Thermal Properties of Industrial Safety Helmets

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Abstract: The aim of this paper is a numerical simulation of heat and moisture exchange properties of industrial helmet. In order to help designer to optimize the helmet thermal properties, the effect of thermal conductivity and liner thickness on the microclimate temperature is investigated. The liquid moisture diffusion in the comfort liner is modeled by the Darcy’s law. The energy transport equation is based on the local thermal equilibrium assumption. A control volume finite difference method is used for solving the differential equations system. The effect of thickness and porosity of the comfort liner on the moisture diffusion is presented. Relevance to industry: Improving thermal comfort of industrial safety helmet becomes one of the major interest of helmet designers. This paper presents a numerical simulation of heat and mass transfer from the head to the helmet microclimate, which can avoid using thermal manikins and controlled human trials.

Key words: Industrial safety helmet; Thermal properties; heat and mass transfer.

Nomenclature

A: liner surface area [m²]  
C: specific thermal capacity [J/KgK]  
Cp: specific heat [J kg⁻¹K⁻¹]  
Deff: effective diffusivity [m²s⁻¹]  
Ei: liner thickness [m], i = 1, 2, 3, 4  
F: reflection coefficient.  
h: convective heat transfer coefficient [W/m²K]  
g: gravitational constant [m s⁻²]  
H: ambient relative humidity  
K: thermal conductivity [W/mK]  
Kg, Ks: relative permeabilities of gas and liquid.  
L: intrinsic permeability [m²].  
M: molar mass [kg mol⁻¹]  
\dot{M}_{evap}: evaporation rate [kg m⁻³s⁻¹]  
m: liner weight [Kg].  
P: pressure [Pa]  
Q_{longwave}: long-wave radiation [W].  
Q_{conv}: heat convective exchange [W].  
Q_{cond}: heat conductive exchange [W].  
Q_{abs}: solar radiation[W].  
r: radial distance [m].  
R: universal gas constant [J mol⁻¹K⁻¹]  
rh: head radius [m]  
S_{evap}: heat evaporation exchange [W].  
S: relative saturation  
T: temperature [°C or K]  
t: time [s]  
Δt: time increment [s]  
U: moisture content [kg of water/ kg of solid]

V: velocity [m s⁻¹]  
\Delta h_{evap}: latent heat of evaporation [J kg⁻¹]  
Δr: Thickness of control volume [m]  
w: averaging volume [m]  

Greek symbols

α: heat transfer coefficient [W m⁻²s⁻¹K⁻¹]  
β: mass transfer coefficient [m s⁻¹]  
ε: porosity  
λ_{eff}: effective thermal conductivity [W m⁻¹K⁻¹]  
μ: dynamic viscosity [kg m⁻¹s⁻¹]  
ν: cinematic viscosity [m²s⁻¹]  
ρ: density [kg m⁻³]  
σ: surface tension [Nm⁻¹]

Subscripts

a: air  
atm: atmospheric  
c: capillary  
cr: critical  
eq: equilibrium  
g: gas  
i: spatial index  
ir: irreducible  
l: liquid  
psf: fibre saturated point  
s: solid  
sat: saturated  
v: vapour  
vs: saturate vapour  
ω: ambient
INTRODUCTION

The use of industrial safety helmets is taken for granted the head protection against small falling objects striking the top of the shell in industrial environments. Most studies have discussed the impact energy absorption provided by the helmets to the wearers. Moreover, physiological aspects of safety helmets have become the most important challenges facing helmets design community. In addition, many workers are not willing to wear helmets at work because they are not comfortable. Wearing a headgear reduces airflow over the head which may affect heat loss from the head to the environment, and could lead to an increase in heat-related stress. Different factors which can negatively affect the potential wearer of safety helmet such as: weather protection, thermal properties, helmet compatibility and volume. Helmet thermal properties become the most important factors especially in hot climate.

