2i} \right) + \frac{K_{1i}}{C_{2i}} * \left(\left(T_{1i} - T_{2i} \right) + \frac{K_{2i}}{C_{2i}} * \left(T_{3i} - T_{2i} \right) + \frac{\dot{H}_{M_{2i}}}{C_{2i}} - \frac{\dot{C}_{s_{2i}}}{C_{2i}} T_{2i} \qquad (3)$$

Equation (3) contains five terms, where $\dot{C}$ is the heat capacity flow rate (W/K) and the subscript *S* stands for sweat. The first term corresponds to the heat exchange between the source of heat (part 1, lungs-heart) and the shell layer of *body part i*. The second term describes the heat transfer by conduction between the core *(1i)* and the shell *(2i)* layers. The third term represents the heat transfer by conduction between the skin (*3i*) and the shell layers. The forth term represents the metabolic heat production in the shell layer of the *body part i*. The last term is the heat lost by sweat which is assumed to be produced in the shell layer.

The heat balance equation for the third layer, skin, for each naked part of the body is:

$$\begin{aligned} \frac{dT_{3i}}{dt} &= \frac{K_{2i}}{C_{3i}} \left(T_{2i} - T_{3i} \right) + \frac{K_{rad,i}}{C_{3i}} \left(T_r - T_{3i} \right) + \frac{K_{conv,i}}{C_{3i}} \left(T_a - T_{3i} \right) \\ &+ \frac{\dot{C}_{s_{2i}}}{C_{3i}} T_{2i} - \frac{\dot{C}_{s_{3i}}}{C_{3i}} T_{3i} - \frac{\dot{m}_{g_{3i}} \Delta h}{C_{3i}} \end{aligned} \qquad (4)$$

where $\dot{m}$ is the mass flow rate (kg/s), Δh is the enthalpy of vaporization per unit mass (J/kg) and the subscript *g* stands for vapour.

The equation (4) terms represent the heat transfer by conduction between the skin (*3i*) and the shell *(2i)* layers; by radiation *(rad)* between the skin and the environment and by convection *(conv)* between the skin and the environment, respectively; by sweat produced in the shell layer and passing the skin layer, respectively and finally, by the evaporation occurring at the skin surface.

The equations for the third layer, skin, for the covered parts of the body are:

$$\frac{dT_{3i}}{dt} = \frac{K_{23i}}{C_{3i}} * \left(T_{2i} - T_{3i}\right) + \frac{K_{34i}}{C_{3i}} * \left(T_{4i} - T_{3i}\right) + \frac{\dot{C}_{s_{2i}}}{C_{3i}} T_{2i} - \frac{\dot{C}_{s_{3i}}}{C_{3i}} T_{3i} - \frac{\dot{m}_{g_{34}} \Delta h}{C_{3i}} - \frac{\dot{C}_{L_{34}}}{C_{3i}} T_{3i} \tag{5}$$

The first term represents the heat transfer by conduction between the skin (*3i*) and the shell *(2i)* layers, the second term represents the conduction between the skin and the first layer of cloths in the covered *body part i*. The following two terms represent the heat transfer by sweat produced in the shell layer and passing in the skin layer, respectively. The last two terms take into account the heat transfer by water vapour *(g)* and liquid mass *(L)* transfer for the first layer of clothing.

The heat balance equations for the internal layer (n=4-[z-1]) of the cloths are:

$$\frac{dT_{ni}}{dt} = \frac{K_{(n-1)(n),i}}{C_{ni}} \left(T_{(n-1),i} - T_{ni}\right) + \frac{K_{(n)(n+1),i}}{C_{ni}} \left(T_{(n+1),i} - T_{ni}\right) + \frac{\dot{C}_{L(n-1)(n),i}}{C_{ni}} T_{(n-1),i} + \frac{\dot{m}_{g(n-1)(n),i} \Delta h}{C_{ni}} - \frac{\dot{C}_{L(n)(n+1),i}}{C_{ni}} T_{(n),i} - \frac{\dot{m}_{g(n)(n+1),i} \Delta h}{C_{ni}} \tag{6}$$

The first two terms represent the heat transfer by conduction between the cloth layers *(n-1,i, n,i and n+1,i)*. The following terms take into account the heat transfer by water vapour *(g)* and liquid mass *(L)* transfer between the various layers of clothing.

