SIMULATION OF THERMAL BUILDING STATE IN SUMMER — STUDY OF RESULTS UNCERTAINTIES FOR THERMAL AMBIENT PREDICTION

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ABSTRACT

In this paper, the authors have developed a double study on the building thermal comfort models. The first step concerns the comparison between three models well known in specialized literature: FANGER’s thermal comfort model taken as the reference model, elaborated by Denmark University of Lingby; DEVAL and BERGER’s model, elaborated by Centre National de la Recherche Scientifique of France; and SHERMAN’s model, elaborated by University of Berkeley, USA. After a complete description of the three models, they only compared their results, the predicted mean vote, with a protocol defined in the text. This leads to predict the user’s thermal sensation PMV with each model, on two climatic sets, warm and hot in summer, taking an example of a building. Comparison shows quasi constant analogy or differences between the reference model and others. With the warm climatic set, FANGER’s and SHERMAN’s model provide almost the same results, and the results obtained with DEVAL and BERGER’s model have a constant 0.5 PMV unity difference. With the hot climatic set, a 0.25 PMV unity constant difference is observed for the SHERMAN’s model, whereas DEVAL and BERGER’s model results are almost similar.

The second step of the study concerns the propagation of data uncertainties on the PMV output of the three models. Two methods are used in order to define the uncertainty result interval: the probabilist Quasi Monte Carlo method and the Finite Differences Differential Analysis. Authors present those two methods and define hypothesis for each data uncertainty domain. In the first time, they observe the Quasi Monte Carlo method allows a similar uncertainty field to that of Finite Differences Differential Analysis method. They conclude on the quality of Finite Differences Differential Analysis method, which has proven its reliability and its performance with its very low computation time compared with the Quasi Monte Carlo method. Then, they obtain uncertainties with 1 Predicted Mean Vote unity wide domain. Finally, they notice that the accumulation of uncertainties due to the modelization and the data uncertainties can provide important variations of results, which must be known by building engineers and designers.

1. INTRODUCTION

For several decades, the physical representation of thermal interactions between the body and the thermal ambient in which the human being lives has been the subject of many studies dealing essentially with ergonomics. The research and the observation of thermal comfort conditions are usually the main purposes of these works, the application field being that of moving habitable spaces (aeronautic cell of planes, astronotic cell, military vehicles).

The models used to represent these phenomena are in most cases based upon the steady state behaviour of heat exchanges. On the one hand, thermal transfer through the body’s envelope (clothes) are considered as not having thermal capacity. On the other hand, as the thermal system of the human body itself is stabilized, it is unnecessary to use the general equation of heat conduction.

The two main purposes of our work are:

First, the results obtained with the three models will be compared as far as thermal sensation is concerned. These models due to the following authors are well known in specialized literature:

- model of P.O FANGER (no. 1), University of Lyngby (Denmark) [1]
- model of J. DEVAL and X. BERGER (no. 2), C.N.R.S. (France) [2]
- model of M. SHERMAN (no. 3), University of Berkeley (USA) [3]

Secondly, the uncertainty of the results obtained from these models (the number associated with thermal sensation: the predicted mean vote PMV) will be observed. Such a step usually consists of studying these two types of uncertainties associated with the modelisation principle:

- the uncertainty corresponding to modelisation, considering that the different models have been tested experimentally.
• the uncertainty corresponding to the propagation of uncertain data in the calculating code.

In this study, model no. 1 (FANGER) will be assumed to correspond to the reality of phenomena, given its experimental test. It will be taken as the reference model. The other two models (no. 2 and no. 3) are likely to produce variations which our study intends to analyze.

1.1 Analysis of Results Variations between Models (Fig. 1)

The first purpose of this work is to compare the different models elaborated in Europe and USA which allow the evaluation of thermal sensation PMV (marked Y in the text to simplify notation) perceived by a person placed in a certain thermal ambient. The comparison of the predicting models of thermal sensation Y implies the analysis of the variations for each mode of transfer, that is to say the decomposition of the results of the heat flows to which leads the exchange rules established by the different authors (FANGER, DEVAL, SHERMAN). However, in this study, our comparison will be bound to that of the model response, thermal sense Y, in order to simplify the report of the results and to analyze the variations on the main criterion Y.