Therefore, helmet comfort and physiological aspects of safety helmets have been a field of increasing interest. A number of manikin heads have been built in order to study the heat transfer from the head to the helmet microclimate. Abeysekera et al. were interested in industrial helmet characteristics and measure the external heat flux required to maintain a constant temperature on the surface of a manikin head in a climate chamber. He confirmed that the measurement of the thermal properties of helmets using thermal manikins and controlled human trials, have led to some improvements in the design of protective headwear. Hsu et al. has tested different types of helmets. The average temperature beneath the helmet shell, the speed of head dissipation through convection, and the temperature contour beneath the helmet shell were used to describe the thermal properties of helmet. Davis et al. has tried to evaluate subjects’ physiological and psychological responses of forest workers in a high temperature environment. Three helmets are compared by the evaluation of the dome space environmental conditions with the dry-bulb and wet-bulb temperatures.

The problem of finding simplified methods to solve the helmet material selection and design problem is based on numerical analysis of impact response of safety helmets or the experimental treatment of the subject. In addition, many designers are interested in the helmet performance in impact and shock absorbing considering the comfort factor with secondary importance. However, helmet designers have to take at the same time mechanical and thermal characteristics of industrial helmet used especially in high temperature environment.

It’s interesting to note that the moisture-transport process in clothing under a humidity transient is one of the most important factors influencing the dynamic comfort of a helmet wearing in practical wear situations. Several investigators have developed models for moisture transport in porous polymeric materials. Henry proposed a system of differential equations to describe the coupled heat and moisture diffusion into bales of cotton. Recently, Nishimura et al. has simulate numerically moisture transport phenomenon in a fiber assembly. In many cases, the results are sensitive to boundary heat and mass transfer coefficients and to thermal radiative properties of the experimental apparatur.

In this paper, we study numerically the thermal properties of industrial helmet. The influences of external room temperature, material properties and liner thickness on the microclimate heat will be emphasized, through which the optimal liner characteristics and dimensions are discussed.

Heat Transfer Model: In our model, the helmet consists of four parts (Figure 1): the microclimate, the comfort liner, the foam liner and the helmet shell. The temperature is determined in each liner. The helmet is assumed one dimensional, because the heat is taken stable all over each liner. The solar radiation penetrating the helmet are assumed equally spread on the helmet shell surface. The convection heat transfer coefficient is taken uniform all over internal and external liners.

Heat Transfer Mechanism: Hanna concluded that the warm weather is not the only cause of heat stress of helmet wearer. Six main factors are involved in causing heat stress: temperature, radiant temperature of the
surroundings, humidity, movement of air, physical activity and protective clothing. The examination of the above six factors reveals three comprehensive causes of heat stress: environmental heat load, metabolic heat production and clothing (or equipment). Heat can be gained or lost from the head by conduction, convection, radiation, and evaporation of sweat.

Heat may be gained or lost from the head wearing a helmet by conduction, convection and radiation. These heat transfer can be written according the following relation stress \[^4\]:

\[ Q = Q_{\text{cond}} + Q_{\text{conv}} + Q_{\text{adv}} + Q_{\text{sangwave}} \]  

Where heat change is: \( Q = \frac{mc\Delta T}{dt} \)

An initial microclimate heat was given to the helmet microclimate equal to 35°C which is the average temperature of the environmental chamber in \[^6\] study. The initial liners temperatures are given as:

\[ T(0, r = r_{\text{helmet}}) = 37^\circ C \]  

\[ T(0, r = r_{\text{helmet}} + E_1) = 35^\circ C \]  

\[ T(0, r = r_{\text{helmet}} + E_1 + E_2) = 36^\circ C \]  

\[ T(0, r = r_{\text{helmet}} + E_1 + E_2 + E_3) = 37^\circ C \]  

\[ T(0, r = r_{\text{helmet}} + E_1 + E_2 + E_3 + E_4) = 38^\circ C \]  

\[ T(0, r = r_{\text{helmet}} + E_1 + E_2 + E_3 + E_4 + \infty) = T_{\text{lim}} = 38^\circ C \]  

