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# Local radiative heat transfer on a human body. Analyses through Modelling.

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## Abstract :

In usual moderate climate, convective and radiative heat exchanges are the main avenue for heat losses on a human body. For the evaluation of those processes, many problems are encountered and are different through calculation or measurement.

If a thermal mannequin is used the total dry losses are measured but it is difficult to determine the proportion of each component. On the other hand if those heat losses have to be calculated, then all local coefficients and temperatures are needed.

Radiation is now quite easy to calculate with accuracy. The approach proposed here is to find a better estimation of the radiative heat transfer coefficients through a modelling. So that if the same thermal conditions are performed with the mannequin, we will be able to evaluate the convective heat coefficients from the total sensible measured losses and the calculated radiative ones. Before doing these experiments, several numerical tests have to be done to find the best thermal configuration and analyse the effects of temperature or emissivity changes.

## Introduction

In usual indoor climate, sensible heat transfer represent more than 70 % of the total heat exchanges and have to be known with a good precision. When there is no sun, sensible losses are composed of convective, radiative and conductive transfer. Most of the time conduction is negligible.

The usual equations for heat flux calculations are [ASHRAE 1998] given in W/m<sup>2</sup>:

$$\text{Convection : } \varphi_C = f_{cl} \cdot h_c \cdot (T_s - T_{air}) \quad (1)$$

$$\text{Radiation : } \varphi_R = f_{cl} \cdot h_r \cdot (T_s - T_{mrt}) \quad (2)$$

$$\text{Dry : } \varphi_{Dry} = \varphi_C + \varphi_R = f_{cl} \cdot h_0 \cdot (T_s - T_{op}) \quad (3)$$

For  $h_c$  the convective heat exchange the widely accepted approximation are :

$$\text{natural convection : } h_c = \alpha \cdot (T_s - T_{air})^\delta$$

$$\text{forced convection : } h_c = \beta + \chi \cdot V_{air}^\eta$$

$\alpha$ ,  $\delta$ ,  $\beta$ ,  $\chi$  and  $\eta$  are coefficients that vary from one authors to another.

The radiative heat transfer coefficient  $h_r$  is estimated through:  $h_r = 4 \cdot \epsilon \cdot \sigma \cdot f_{eff} \cdot \{(T_s - T_{mrt})/2\}^3$

Where  $V_{air}$  is the air velocity,  $T_{air}$  air temperature and  $T_{mrt}$  mean radiant temperature,  $T_s$  is the mean surface temperature of the body (skin or clothing),  $T_{op}$  operative temperature,  $h_c$ ,  $h_r$  and  $h_0 = h_c + h_r$  are the heat transfer coefficients,  $f_{cl}$  is the clothing area factor,  $f_{eff}$  is the effective radiative coefficient depending on the posture,  $\epsilon$  is the mean body emissivity,  $\sigma$  the Stefan-Boltzman constant.

In all these equations each variable are more or less difficult to estimate. But most of them depend on the others.

While using a mannequin only  $\Phi_{Dry}$ , and climatic condition are measured ( $V_{air}$ ,  $T_{air}$ ,  $T_{mrt}$ ). Then coefficients are estimated. If a simulation is performed all coefficient are needed and then the fluxes are calculated.

Most papers deal with global heat exchanges but It has to be underlined that the conditions under study correspond to climatic chamber where surfaces temperature are quite homogen and radiant asymmetry are not too strong. To simulate human thermal physiological reactions in a complex thermal environment, both transient and inhomogeneous, local values of all coefficients are needed.

Convective heat transfer is difficult to calculate on a real body shape because local values of  $h_c$  are not known. Radiative exchanges are now quite easy to calculate with accuracy as long as all the data are known with a good precision ; temperature and emissivity of each surface, geometry of the body and the enclosure.

The aim of this paper is to make a numerical analysis to determine the sensitivity of the radiative local heat exchanges to different parameters. Then if radiation is calculated with a good precision convective heat transfer will be easy to determine from measured dry heat losses.

In our laboratory a 6 or 7 segments human thermoregulation model has been used for many years [Thellier 1994]. Therefore the analysis and comparison of our results will be done on the same body segments. Some example of local heat transfer coefficients of the literature given in table 1.