The heat balance equation for the last cloth layer (z) is:

$$\frac{dT_{zi}}{dt} = \frac{K_{(z-1),i}}{C_{zi}} \left(T_{(z-1),i} - T_{zi}\right) + \frac{K_{rad,i}}{C_{zi}} \left(T_r - T_{zi}\right) + \frac{K_{conv,i}}{C_{zi}} \left(T_a - T_{zi}\right) + \frac{\dot{C}_{L(z-1)(z),i}}{C_{zi}} T_{(z-1),i} + \frac{\dot{m}_{g(z-1)(z),i} \Delta h}{C_{zi}} - \frac{\dot{m}_{g(z)(w),i} \Delta h}{C_{zi}} \tag{7}$$

The first term represent the heat transfer by conduction between the last cloth layers *(z-1,i and z,i)*. The following two terms account for the heat transfer by radiation *(rad)* between the cloth layer and the environment and by convection *(conv)* between the cloth layer and the environment, respectively. The last three terms take into account the heat transfer by liquid mass *(L)* transfer to the last cloth layer and the water vapour *(g)* transfer between the two last layers of clothing and from the last one to the environment *(w)*.

Two further equations are added to calculate the water vapour density $\left(\rho_v\right)$ in the cloth layers and they have been taken from Gibson and Carmachi cloth model, integrating the variation along the cloth thickness $\left(\Delta x\right)$:

$$\varepsilon_\gamma \frac{d\,\rho_v}{d\,t} = D_{eff} \frac{\left(\rho_{v(n-1),i} - \rho_{v(n),i}\right)}{\Delta x} + \dot{m}_{sv} - \rho_v \frac{\left(\varepsilon_{\gamma_{t_i}} - \varepsilon_{\gamma_{t_{i-1}}}\right)}{\Delta t} \tag{8}$$

The first term on the right hand side of equation (8) describes the diffusion transfer (D_{eff} is the effective gas phase diffusivity), the second term accounts for the mass rate of desorption from solid phase to vapour phase and the last term describes the changes of the volume fraction (ε_γ) occupied by the gas phase (air and water vapour) in the cloth layer. Apart from the gas phase, the dry solid fibre *(ds)* and the water bounded in the solid phase occupy the remaining part of this volume. In consequence, ρ (density), c_p (heat capacity) and k_{eff} (effective thermal conductivity) in the cloth layers, are average properties depending on the volume fraction of each component (air, water, vapour and fibre) and they had to be updated in each time step.

The mass rate of vapour sorption is modelled assuming that the material at the fibre surface immediately come into equilibrium with the relative humidity of the gas phase at that point, and so, the mass flux into and out the fibre is calculated by:

$$\dot{m}_{sv} = \frac{D_{solid}\rho_{ds}}{d_f^2}\left(R_{total} - R_{surface}\right) \tag{9}$$

which depends on the difference between the instantaneous fibre regain $(R_{total})$and the equilibrium regain at relative humidity, ($R_{surface}$). D_{solid} is the solid phase diffusion coefficient (m^2) and d_f is the fiber diameter (m).

3.3 Algorithm and numerical solution

The program was written in Fortran. The main program is where all the balance equations described above (1-8) are numerically solved by using the Runge-Kutta-Merson method[15]. This method was chosen by its simplicity and robustness in solving this kind of differential equations. The initial temperature values in all body parts and layers (core, shell, skin and cloth) and the water vapour concentration at the cloth layers in all covered body parts are given and can be modified by the user. The main objective of the program is to estimate the temperatures and water vapour concentration, as function of time, in the different parts of the body covered and for the different thermal environment tested.

4 RESULTS

Two different situations are here reported in order to evaluate the presence of clothing. The air and radiant temperature of the environment are kept constant and equal to 20 ºC and a relative humidity of 65%. The basic value for metabolism is taken from the literature for an office work and the body is covered with summer cloths. Figure 5 presents the central body temperature along the time, for the naked case. Part 1 remains nearly with a constant temperature, exchanging heat with all parts and layers.