The boundary conditions consider the helmet in contact with an uniform temperature environment:

\[ T(t, r = r_{\text{helmet}} + E_1 + E_2 + E_3 + E_4 + \infty) = T_{\text{lim}} = 38^\circ C \]  

Materials: It is commonly accepted that industrial helmets shell can be produced using ABS (acrylonitrile-butadiene-styrene). The inner liner is generally made from expanded polystyrene (EPS) foam. The comfort material is made of urethane foam. Table 1 shows material details of the complete helmet system.

Mathematical model:

A- Shell Temperature Variation:

For this liner, there is different heat transfer mechanisms. Heat is transferred by: convection with the surrounding air, conduction with the lower liner and solar radiation. The temperature variation of this liner can be described by the following relation:

\[ Q = \frac{mc\Delta T}{dt} = Q_{\text{cond}} + Q_{\text{conv}} + (1 - F)Q_{\text{solar}} + Q_{\text{sangwave}} \]  

Where:

\[ Q_{\text{cond}} = -k_iA_i \left( \frac{T_{\text{helmet}} - T_{\text{lim}}}{dr} \right) \]  

\[ Q_{\text{conv}} = -h A_i \left( T_{\text{helmet}} - T_{\text{lim}} \right) \]  

\[ m_i = \frac{E_i}{2} \rho_i \]  

We may now substitute each component in the equation 9. This allows the temperature equation variation to be written as:

\[ T_{\text{helmet}} = \left( 1 - \frac{2h}{\rho E_i} \right) \left( 1 - \frac{k_i}{\rho c E_i} \right) T_{\text{lim}} + \left( \frac{2k_i}{\rho c E_i} T_{\text{lim}} \right) \frac{dT}{dt} \]  

\[ + \left( \frac{2h}{\rho E_i} \right) \left( 1 - \frac{2h}{\rho E_i} \right) \left( 1 - \frac{k_i}{\rho c E_i} \right) T_{\text{lim}} \]  

b- Comfort Temperature Variation: The comfort liner is in contact with the helmet microclimate. From Davis et al.,\[^6\] work, the temperature of the microclimate becomes greater than outside and the relative humidity rises because of water evaporation from the head. We can define the “cooling power” of water through its heat of vaporization, which at 35°C corresponds to approximately 0.67 W for an evaporation rate of 1 g h\(^{-1}\). Taking perspiration rates under moderate exercise from the literature\[^{19}\], and converting them using the skull area, one obtains a typical overall perspiration rate of about 17 g h\(^{-1}\). This represents a potential cooling power for the nude head of about 11.4 W.

The temperature variation of this liner can be described by the following relation:

\[ Q = \frac{mc\Delta T}{dt} = Q_{\text{cond}} + Q_{\text{conv}} + Q_{\text{sangwave}} + S_{\text{evap}} \]  

Where:

\[ Q_{\text{cond}} = -k_{\text{arr}}A_i \left( \frac{T_{\text{helmet}} - T_{\text{lim}}}{dr} \right) - k_{\text{arr}}A_i \left( \frac{T_{\text{helmet}} - T_{\text{lim}}}{dr} \right) \]  

\[ Q_{\text{conv}} = 0 \]  

\[ m_i = \rho_i \frac{E_i}{2} \]  

We may now substitute each component in the equation 14. This allows the temperature equation variation to be written as:
Table 1: Material properties of industrial helmet