Dedear [2000] performed experiments using a thermal mannequin. A comparison is made between the fluxes lost from the nude surface ( $\epsilon_{\text{nude}}=0.95$ ) and from the

same one covered with aluminium ( $\epsilon_{\text{al}}=0.1$ ) in the same thermal conditions ( $T_{\text{air}}=T_{\text{mrt}}=T_{\text{op}}$ ). Taking into account that the radiative losses depends strongly on the emissivity of the body, the following equation is obtained  $h_{r,\text{nude}}/\epsilon_{\text{nude}}=h_{r,\text{al}}/\epsilon_{\text{al}}$ . It has been considered that in the two cases convection is the same, so finally  $h_r$  is determined :

$$h_{r(\text{nude})} = (1+\epsilon_{\text{al}}/\epsilon_{\text{nude}}) (h_{0,(\text{nude})}-h_{0,(\text{al})})=1.12(h_{0,(\text{nude})}-h_{0,(\text{al})})$$

Table 1 : Local heat transfer coefficients given by different authors.

posture	simple shapes $\epsilon_{\square}=?$ , natural convection Stowijk [1970]				Mannequin $\epsilon_{\square}=0.96$ Ichiura [95]		Mannequin $\epsilon_{\square}=0.95$ , $v_{\text{air}}<0.1$ m/s Dedear [2000]						
	S	$h_r$	$h_c$	$h_o$	standing		Seated				Standing		
					$h_r$	S	$h_r$	$h_c$	$h_o$	$h_r$	$h_c$	$h_o$	
Head	0.05	6.40	0.66	7.06		4.30	0.100	3.90	3.70	7.60	4.10	3.60	7.70
Trunk	0.54	5.24	1.86	7.10		3.77	0.459	4.30	2.80	7.11	4.35	3.13	7.48
Arms	0.31	5.24	3.95	9.19		3.95	0.250	4.97	3.57	8.53	5.08	3.23	8.31
Hands	0.09	3.49	6.05	9.54		3.70	0.075	3.90	4.50	8.40	4.10	4.10	8.20
Legs	0.64	5.24	3.61	8.85		4.50	0.503	4.88	3.81	8.69	4.65	4.10	8.75
Feet	0.13	4.65	5.93	10.58		7.30	0.084	4.20	4.20	5.10	3.90	5.10	5.10
<b>Gobal</b>	<b>1.75</b>	<b>4.30</b>	<b>3.37</b>	<b>7.67</b>		<b>4.70</b>	<b>1.471</b>	<b>4.50</b>	<b>3.30</b>	<b>7.80</b>	<b>4.50</b>	<b>3.40</b>	<b>7.90</b>

## METHOD

The usual equation (2) used for radiative heat transfer is a simplification from the general one for the entire body:  $\Phi_R=A_D.f_{\text{eff}}.f_{\text{cl}}.\epsilon.\sigma.(T_s^4-T_{\text{mrt}}^4)$  (W) (5)

$A_D$  is the total body surface,  $A_R$  is the radiative area,  $f_{\text{eff}}=A_r/A_D$  and depends on the posture.  $\epsilon$  is the emissivity of the body. This equation is correct as long as the view factor from the body to the environment is one. The fact that the body sees itself is encounter in  $f_{\text{eff}}$ . It also assumes that the body area is small compared to enclosure area and that all the emissivities of the enclosure are close to one.

If the flux is written in a usual way in thermal sciences, a detailed description of the environment is needed. The enclosure and the body are described by  $N$  surfaces ( $n_E$  surfaces for the environment and  $n_b$  for the body,  $N=n_E+n_b$ ). The hypothesis are; all the surfaces are grey and diffuse, each surface  $i$  is isothermal and its temperature fixed to  $T_i$ .

$\Phi_i^{\text{net}}$  is the net radiative flux exchange by the  $i^{\text{th}}$  segment of the body ( $i=1, n_b : n_b=6$  or  $7$ ).

$$\Phi_i^{\text{net}} = \sum_{j=1}^N \Phi_{i,j}^{\text{net}} = \sum_{j=1}^N S_i \cdot \epsilon_i \cdot B_{i,j} \cdot \sigma \cdot (T_i^4 - T_j^4) \quad (6)$$

$\Phi_{i,j}^{\text{net}}$  is the net radiative flux exchange between the  $i^{\text{th}}$  segment of the body and the other  $j^{\text{th}}$  surfaces ( $j=1, N$ ).

$S_i \cdot \epsilon_i \cdot B_{i,j}$  is the "exchange surface".  $B_{i,j}$  is the Gebhart factor that represent the portion of the energy emitted by surface  $i$  and absorbed by  $j$ . It takes into account that the emission from  $i$  can reach directly  $j$  or be reflected on all the other surfaces. (fig. 1). It depends on the emissivities of all the surfaces, and the view factors  $F_{i,j}$ .

