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ANALYSIS OF HUMAN'S RADIATIVE EXCHANGE IN A COMPLEX ENCLOSURE

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ABSTRACT
The human being’s thermal comfort depends on the heat exchanges with the environment (convection, radiation, etc.). These are difficult to evaluate accurately and may need complex metrology. We are particularly interested in infra-red radiative exchanges, which can represent a large part of the global sensible heat exchanges (up to 70 %).

In complex thermal conditions, in a vehicle for example, the person is exposed to different radiative sources like a very hot dashboard in summer (up to 80°C) or ice-cold windows in winter (below 0°C). As surface temperatures in the vehicle vary greatly, care is needed when choosing the positions of the fluxmeters on the human body. To define these positions we use a model which calculates the net radiative heat fluxes between the driver and his environment.

The first step of the study uses Gebhart method for a quick and simple evaluation of the fluxes. The vehicle and the driver are represented by a grey, diffuse enclosure composed of 22 surfaces: 7 describing the human body (head, legs, etc.) and 15 for a simplified geometry of the surroundings (windshield, windows, etc.). The temperatures and radiative properties are known. After a preliminary calculation of the view factors, using the Monte-Carlo method, and then of the Gebhart factors, net radiative heat fluxes between each of the body segments and each of the environmental surfaces \( \phi_{i,j} \) can be estimated rapidly.

This tool allows us to point out the major elements of the radiative ambience for a given thermal condition. These elements are considered as "active", i.e. playing a major role in direct or indirect (after reflection on other surfaces) exchanges.

We will be able to optimise the metrology (by reducing the number of sensors and by determining the best locations to place them), based on the determination of the "active" surfaces.

**Key words:** Radiative exchanges human thermal comfort

**Nomenclature**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B )</td>
<td>Gebhart factor</td>
</tr>
<tr>
<td>( F )</td>
<td>form factor</td>
</tr>
<tr>
<td>( S_{i} )</td>
<td>area of surface ( i ), m²</td>
</tr>
<tr>
<td>( T )</td>
<td>temperature, K</td>
</tr>
<tr>
<td>( \varepsilon )</td>
<td>hemispherical emissivity</td>
</tr>
<tr>
<td>( \phi )</td>
<td>radiative flux, W</td>
</tr>
<tr>
<td>( \rho )</td>
<td>hemispherical reflectivity</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>Stefan-Boltzmann constant, W.m⁻².K⁻⁴</td>
</tr>
</tbody>
</table>

Greek symbols

\( B \) Gebhart factor
\( \varepsilon \) hemispherical emissivity
\( \phi \) radiative flux, W
\( \rho \) hemispherical reflectivity
\( \sigma \) Stefan-Boltzmann constant, W.m⁻².K⁻⁴

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1. INTRODUCTION
The main aim of this study was to implement a method for simplifying the calculation of the radiative exchanges between a human being and an environment in which the temperatures of the surfaces were heterogeneous. Most of the time, radiative exchanges are calculated using a mean radiant temperature which completely masks the variations. It must be mentioned that heterogeneity often results in complaints about local discomfort and that radiative exchanges represent a high proportion of dry exchanges. It is impossible to measure radiative exchanges, so they must be calculated very precisely.

After emitting several hypotheses, we assimilated the problem to the calculation of the net radiative fluxes exchanged in a closed compartment having a complex geometry. We faced this problem during the study of the thermal comfort of a car driver.

We first describe the method used to calculate the radiative exchanges and then, in the second part, adapt this computing tool to the evaluation of the net radiative fluxes exchanged between a driver and his car. The objective is to bring out which elements of the inside of the car influence the radiation balance of the human body so as to write the radiation balance $\phi$ of element $i$ in the form $\phi_i = \sum_{k=1}^p \phi_{ik}$, where $\phi_{ik}$ are the net fluxes exchanged between $i$ and the $p$ preponderant surfaces of an enclosure comprising $n$ surfaces ($p \leq n$).