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Mass density (Kg/m³)</th>
<th>Thickness (mm)</th>
<th>Thermal conductivity (w/Km)</th>
<th>Specific thermal capacity (J/KgK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shell</td>
<td>ABS</td>
<td>1470</td>
<td>10</td>
<td>0.25</td>
<td>2.3</td>
</tr>
<tr>
<td>Inner liner</td>
<td>EPS</td>
<td>50</td>
<td>30</td>
<td>0.036</td>
<td>1.4</td>
</tr>
<tr>
<td>Comfort liner</td>
<td>polyester</td>
<td>1390</td>
<td>3</td>
<td>0.033</td>
<td>1340</td>
</tr>
</tbody>
</table>

\[
T_{i+1} = \left( 1 - \frac{2k_{i+1} dt}{(E_{i+1}c_{i+1}\rho_{i+1} + E_{i+1} c_{i+1} \rho_{i+1}) E_{i+1}} \right) T_i + \left( \frac{2k_{i+1} dt}{m c E_{i+1}} \right) \Bigg( T_{i+1} - \frac{2k_{i} dt}{(E_{i}c_{i}\rho_{i} + E_{i} c_{i} \rho_{i}) E_{i}} \Bigg) T_{i-1} + \left( \frac{2 dt}{\rho E c} \right) (Q_{\text{cond}} + Q_{\text{evap}}) 
\]

Where:
\[
Q_{\text{cond}} = -k_{i} A \left( \frac{T_{i} - T_{i+1}}{r} \right) - k_{i} A \left( \frac{T_{i} - T_{i-1}}{r} \right) 
\]

We may now substitute each component in the equation 19. This allows the temperature equation variation to be written as:

\[
T_{i+1} = \left( 1 - \frac{2k_{i+1} dt}{(E_{i+1}c_{i+1}\rho_{i+1} + E_{i+1} c_{i+1} \rho_{i+1}) E_{i+1}} \right) T_i + \left( \frac{2k_{i+1} dt}{m c E_{i+1}} \right) T_{i+1} + \left( \frac{2k_{i} dt}{(E_{i}c_{i}\rho_{i} + E_{i} c_{i} \rho_{i}) E_{i}} \right) T_{i-1} + \left( \frac{2 dt}{\rho E c} \right) \Bigg( Q_{\text{cond}} + Q_{\text{evap}} \Bigg) 
\]

III- Moisture Transfer Trough Comfort Liner:

1- Physical Model and Boundary Conditions:
In many cases, the comfort liner in helmet is made of urethane foam, covered with nylon or polyester webbing. In this study, we try to analyse moisture transfer from the head to the comfort liner. In our model, the comfort liner is covered with polyester fabric and we assume that the moisture transfer is limited to this fabric without taking into account the urethane foam. On the other hand, we neglect moisture transfer around the wearer neck. In this work, the helmet is standard without ventilation system.

Figure 2 shows the fibrous porous fabric in the shape of full half circle. One side of this fabric is exposed to an air-vapour mixture with fixed characteristics (velocity, temperature and humidity). The other, adiabatic and permeable, can also represent a plane of symmetry. The side length (E) is the fabric thickness. The porous fabric is composed of three phases which are: a nondeformable solid phase, a liquid phase and a gaseous phase which contains air and water vapour. Therefore, the model can be simplified to one dimensional physical configuration according to the r direction.

The moisture transfer in such system can be described by Whitaker theory (21). For this unsaturated porous media, a mathematical model governing heat and mass transfer is established. In order to obtain a closed set of governing macroscopic equations the following assumptions are made:
- The fibrous system is represented by an ideal and isotropic continuum medium.
- The three phases (solid, liquid and gas) are in local thermodynamic equilibrium.
- The compression-work and viscous dissipation are negligible.
- In the thermodynamic sense, the gas phase is considered as an ideal gas.
- The dispersion and tortuosity terms are interpreted as diffusion term.