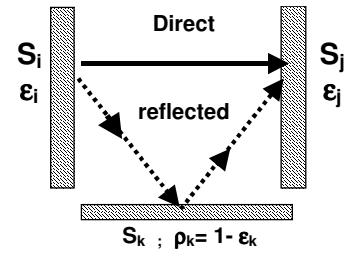


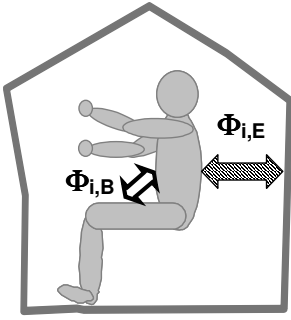
Figure 1 : Representation of the Gebhart factor

The total net heat flux exchanged by the entire body can be written:

$$\Phi = \sum_{i=1}^{n_b} \Phi_i^{\text{net}} = \sum_{i=1}^{n_b} \left[ \sum_{j=1}^N S_i \cdot \epsilon_i \cdot B_{i,j} \cdot \sigma \cdot (T_i^4 - T_j^4) \right] \quad (7)$$

This flux (eq 6) can be separated into two terms

$$\Phi_i^{\text{net}} = \sum_{j=1}^{n_b} \Phi_{i,j}^{\text{net}} + \sum_{j=n_b+1}^N \Phi_{i,j}^{\text{net}} = \Phi_{i,B}^{\text{net}} + \Phi_{i,E}^{\text{net}} \quad (7)$$



- $\Phi_{i,B}^{net}$  is the flux exchanged by the  $i^{th}$  segment with the entire Body,
- $\Phi_{i,E}^{net}$  is the flux exchanged by the  $i^{th}$  segment with the entire Enclosure.

The same decomposition can be written for the entire

$$\text{body: } \Phi = \sum_{i=1}^{nb} \Phi_i^{net} = \sum_{i=1}^{nb} [\Phi_{i,B}^{net} + \Phi_{i,E}^{net}] = \Phi_B^{net} + \Phi_E^{net} \quad (8)$$

This expression (8) can be compared with equation (5) by using the usual definition of the mean radiant temperature which is "the temperature of a uniform black enclosure in which a solid body or occupant would exchange the same amount or radiant heat as in the existing non-uniform environment".

In this definition the first part, "uniform black enclosure" leads to  $\epsilon_j=1$  and  $T_j=T_{mrt}$  for the enclosure ( $J=n_b+1$  to  $N$ ). in the second part "existing non uniform environment" is difficult to interpret.

If "environment=enclosure" then we get:

$$\Phi_{i,E,real}^{net} = \Phi_{i,E,Unif}^{net}$$

$$\Phi = \sum_{i=1}^{nb} \left[ \sum_{j=1}^N S_i \epsilon_i B_{i,j} \sigma (T_i^4 - T_j^4) \right] = A_D \cdot f_{eff} \cdot f_{cl} \cdot \epsilon \cdot \sigma (T_s^4 - T_{mrt}^4)$$

With  $A_D = \sum_{i=1}^{nb} S_i$  body area

If for a segment the environment is also composed of the other part of the body then the definition is more complex.

### a) Black body surfaces and isothermal enclosure

In a simple case the comparison between those two equations can be done:

- Black body surface (human body and enclosure)
- :  $\epsilon_i = 1$  then  $B_{i,j} = F_{i,j}$
- Nude mannequin  $f_{cl}=1$
- Isothermal mannequin  $T_i = T_s$  for  $i=1$  to  $n_B$
- Isothermal enclosure  $T_j = T_m$  for  $j=1$  to  $n_E$

$$\Phi_B^{net} = 0$$

$$\Phi = \sum_{i=1}^{nb} \Phi_i^{net} = \Phi_E^{net} = \sigma \cdot (T_s^4 - T_m^4) \sum_{i=1}^{nb} [S_i \cdot \sum_{j=nb+1}^N F_{i,j}] \quad (7')$$

$$\text{and } \Phi = A_D \cdot f_{eff} \cdot \sigma \cdot (T_s^4 - T_{mrt}^4) \quad (8')$$

The definition of  $T_{mrt}$  leads to  $T_{mrt}=T_m$  thus: the comparison between (7') and (8') leads to :

$$f_{eff} = A_R / A_D = \left\{ \sum_{i=1}^{nb} S_i \sum_{j=nb+1}^N F_{i,j} \right\} / \left\{ \sum_{i=1}^{nb} S_i \right\}$$

The same equation can be written for each segment.