Figures 6 and 7 present the temperature along the time, for the naked case, into two different body parts: chest and foot. Due to the part thickness, it can be observed a larger difference between the core and skin temperatures for the chest part. The foot temperature remains more or less constant.

The dressed case is now presented, and Figure 8 presents the central body temperature along the time. The heat exchange with the cloth layers, which have been simulated with an initial temperature of 28 and 27 ºC, is visible along the time, showing a small decreased in the central temperature.

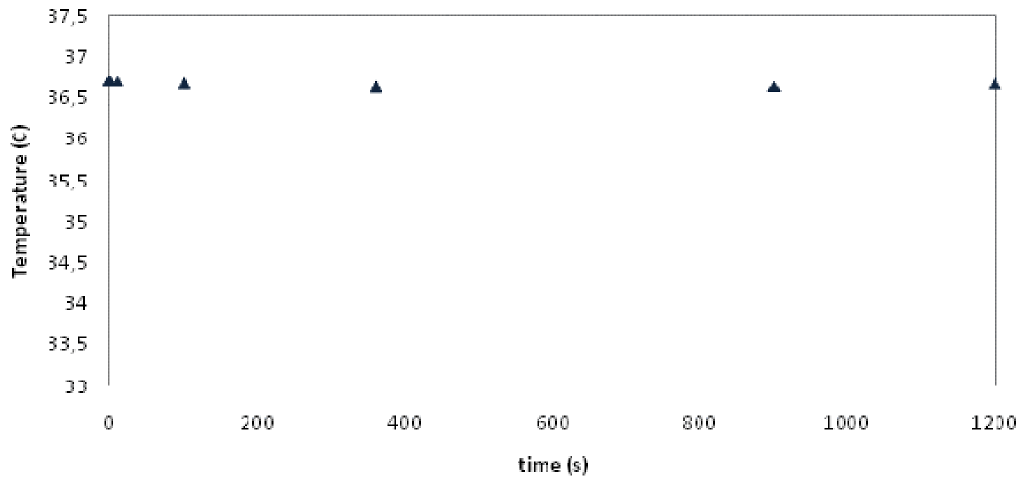

Figure 5: Heart and lungs temperature along time, for a naked body.

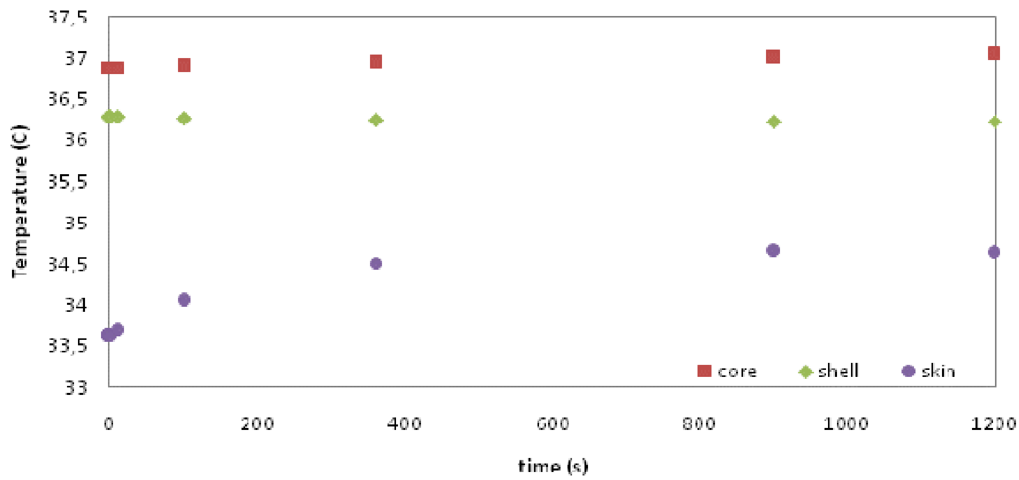

Figure 6: Chest temperature along time for the three different layers (core, shell and skin), for a naked body.