**a- Generalized Darcy's law:** Darcy's law is generalized by using the concept of relative permeability. For the gaseous phase, since no gravitational effect, the average velocity \( \bar{V}_g \) is given by:

\[
P_g = \frac{LK}{\mu_g} (\bar{V}_g)
\]

(22)

where \( K \) is the intrinsic permeability, \( K_g \) the relative permeability to the gaseous phase, \( \bar{V}_g \) the average intrinsic pressure of the gaseous mixture and \( \mu_g \) the viscosity of the gaseous phase. For the liquid phase, the average velocity \( \bar{V}_l \) is given by:

\[
\bar{V}_l = -\frac{K_l}{\mu_l} \left[ \nabla (\bar{P}_l - P_c) + \bar{R}_l \right]
\]

(23)

where \( K_l \) the relative permeability to the liquid phase, \( P_c \) the capillary pressure, \( \mu_l \) the viscosity of the liquid phase, \( g \) the gravitational constant and \( \rho \) the density of liquid.

The capillary pressure \( P_c \) is considered as a characteristic of the porous medium and is a function only of the temperature and moisture content. The capillary pressure is defined as:

\[
P_c = \bar{P}_g - \bar{P}_l
\]

(24)

**b- Mass Conservation Equations:** For the gas phase, the average density \( \bar{\rho}_g \) is not constant. The mass conservation equation is given by:

\[
\frac{\partial \bar{\rho}_g}{\partial t} + \nabla \cdot (\bar{\rho}_g \bar{V}_g) = \dot{\dot{m}}
\]

(25)

Where \( \bar{\rho}_g \) is the intrinsic average density of the gas phase. Considering the vapor and air as perfect gases, this phase is considered as an ideal mixture. The mass conservation equation for the vapour phase is given by:

\[
\frac{\partial \bar{P}_v}{\partial t} + \nabla \cdot (\bar{P}_v \bar{V}_v) = \dot{\dot{m}}
\]

(26)

With

\[
\bar{P}_v \bar{V}_v = \bar{P}_g \bar{V}_g - \bar{\rho}_g \dot{\Delta}_{\text{eff}} \nabla \left( \bar{P}_g \right)
\]

\[
\dot{\Delta}_{\text{eff}} = \text{the coefficient of the effective diffusion of the vapour in the porous medium. This coefficient takes into account the resistance to the diffusion due the tortuosity and the effects of constriction.}

Assuming that liquid density is constant, the mass conservation equation of the liquid phase is:

\[
\frac{\partial \bar{\rho}_l}{\partial t} + \nabla \cdot (\bar{\rho}_l \bar{V}_l) = -\frac{\dot{\dot{m}}}{\rho_l}
\]

(28)

Where \( \dot{\dot{m}} \) is the mass rate of evaporation and \( \varepsilon \) is the volume fraction of the liquid phase.

**c- Energy Conservation Equation:**

The energy equation is given by:

\[
\frac{\partial}{\partial t} \left( \bar{\rho}_c C_s T \right) + \nabla \left( \bar{\rho}_c C_s \bar{V}_s + \sum \bar{\rho}_i C_i \bar{V}_i \right) \nabla - \nabla (\lambda_s \nabla T) = -\Delta H_{\text{vap}} \dot{\dot{m}}
\]

(29)

\( \Delta H_{\text{vap}} \) is a constant defined by:

\[
\Delta H_{\text{vap}}^\phi = \Delta H_{\text{vap}}^\phi + (C_{s_{\text{vap}}} - C_{s_{\text{sat}}}) \cdot T
\]

(30)

\( \Delta H_{\text{vap}} \) is the latent heat of vaporization, \( \lambda_{\text{vap}} \) and \( \bar{\rho}_s C_s \) are, respectively, the effective thermal conductivity and the constant pressure heat capacity of the porous medium, \( \bar{\rho}_s C_s \) is given by:

\[
\bar{\rho}_s C_s = \bar{\rho}_s C_{s_{\text{sat}}} + \bar{\rho}_s C_{s_{\text{vap}}} + \bar{\rho}_v C_{s_{\text{vap}}} + \bar{\rho}_a C_{s_{\text{sat}}}
\]

(31)

**d- Thermodynamic Relations:** The partial pressure of the vapour is equal to its equilibrium pressure:

\[
P_v = P_{v_{\text{eq}}} (T, S)
\]