2. METHOD FOR COMPUTING NET FLUXES EXCHANGED
Among the various methods for calculating radiative fluxes within a closed grey diffuse enclosure [Siegel, 1992], we chose the matrix inversion method explicitly bringing in the Gebhart factors. By definition, the Gebhart factor $B_{ij}$ (or absorption factor) between two surfaces $S_i$ and $S_j$ represents the fraction of the energy emitted by $S_i$ that is absorbed by $S_j$. It is an "improved" view factor that takes all the optical paths from $S_i$ to $S_j$ into account whether the paths are direct or include reflections on the other surfaces. It thus depends on all the view factors $F_{ij}$ (which only depend on the geometry) and also on the radiative properties of all the surfaces.

2.1. Hypotheses - establishing the equations
We made the following assumptions:
- Each surface is isothermal, opaque, grey, and diffusing both for emission and reflection.
- The flux is uniformly distributed over the walls.
- The ambient medium is transparent and without effect.
- The temperatures and emissivities of the surfaces are known.

The net flux exchanged $\phi_{i,net}$ can be expressed as the difference between the flux emitted by $S_i$ and the flux coming from other surfaces which is absorbed by $S_i$.

We thus obtain:

$$\phi_{i,net} = \varepsilon_i S_i \sigma T_i^4 - \sum_{j=1}^{n} \varepsilon_j S_j B_{ij} \sigma T_j^4$$

$$\varepsilon_i S_i \sigma T_i^4$$ energy emitted by $i$.

$$\varepsilon_j S_j B_{ij} \sigma T_j^4$$ energy emitted by $j$ and absorbed by $i$. 

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Using the equations of reciprocity \( \varepsilon_i S_i B_i = \varepsilon_j S_j B_j \) and complementarity \( \sum_{j=1}^{n} B_j = 1 \) in equation (1), we have:

\[
\phi_{i,net} = \sum_{j=1}^{n} \varepsilon_j S_i B_j \sigma T_i^4 - \sum_{j=1}^{n} \varepsilon_i S_j B_j \sigma T_j^4 = \sum_{j=1}^{n} \varepsilon_i S_i B_{ij} \sigma (T_i^4 - T_j^4) = \sum_{j=1}^{n} \phi_{j,net}
\]

The net flux \( \phi_{i,net} \) exchanged between two surfaces \( S_i \) and \( S_j \) can then be written:

\[
\phi_{j,net} = \varepsilon_i S_i B_{ij} \sigma (T_i^4 - T_j^4)
\]

(2)

In addition, using equation (2), we evaluate the uncertainties \( \Delta \phi_{i,net} \) associated with each net flux from the absolute errors on \( B_{ij} \) (and thus \( F_{ij} \)). The measurement errors on the temperatures and emissivities are assumed to be known.

2.2. Calculation of \( B_{ij} \)

An exact calculation of the \( B_{ij} \) factors would require a ray following method involving the radiative properties of each surface. This approach would be too complicated for the objectives fixed. Another method consists in deducing the form factors \( F_{ij} \), which, for complex geometries, are calculated by a Monte-Carlo statistical method [Bru,1983]. The quanta of energy are emitted by all the surfaces \( i \) and are counted when they arrive on surface \( j \) (\( N_{ij} \)). The \( F_{ij} \) are deduced from the \( N_{ij} \) in such a way as to respect the closing and reciprocity conditions : \( \sum_{j=1}^{n} F_{ij} = 1 \) and \( S_i F_{ij} = S_j F_{ji} \).

The \( B_{ij} \) are calculated from a linear system [Siegel,1992] that directly gives the equation for figure 1.

\[
B_{ij} = F_{ij} \varepsilon_j + \sum_{k=1}^{n} \rho_k F_{ik} B_{kj}
\]

(3)

Figure 1 : Optical path between two surfaces

- \( F_{ij} \varepsilon_j \) is the fraction of the direct flux emitted by \( i \) and absorbed by \( j \).
- \( \sum_{k=1}^{n} \rho_k F_{ik} B_{kj} \) is the fraction of the flux reflected on the other surfaces and then absorbed by \( j \).