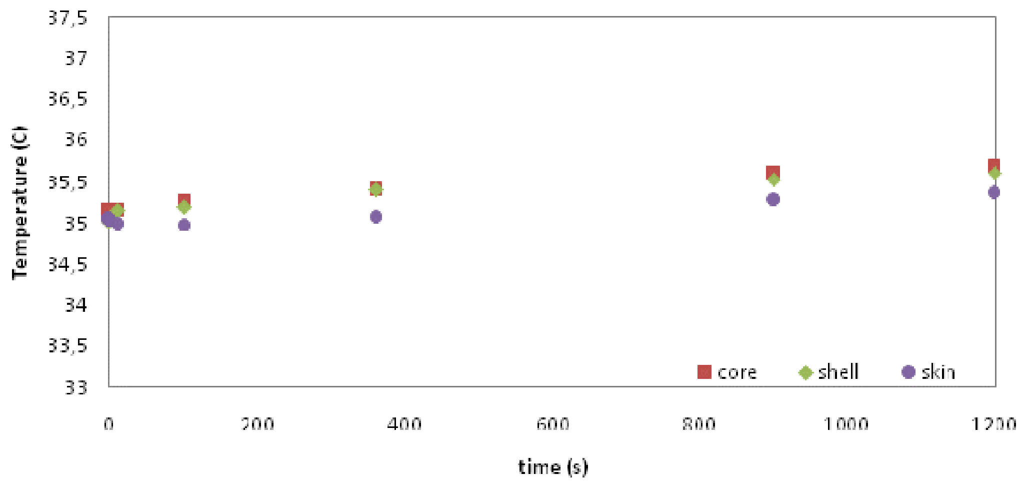

Figure 7: Foot temperature along time for the three different layers (core, shell and skin), for a naked body.

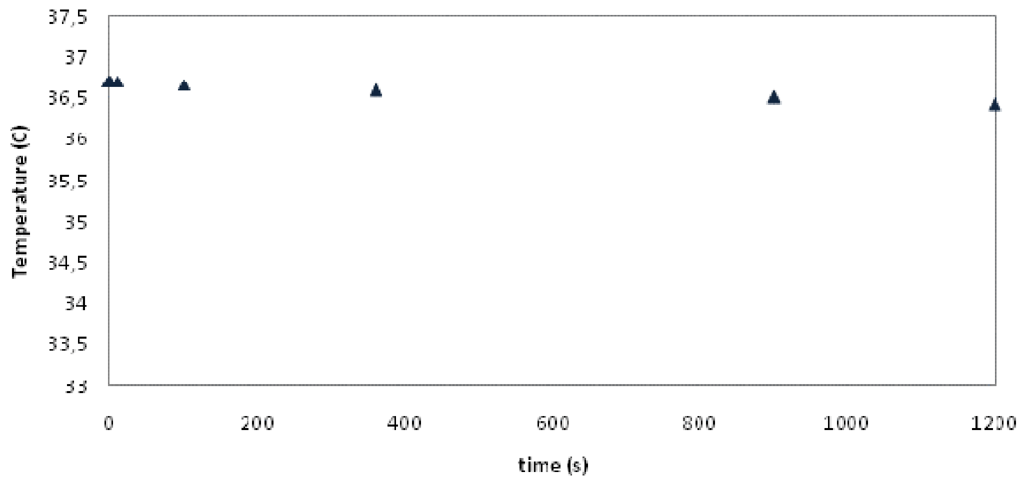

Figure 8: Heart and lungs temperature along time, for a dressed body.

In Figure 9, the temperatures along the time, for the five layers of the chest body part are presented. The heat exchange between the skin layer and the cloth layers is visible along the time. The first layer of cloth has been also simulated as air layer (cloth with the air properties) and in this way, some differences are also observed.