(32)

\( S \) is the liquid saturation defined by \( S = \frac{\varepsilon_l}{\varepsilon} \)

(33)

The gaseous phase is assumed to be an ideal mixture of perfect gases:
\[ P_g = \beta_g \frac{RT}{M_g} \]  
\[ P_g = P_0 + P_i \]  
\[ \beta_g = \beta_v + \beta_a \]

### e- Initial Conditions
Initially, the temperature, the gas pressure and liquid saturation are uniform in the porous medium.

\[ T_i(r; t = 0) = T_{ini} \]  
\[ P_i(r; t = 0) = P_0 \]  
\[ \beta_i(r; t = 0) = \beta_{ini} \]

### d- Boundary Conditions
The free stream temperature, pressure and vapour concentration are constant and uniform. On the adiabatic and pervious sides, the mass and heat flux are null.

\[ \lambda_{(i)} \frac{\partial T}{\partial r} = 0 \]

On the permeable side, heat and mass fluxes can be written as follows:

\[ \left( \beta_g \xi V_1 + \beta_v \xi V_y \right) n_2 = h_m \left( \beta_g - \beta_0 \right) \]  
\[ \lambda_{(ef)} \frac{\partial T}{\partial r} + \Delta H_{vap} \left( \beta_g V_1 \right) n_2 = h_4 \left( T_T - T \right) \]  
\[ \beta_{ef} = P_{ef} \]

Where \( n_2 \) is the component of normal vector.

### RESULTS AND DISCUSSION

#### I/ Heat Transfer

1- **Microclimate Temperature Variation:** Figure 4 shows the temporal variation of the microclimate temperature. A comparison between our results with those from the experiment (Davis et al., 2001) shows a very good agreement. It can be seen that the temperature increases in the space between the subject’s head and the helmet until a steady state is reached, about 20 min.

![Fig. 3: Characteristics of the discretized domain](image)

![Fig. 4: Comparison between numerical prediction and experimental measurement](image)

2- **Effect of Liner Thickness on the Microclimate Temperature:**

a- **Effect of Microclimate Thickness:** It is worth mentioning that the temperature between the subject’s head and the helmet increased with the microclimate thickness (Figure 5). These results are in agreement with experiment results of G.T.Egglestone et al.\(^1\). It was observed that the microclimate temperature increased with the composite helmet insulating...
properties. The practical interest of these results is to inform helmet wearer to choose carefully a suitable helmet size. Tacking into account this technical point, the helmet designer have to hug the helmet to the head form.

**b- Effect of Comfort Liner Thickness:** The effect of comfort liner thickness on the microclimate temperature is shown in Figure 6. It can be seen that an increasing of comfort liner thickness decreases the microclimate temperature. Using a 2cm liner thickness instead of 5 mm, reduces the steady temperature by 1 °C. Therefore, the helmet designer have to thicken the comfort liner and to take into account, at the same time, the helmet form constraints.

**c- Effect of Inner Liner Thickness:** For helmet inner liner, the best choice is a foam, which can absorb the most energy per unit volume, while limiting the load on the human head to a less than damaging level. In the study of John et al., the foam thickness is usually determined by other constraints such as the practicality, styling, helmet weight or aerodynamics. Figure 7 demonstrates that the inner liner contributes, by its high insulation (low thermal conductivity) and the required thickness, to reduce microclimate temperature when the liner becomes more and more thick. The helmet designer has to search for a compromise between the helmet weight and its constraints form and to maximise the inner thickness.