$$\Phi_{i,B}^{net} = 0 \text{ then } \Phi_i^{net} = \Phi_{i,E}^{net} = S_i \cdot \sigma \cdot (T_s^4 - T_m^4) \sum_{j=nb+1}^N F_{i,j}$$

$$\Rightarrow f_{eff,i} = \sum_{j=nb+1}^N [F_{i,j}] \quad \text{and} \quad f_{eff} = \left\{ \sum_{i=1}^{nb} S_i \cdot f_{eff,i} \right\} / \left\{ \sum_{i=1}^{nb} S_i \right\}$$

Heat transfer coefficients can then be calculated:

$$h_{r(i)} = f_{eff(i)} \cdot \sigma \cdot (T_s^2 + T_{mrt}^2) \cdot (T_s + T_{mrt})$$

### b) real cases

In real case where the enclosure and the body are not isothermal and emissivities are different from 1. The equations are more complicated to interpret.

In the equation  $\Phi_R = A_D \cdot f_{eff} \cdot f_{cl} \cdot \epsilon \cdot \sigma \cdot (T_s^4 - T_{mrt}^4)$  that define an equivalent enclosure the hypothesis are:  $\epsilon$  and  $T_s$  are mean values suppose to be the same all over the body :  $\epsilon_i = \epsilon$  and  $T_i = T_s$  for  $i=1$  to  $n_b$ . In the definition of  $T_{mrt}$  if we consider that the enclosure then:  $\epsilon_j = 1$  and  $T_j = T_{mrt}$  for the enclosure ( $j = (n_b+1)$  to  $N$ ) :

Real environment:  $\Phi^{net} = \Phi_B^{net} + \Phi_E^{net}$

$$\Phi^{net} = \sum_{i=1}^{nb} \left[ \sum_{j=1}^{nb} S_i \epsilon_i B_{i,j} \sigma (T_i^4 - T_j^4) + \sum_{j=nb+1}^N S_i \epsilon_i B_{i,j} \sigma (T_i^4 - T_j^4) \right]$$

Equivalent conditions:  $\Phi^{net} = \Phi_{B,equ}^{net} + \Phi_{E,equ}^{net}$   $\Phi_{B,equ}^{net} = 0$

$$\Phi^{net} = \sum_{i=1}^{nb} \left[ \sum_{j=nb+1}^N S_i \epsilon_i B_{i,j} \sigma (T_s^4 - T_{mrt}^4) \right] = A_D \cdot f_{eff} \cdot \epsilon \cdot \sigma \cdot (T_s^4 - T_{mrt}^4)$$

$$f_{eff} = \left[ \sum_{i=1}^{nb} S_i \sum_{j=nb+1}^N B_{i,j} \right] / \left[ \sum_{i=1}^{nb} S_i \right]$$

But here the problem occur to estimate  $T_s$ ,  $\epsilon$  and  $T_{mrt}$

If the same equation is written for a segment

Real environment:

$$\Phi_i^{net} = \sum_{j=1}^{nb} S_i \epsilon_i B_{i,j} \sigma (T_i^4 - T_j^4) + \sum_{j=nb+1}^N S_i \epsilon_i B_{i,j} \sigma (T_i^4 - T_j^4)$$

Equivalent conditions:

Those conditions are impossible to fix it depends if the other segment of the body are part of the environment or not

If the entire environment is consider then

$$\Phi_i^{net} = \Phi_{i,equ}^{net}$$

$$\sum_{j=1}^{nb} S_i \epsilon_i B_{i,j} \sigma (T_i^4 - T_j^4) + \sum_{j=nb+1}^N S_i \epsilon_i B_{i,j} \sigma (T_i^4 - T_j^4) = S_i \cdot f_{eff,i} \cdot \epsilon_i \cdot \sigma (T_i^4 - T_{mrt}^4)$$

$$\sum_{j=1}^N B_{i,j} (T_i^4 - T_j^4) = f_{eff,i} (T_i^4 - T_{mrt}^4)$$

If the environment is only the enclosure then

$$\Phi_i^{net} = \Phi_{i,B}^{net} + \Phi_{i,E}^{net} = \Phi_{i,B}^{net} + \Phi_{i,E,equ}^{net}$$

$$\sum_{j=nb+1}^N B_{i,j} (T_i^4 - T_j^4) = f_{eff,i} (T_i^4 - T_{mrt}^4)$$

It can be seen on this equation that in the definition above it has to be precise if the other parts of the body is part of the environment or not.