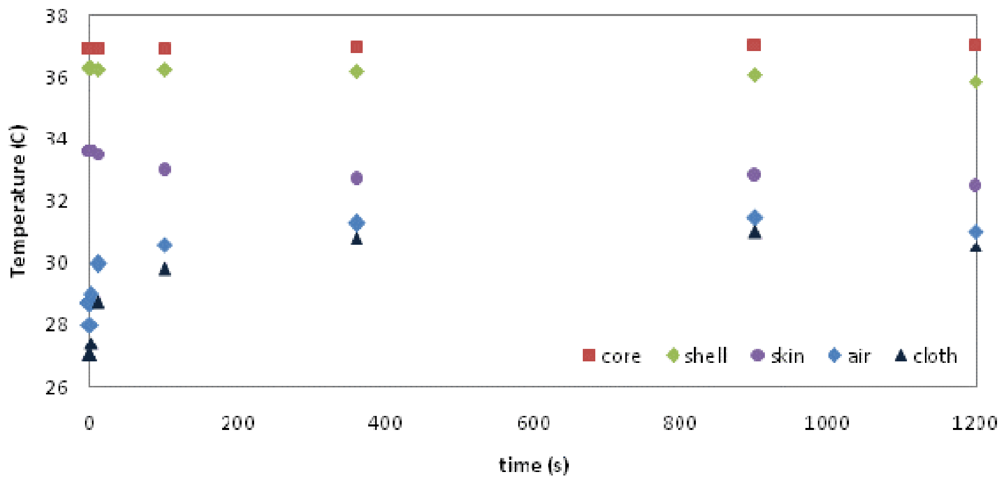

Figure 9: Chest temperature along time for the five different layers (core, shell, skin, air and cloth), for a dressed body.

The environment temperature has also some effect in the exterior layer of clothing. And this effect is more pronounced in the foot case (Figure 10), due to its smaller volume.

The temperature along the chest thickness is presented into Figure 11. The five nodes temperatures (core, shell, skin, air and cloth) are shown for the initial condition and three times (after 1 s, 10 s and 100s). The last three layers are almost coincident, because the air layer and the cloth layer thicknesses are very small.

The water vapour concentration along the time in the two cloth layers is presented into Figure 12. Very small differences have been calculated for the two layers in each part but some differences can be observed in the chest and foot parts, especially in the first instants of contact between the cloths and the skin. As initial conditions, the relative humidity of 65% has been assumed for the two layers.

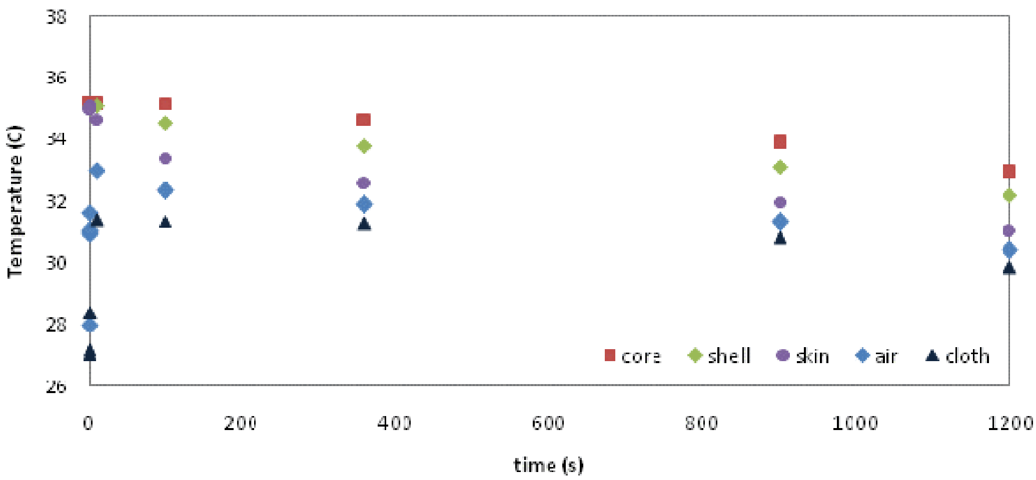

Figure 10: Foot temperature along time for the five different layers (core, shell, skin, air and cloth), for a dressed body.