**3- Effect of Liner Conductivity on the Microclimate Temperature:**

**a- Effect of Thermal Shell Conductivity:** The impact energy absorption provided by a safety industrial helmet is always of critical importance in material selection and design problem. Nevertheless, the shell thermal properties are determinants for helmet comfort especially in high temperature environment. In general two kinds of material are used for the outer shell helmet: one is thermo-injected plastic (for instance ABS or Polycarbonate) the other is reinforced resin material known among the public as ‘fibreglass’. The thermal conductivity of these materiel varies between 0.1 and 0.7 W/mK. In this range, the thermal conductivity variation has a slight effect on the shell temperature (0.2°C) as shown in Figure 8 and no considerable effect on the microclimate temperature (Figure 9). This trend can be explained by the high insulating property of the expended polystyrene liner. The practical interest here is to choose a shell material with a significantly insulation properties.

![Fig. 5: Microclimate temperature for different thickness](image1)

**Fig. 5:** Microclimate temperature for different thickness

![Fig. 6: Temporal microclimate temperature variation for different comfort liner thickness](image2)

**Fig. 6:** Temporal microclimate temperature variation for different comfort liner thickness

![Fig. 7: Temporal microclimate temperature variation for different inner liner thickness](image3)

**Fig. 7:** Temporal microclimate temperature variation for different inner liner thickness

![Fig. 8: Temporal helmet shell temperature for different thermal conductivity K(W/mK).](image4)

**Fig. 8:** Temporal helmet shell temperature for different thermal conductivity K(W/mK).
b- Effect of Inner Liner Conductivity: The inner liner is generally made from expanded polystyrene (EPS) or polypropylene (EPP) foam. The thermal conductivity of these foams depends on different parameters such as mass density and temperature\(^{[14]}\). Figure 10 indicates that the thermal conductivity of this liner has a significant effect on the comfort and microclimate temperature. When the thermal conductivity passes from 0.036 to 0.2 W/mK, the comfort liner temperature decreases by about 4 °C and its steady state is delayed after 50 minutes (Figure 11). On the other hand, the microclimate temperature decreases by 0.5°C for the same thermal conductivity variation. On the other hand, Figure 12 indicates that the helmet shell temperature is not considerably affected by the inner liner conductivity.

\[\text{Fig. 9: Temporal microclimate temperature for different thermal conductivity of helmet shell } K \text{ (W/mK).}\]

\[\text{Fig. 10: Comfort liner temperature for different inner liner thermal conductivity } K \text{ (w/mK).}\]

\[\text{Fig. 11: Microclimate temperature for different thermal conductivity of inner liner } K \text{ (w/mK).}\]

\[\text{Fig. 12: Inner liner temperature for different thermal conductivity } K \text{ (w/mK).}\]

\[\text{c- Effect of Comfort Liner Conductivity: Figure 13 indicates that the comfort liner temperature is in inverse proportion to its thermal conductivity. The temperature increases by 2 °C when the thermal conductivity passes from 0.2 to 1 W/mK. It’s clear that the temperature steady state is delayed for higher values. Similarly, the microclimate temperature is increased by 2°C when the comfort liner conductivity passes from 0.2 to 1 W/mK (Figure 14).}\]

\[\text{Fig. 13: Comfort liner temperature for different inner liner thermal conductivity } K \text{ (w/mK).}\]

\[\text{Fig. 14: Microclimate temperature for different inner liner thermal conductivity } K \text{ (w/mK).}\]

\[\text{4- Effect of Shell Emissivity and Colour: The material emissivity depends on several parameters such as colour and surface state. Figure 15 shows the outer shell temperature for different material emissivity. The material with low emissivity reduces the shell temperature for constant room temperature (figure 15).}\]

\[\text{Fig. 15: Outer shell temperature for different material emissivity.}\]
This trend is in agreement with many scientific and industrial studies on modified industrial helmets evaluation\(^\text{(13)}\). According to most of them, white helmets had some advantages in comfort towards reduction of heat, compared with other colours. In this way, improving insulation against solar heat focused on changing the surface of the helmet shell and increasing its emmissivity.

The inner and microclimate temperatures are not affected by the material emmissivity (Figure 16 and 17). These results can be explained by the fact that the inner liner has a low thermal conductivity.