## RESULTS

The main problem for the calculation of radiative exchanges is that first view factors are needed. To perform this precise description of the geometry is

needed. The method that has been used in our laboratory for many years is the Monte-Carlo method that calculate the view factors between small plane surfaces that are then regrouped in "group surface" that have the same temperature and thermal properties. In the example given here the body and the enclosure are composed first of thousands of elementary surfaces that have been created with a CAD software. Then groups are created so that the body is composed of 7 groups that correspond to our human thermoregulation model, the enclosure in that case is composed of 21 groups.

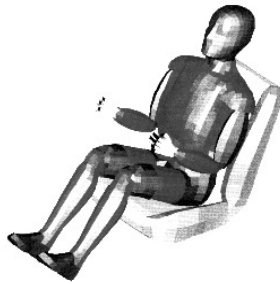


Figure \*\*: representation of the human body for view factors calculation.

**a) Black body surfaces**

In this case all the surface are black body surfaces, The body temperature is fixed to  $T_s=33^\circ\text{C}$  for all segments and the enclosure varies from  $10^\circ\text{C}$  to  $40^\circ\text{C}$ . First the  $f_{\text{eff}}$  is calculated from equation (\*\*). The results are given in Tab.2. It can be noticed that the global values are close to those found in the literature.

Table.2: Area and effective radiant factor for each segment for 3 different CAD descriptions.

segments	N° 1		N°2		N°3	
	$S_i$	$f_{\text{eff}}$	$S_i$	$f_{\text{eff}}$	$S_i$	$f_{\text{eff}}$
Head	0.125	0.859	0.145	0.939	0.169	0.792
Trunk	0.496	0.833	0.404	0.705	0.379	0.680
Right Arm	0.087	0.861	0.173	0.572	0.334	0.668
Left Arm	0.086	0.865	0.162	0.623		
Hands	0.072	0.839	0.036	0.844	0.078	0.885
Legs	0.471	0.774	0.405	0.903	0.702	0.770
Feet	0.152	0.888	0.089	0.942	0.088	0.734
<b>Total</b>	<b>1.489</b>	<b>0.825</b>	<b>1.414</b>	<b>0.779</b>	<b>1.750</b>	<b>0.737</b>

In the configuration n°1 and 2 the total area is smaller than in n° 3 because the body is seated in a seat and the surface in contact have not been taken into account in the radiation calculation.

In black body surface condition we can then calculate  $h_{r(i)} = \Phi_{R,(i), \text{ calculated}} / S_i \cdot (T_i - T_{\text{mrt}})$ . Results are given in table 3.

Table ?? : local radiative fluxes and radiative coefficients for different wall temperatures

Seg.	$T_m=20^\circ\text{C}$		$T_m=30^\circ\text{C}$		$T_m=40^\circ\text{C}$	
	$\Phi$	$h_r$	$\Phi$	$h_r$	$\Phi$	$h_r$
Head	-8.51	5.24	-2.06	5.50	5.05	5.78
Trunk	-32.78	5.08	-7.95	5.34	19.47	5.61
Right Arm	-5.93	5.25	-1.44	5.52	3.52	5.79
Left Arm	-5.93	5.28	-1.44	5.55	3.52	5.82
Hands	-4.80	5.12	-1.16	5.38	2.85	5.65
Legs	-28.88	4.72	-7.00	4.96	17.15	5.21
Feet	-10.74	5.42	-2.60	5.69	6.38	5.98
<b>Total</b>	<b>-97.55</b>	<b>5.04</b>	<b>-23.65</b>	<b>5.29</b>	<b>57.94</b>	<b>5.56</b>

Table ?? : local radiative fluxes and radiative coefficients for emissivities.

Seg.	$\epsilon=1$		$\epsilon=0.96$		$\epsilon=0.96$ $\epsilon_{\text{arm}}=\epsilon_{\text{legs}}=0.1$	
	$\Phi$	$h_r$	$\Phi$	$h_r$	$\Phi$	$h_r$
Head	-8.51	5.24	-8.10	4.99	-8.24	5.07
Trunk	-32.78	5.08	-31.22	4.84	-32.37	5.02
Right Arm	-5.93	5.25	-5.64	5.00	-0.64	0.56
Left Arm	-5.93	5.28	-5.64	5.02	-5.99	5.33
Hands	-4.80	5.12	-4.57	4.88	-4.92	5.25
Legs	-28.88	4.72	-27.61	4.51	-3.37	0.55
Feet	-10.74	5.42	-10.21	5.15	-10.49	5.29
<b>Total</b>	<b>-97.55</b>	<b>5.04</b>	<b>-92.99</b>	<b>4.80</b>	<b>-66.01</b>	<b>3.41</b>

**DISCUSSION**

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