Equation (3) can also be written : \( \sum_{k=1}^{n} [\delta_k - \rho_k F_{ik}] B_{kj} = \varepsilon_j F_{ij} \) where \( \delta_k \) is Kronecker’s symbol. The matrix of the \( B_{ij} \) can be obtained from the matrix solution of the equation \( B = M^T F \) with:

\[
M = \begin{pmatrix}
1 - \rho_1 F_{i1} & -\rho_2 F_{i2} & \cdots & -\rho_n F_{in} \\
-\rho_1 F_{j1} & 1 - \rho_2 F_{j2} & \cdots & -\rho_n F_{jn} \\
\vdots & \vdots & \ddots & \vdots \\
-\rho_1 F_{ni} & \cdots & \cdots & 1 - \rho_n F_{nn}
\end{pmatrix}
\]

and

\[
F = \begin{pmatrix}
F_{11} \varepsilon_1 & F_{12} \varepsilon_2 & \cdots & F_{1n} \varepsilon_n \\
\vdots & \vdots & \ddots & \vdots \\
F_{n1} \varepsilon_1 & \cdots & \cdots & F_{nn} \varepsilon_n
\end{pmatrix}
\]
2.3. Exploitation

Writing the radiation balance as a discrete sum of net fluxes exchanged between two surfaces makes it possible to highlight the principal net fluxes and thus to establish a hierarchical order of fluxes.

Moreover, if equation (2) is considered as the product of an "optic-geometrical" term $S_i \varepsilon_i B_i$ and a term relative to the temperature differences $\sigma (T'_i - T'_j)$, it is possible to work back to the 'physical' causes of an exchange.

Finally, a sensitivity analysis gives an indication of the importance of the physical parameters (areas, emissivities, etc.).

3. APPLICATION TO CAR DRIVER'S RADIATIVE EXCHANGES

3.1. Presentation

The car driver's thermal comfort depends on the heat exchanges he has with the inside of the car. Here we are concerned with the radiative exchanges between the driver and his environment, rightly considered as very non-uniform from several points of view: temperatures of the car body walls, their radiative properties and their complex geometry.

Once seated at the wheel, the driver finds himself exposed to various radiative sources such as a burning hot dashboard or ice-cold windows. The human body is constantly subjected to differences of temperature of the elements around it. It is for this reason that the calculation of its radiative exchanges is indispensable in the investigation of any thermal balance.

Following previous studies, the geometry of the system under study (driver and his compartment) was simplified [Thellier, 1995]. We considered an enclosure representing the inside of the car in which the driver was seated. The person and compartment were divided into more than 500 plane triangular or quadrangular surface elements. This large number of elements led us to group together those with similar radiative properties and temperatures so as to have 22 isothermal panels or groups of surfaces to work with (Figure 2).

The first 7 described the geometry of the human body and represented its major segments (head, trunk, right arm, left arm, hands, legs, feet). The other 15 were used for a geometrical description of the driver's compartment (roof, windows, seat, etc.). The geometry of each surface was taken from a CAD file provided by the manufacturer and simplified for our purposes.
3.2. Results

Two sets of ambient conditions were studied. One was characteristic of a "hot" environment where the average temperature of the 22 surfaces varied between 10°C and 54°C while the other was representative of a "cold" thermal environment where the temperatures of the surfaces were between 1°C and 7°C. All the surface temperatures corresponded to real data obtained on the road (Table 1).

The skin temperatures were taken from a human thermal regulation model (Mather) based on Stolwijk’s model [Thellier,1994, Stolwijk,1970]. This model supplies the local thermal sensory judgments of an individual and his local surface temperatures (skin or clothing) according to the thermal environment he is faced with. It was thus possible to carry out tests varying i) the emissivities and ii) the surface temperatures of the enclosure [Leduc,1999].