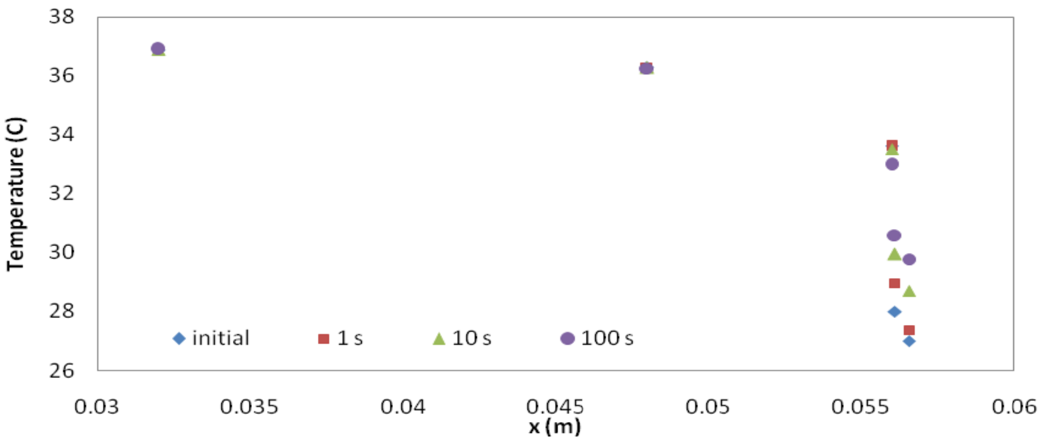

Figure 11: Chest temperature along thickness for the five different layers (core, shell, skin, air and cloth), for a dressed body, at different times.

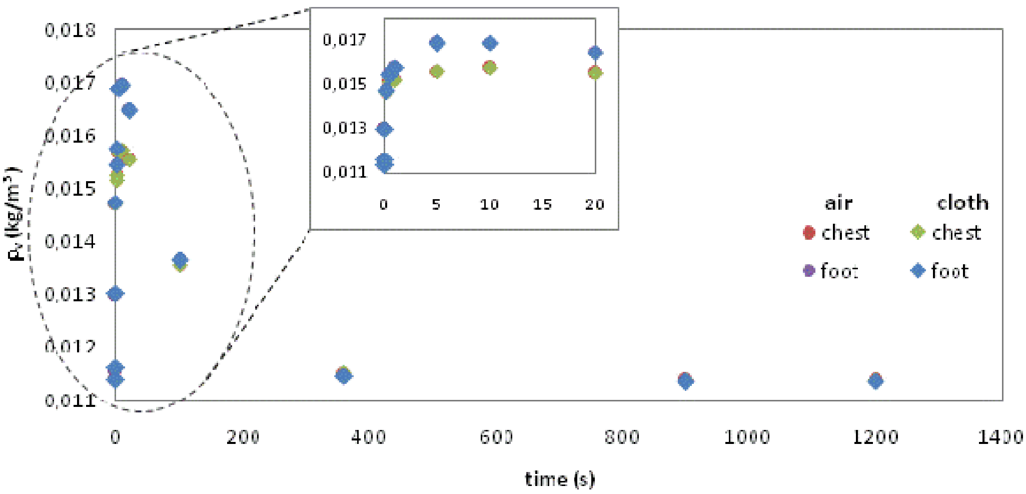

Figure 12: Water vapour, ρ_v, for the air and cloth layers along time.

5 CONCLUSIONS

Thermal human comfort has been studied using a CFD study and a transient thermal model of the human body.

One of the most important conclusions from the CFD results was that by considering the manikin with varying surface boundary conditions is the best way to study the room air flow field and the heat and mass transfer between the manikin, room and its surroundings.

A new transient model based on a thermoregulatory model of the human body, which was considered divided into 16 parts and a model for the heat and mass transfer occurring into the cloth layers of the dressed parts, have been developed.

Some preliminary results of temperature and water vapour concentration along the time and for the different body part layers seemed to correctly model all the complex phenomena.

The integration of the thermoregulation model as a boundary in the CFD code is now being implemented.

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