5-Effect of Room Temperature: Obviously, the surrounding temperature has an important effect on the helmet wearer comfort. Therefore, we try to evaluate the influence of the room temperature on the shell and microclimate one. The temperature takes three levels: 32 °C, 36°C and 42°C. These levels are chosen to imitate the helmet behaviour in hot climate. The room temperature variations indicate that the shell and microclimate temperatures increase with the room temperature (Figure 18 -19). From Figure 18, we see that shell temperature increases by 11 °C as room temperature increases from 32°C to 42°C. On the other hand, this leads to a microclimate temperature rise from 37°C to 42°C (Figure 19).

II/ Moisture Transfer Model and Discussion:
1- Validation: Figure 20 shows the relative humidity normalised by the final equilibrium value. The individual points are taken from the Gibson experiment \(^\text{(8)}\) and the line show the prediction from the model. After an initial equilibrium period at 0% r.h, the humidity was risen to 65% in a single step. It is observed that the model is able to predict the moisture.
sorption with satisfactory accuracy. According to these results, polyester fabric has a small mass energy exchange with his environment. This can be explained by the low fibre hygroscopicity of the polyester.

Figures 21 and 22 show the predicted water vapour concentration distribution during moisture diffusion into the void spaces in the fabric respectively for different thickness and porosity. It is clear that the diffusion of water-vapour into the fabric through the void spaces is a fast process with a transient period which is related to fabric thickness and porosity. The water vapor concentration reaches steady and near-uniform distributions very quickly in all fabrics.

Fig. 17: Microclimate temperature for different material shell emissivity

Fig. 18: Shell temperature for different room temperature.

Fig. 19: Microclimate temperature for different room temperature.

Fig. 20: relative humidity comparison between numerical and experimental prediction.
Figures 23 and 24 illustrate that the penetration of liquid water into polyester fabric by capillary action is a fast process with a transient period, which is related to fabric thickness and porosity. As shown in figure 23, the transient period with a porosity of 0.8 is much higher and significant compared with a porosity of 0.4. Comparatively, the liquid fraction diffusion in fabric has almost the same patterns. It is interesting to note that there is an optimum point for liquid fraction depending on fabric porosity. Also, this transient period tends to increase with fabric thickness (figure 24).

Fig. 21: Distribution of water-vapor concentration in the void spaces in fabric for three thickness.

Fig. 22: Distribution of water-vapor concentration in the void spaces in fabric for three porosity.

The practical interest of these can be described as: when the relative humidity in the microclimate rises to 50%, the fabric takes about 20 minutes to be saturated by liquid. After this, the head surface becomes more and more wet.

The main conclusions of this study can be summarised in the following points:

• Safety helmet should be adjusted to fit the size of the users' heads for better comfort. On the other hand, the helmet designers have to hug the helmet to the head form reducing the microclimate temperature.

Conclusions: This study emphasizes the critical importance of taking into account thermal comfort in helmet material selection and design problem. The effect of liner thickness and material thermal conductivity on the microclimate temperature, are discussed in order to be optimised. A numerical approach is performed in order to investigate heat and moisture transfer in a standard helmet. In addition to energy approach used to choose material with good performance in impact and shock absorbing, the helmet designer is led to compromise mechanical with thermal properties. Some of practical points are suggested to improve helmet comfort and reduce microclimate temperature.
thickness around the wearer head.

- The inner liner must be as thick as possible in order to reduce microclimate temperature.
- The material used in helmet shell have close thermal conductivity values therefore, they have a slight effect on the microclimate temperature. Consequently, designers have to choose material with considerable insulation properties.
- High conductivity of inner liner are recommended to optimise helmet comfort.
- For comfort liner, high porosity is recommended to store more liquid volume and delay the discomfort feeling.
- Helmet designer have to compromise the thickness of comfort liner in order to reduce microclimate temperature and increase liquid volume storage.
- The comfort liner have to be as thick as possible in order to reduce the microclimate temperature.

REFERENCES