<table>
<thead>
<tr>
<th>Group number</th>
<th>Name</th>
<th>cold’ environment</th>
<th>'hot' environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Dashboard</td>
<td>5.5</td>
<td>24.5</td>
</tr>
<tr>
<td>11</td>
<td>Back roof</td>
<td>3.5</td>
<td>18.5</td>
</tr>
<tr>
<td>12</td>
<td>Uprights</td>
<td>4.5</td>
<td>20</td>
</tr>
<tr>
<td>13</td>
<td>Driver's seat</td>
<td>3</td>
<td>29</td>
</tr>
<tr>
<td>14</td>
<td>Windows</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>15</td>
<td>Windscreen</td>
<td>0.5</td>
<td>17</td>
</tr>
<tr>
<td>16</td>
<td>Head-rest</td>
<td>4.5</td>
<td>27.5</td>
</tr>
<tr>
<td>20</td>
<td>Doors</td>
<td>3</td>
<td>17</td>
</tr>
<tr>
<td>21</td>
<td>Front roof</td>
<td>3.5</td>
<td>34</td>
</tr>
</tbody>
</table>

3.2.1. Display of active surfaces

Once the matrix $\phi_i$ had been established, it was necessary to present the results as a whole. We obtained a rapid display of the various net fluxes by means of a color table (Figure 3) bringing out the predominant radiative exchanges. Each square $(i,j)$ of the table corresponds to a net exchanged flux $\phi_{ij}$, the value of which corresponds to the brightness of the color. This display instrument is a very handy investigation device as it highlights the surfaces that are important for radiative exchanges among any of the enclosure surfaces.

This table must fulfil two essential conditions:

- Be symmetrical since $\phi_{ij} = -\phi_{ji}$.
- Have a scale suited to the uncertainty on the fluxes.

Figure 3 gives an example of the radiative exchanges for a hot configuration with the given temperatures and emissivities. The highest fluxes are shown by the darkest squares. Particularly noteworthy is the fact that the radiation of the human body on to itself is negligible relative to the other exchanges.

We could also show two other tables representing the terms $e S B_i$ and $\sigma (T_i^+ - T_j^+)$ of equation (2) in order to see whether high fluxes were due to large temperature differences or to high improved form factors.
3.2.2. Influence of emissivity

The emissivities of the groups were mostly fixed close to 1 except for the so-called reflecting groups composed of the windows and windscreen. In the first example, shown in figure 4, the environment is 'cold' and we consider the radiative fluxes at the head level (32.5°C) for two different window emissivities (\( \varepsilon = 0.9 \) and \( \varepsilon = 0.2 \)). It can be seen that the lowering of the emissivity of the cold window (1°C) leads to a strong reduction in the head-window exchanges. Moreover, since the window becomes a good reflector, a clear increase is seen in the exchanges between the head and the surfaces near the window (exchanges with the dashboard are doubled, this phenomenon being connected with reflection on the window of the flux emitted by the dashboard at 5°C). It should be noted that the head's exchanges with the other body segments are not zero as the subject is warmly dressed and the surface temperature of the clothed parts is much lower than head’s one, which is uncovered.

![Figure 3: Net flux display table](image)

**Figure 3 : Net flux display table**

3.2.3. Influence of temperature

In the second example, figure 5, the surface temperatures are varying from a 'cold' environment to a 'hot' one. We observe the effects on the radiative exchanges of the
head, whose temperature changes from 32.5°C to 33°C. All emissivities were set at 0.9. In the cold environment, practically all the surfaces of the enclosure are to be taken into account.

In the hot environment, the head's exchanges with the roof and the windows are largely preponderant. But it should be noted that the temperatures are close to the head temperature, which means that all the fluxes are smaller than in the 'cold' case.

These series of tests not only brought out the active surfaces of the enclosure (or human body) for a given thermal configuration but also enabled us to observe the effects caused by changes in the thermal conditions.

![Figure 5: Variations of net fluxes on head for different wall temperatures](image)

4. CONCLUSION

The method presented enables the evaluation of the net radiative fluxes between a human being and his environment. This tool has the advantages of being easy to use and, particularly, of being able to adapt to any kind of geometry provided that it is described in a CAD file. After identifying the important radiative fluxes at body level, we used several series of tests to determine which environmental surfaces were active with respect to each segment. For example, it is clear that a window is an active surface in any conditions if its emissivity is high. In contrast, it no longer plays a directly predominant role if its emissivity is low.

We can thus set up measuring systems directly based on these results so as to measure only the essential parameters. This could provide a way of optimizing the positions of the various sensors in order to obtain faster, simpler access to radiative transfers on the human body in complex thermal conditions or envisage better spatial uniformity of the fluxes exchanged by adjusting the emissivities of the surrounding surfaces, to try to better distribute the flux emitted by a heating body, for example.

REFERENCES


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Université Paul Sabatier, 118, route de Narbonne, 31062 Toulouse Cedex 4 - France

- Objectives
- Mathematical model
- Application: Car driver’s radiative exchanges
- Conclusions & Perspectives

OBJECTIVES

- Implement a method for simplifying the calculation of the radiative exchanges between a human being and an enclosure (complex and non homogeneous)

- **Application**: compute car driver’s radiative exchanges
  - Display: active surfaces in complex thermal conditions
  - Analyse: sensitivity of the fluxes to different parameters
**MATHEMATICAL MODEL (1)**

**Computation of net fluxes exchanged**

**Usual method** ⇒ \( \phi_{i,\text{net}} = \phi_{\text{emitted}} - \phi_{\text{absorbed}} \)

**Gebhart method** ⇒ \( \phi_{i,\text{net}} = \sum_{j=1}^{n} \phi_{ij,\text{net}} \)

\[ \phi_{ij,\text{net}} = \varepsilon_i S_i B_{ij} \sigma (T_i^4 - T_j^4) \]

Gebhart factor

- **Exchange Area** (\( m^2 \))
- **Flux density** (\( W/m^2 \))

**MATHEMATICAL MODEL (2)**

**Assumptions**

- Each surface: isothermal, opaque, grey, diffusing (emission and reflection)
- Flux: uniformly distributed over the surface
- Ambient medium: transparent ⇒ \( T_{\text{air}} \) without effect on the fluxes

**Geometry (view factors \( F_{ij} \))**

\( B_{ij} \) Gebhart factors (or absorption factors)

\( T_i \) Boundary conditions

\( \phi_{ij,\text{net}} \) Net fluxes exchanged
Person & Compartment: divided into 22 groups of isothermal surfaces (after simplification)

- Closed enclosure
- Temperatures and emissivity fixed

### Body surfaces

<table>
<thead>
<tr>
<th>Group number</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Head</td>
</tr>
<tr>
<td>2</td>
<td>Trunk</td>
</tr>
<tr>
<td>3</td>
<td>Right arm</td>
</tr>
<tr>
<td>4</td>
<td>Left arm</td>
</tr>
<tr>
<td>5</td>
<td>Hands</td>
</tr>
<tr>
<td>6</td>
<td>Legs</td>
</tr>
<tr>
<td>7</td>
<td>Feet</td>
</tr>
</tbody>
</table>

### Some of the enclosure surfaces

<table>
<thead>
<tr>
<th>Group number</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Dashboard</td>
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<td>11</td>
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<td>Head-rest</td>
</tr>
<tr>
<td>20</td>
<td>Doors</td>
</tr>
<tr>
<td>21</td>
<td>Front roof</td>
</tr>
</tbody>
</table>

\[ \phi_{ij,\text{net}} = S_{ij} \times T_{ij} \]
Influence of Temperature $(\varepsilon_{\text{windows}} = 0.9)$

Influence of windows emissivity $(\varepsilon_{\text{windows}})$

### CONCLUSIONS & PERSPECTIVES

#### Conclusions

- Computation of radiative exchange
  \[ \Rightarrow \text{identification of predominant surfaces} = \text{“active” surfaces} \]
- Methodology well adapted for heterogeneous environment

#### Perspectives

- Optimise the metrology based on the determination of the “active” surfaces
- Inverse analysis to compute an equivalent radiative environment