The comparison of models predicting thermal sensation Y is of great importance for the production of research methods and engineering: knowledge and prediction of thermal ambient for moving habituation (aeronautics, aerospace equipment), prediction of extreme situations (war engines, hostile environment), checking of comfort conditions in buildings (production space, hospital space, standard accommodation....)

Beyond the strict comparison, this study should allow the model’s user to get information about the relative situation of the response it provides (thermal sensation) with regard to the others. Fig. 1 outlines our method.

Our first purpose is to analyze the variations (Fig. 1):

\[ \Delta Y_{1,2} = Y(1) - Y(2) \]  
\[ \Delta Y_{1,3} = Y(1) - Y(3) \]

where Y(1) is the reference model’s output (FANGER).

\[ E = (A; U) \]

Fig. 1: Scheme explicating the first step of the study: comparison of the output Y of different thermal comfort models of FANGER, DEVAL and SHERMAN

(Y represents the Predicted Mean Vote PMV. The occupant of the building is named “user”.)
1.2 Analysis of Variations due to Data Uncertainty in the Models (Fig. 2)

The second problem which has been analyzed in this work is the propagation of data uncertainties in the calculating model. Indeed, each data $e_i$ corresponds to an uncertainty due to:

- its experimental determination ($e_i$ measurement) or
- its own calculation when it is defined by a previous numerical modelisation.

The problem may be simply described in the following way.

If $F$ corresponds to the transfer function of the model, $E$ the data vector and $Y$ the output vector, the evaluation process can be as follows:

$$E = (e_1, e_2, \ldots, e_n) \xrightarrow{MODEL} \text{Transfer function } F \xrightarrow{Y = F(E) = (y_1, y_2, \ldots, y_p)}$$

with $\dim(E) = n$, and $\dim(Y) = p$.

The uncertainty of each data $e_i$ is defined by an interval with amplitude $2\Delta e_i$, such as:

$$e_i - \Delta e_i \leq e_i \leq e_i + \Delta e_i \quad (1)$$

Within the interval $2\Delta e_i$, any value $e_i$ can correspond to the $e_i^*$ data such as:

$$e_i^* = e_i + \delta e_i \quad \text{where} \quad |\delta e_i| \leq \Delta e_i \quad (2)$$

We describe calculation method in section 3.1.1.

As the two values of $2\Delta e_i$ are known, we will focus on the determination of the uncertainty $\Delta Y$ attached to the output vector, that is to say on the uncertainties with the components $y_j$:

$$\Delta Y = (\Delta y_1, \Delta y_2, \ldots, \Delta y_p) \quad (3)$$

$$E + \Delta E \xrightarrow{MODEL} \text{Transfer function } F \xrightarrow{Y + \Delta Y = F(E + \Delta E)}$$

The mathematical studies of this problem show that the uncertainties $\Delta y_j$ cannot be directly calculated from the uncertainties $\Delta e_i$. This complex problem will be developed in section 3.

Considering models predicting thermal sensation, the general problem we have just posed can be defined as:

- the data vector $E$ is defined as:
$$E = (A;U) = (e_1, e_2, \ldots, e_8) = (a_1, \ldots, a_4, u_1, \ldots, u_4) \quad (4)$$

where:

- $A$ stands for the data vector which characterizes the thermal ambient in which the user is.
$$A = (e_1, \ldots, e_8) = (a_1, \ldots, a_4) \quad (5)$$

- $U$ stands for the data vector characterizing the user so that:
$$U = (e_5, \ldots, e_8) = (u_1, \ldots, u_4) \quad (6)$$

with:

- $e_1 = a_1 = T_R$ : average radiant temperature of the room (°C)
- $e_2 = a_2 = T_a$ : average air temperature inside the room (°C)
- $e_3 = a_3 = V_a$ : relative air velocity near the user (ms$^{-1}$)
- $e_4 = a_4 = H_a$ : average relative air humidity ($\%$)
- $e_5 = u_1 = m$ : total metabolism (Wm$^{-1}$)
- $e_6 = u_2 = m_{th}$ : thermal metabolism (Wm$^{-1}$)
- $e_7 = u_3 = R_v$ : average thermal resistance of clothes (m$^2$K$^{-1}$W$^{-1}$)
- $e_8 = u_4 = F_v$ : clothes factor ($\%$)

- the output vector $Y$ is defined as:
$$Y = PMV \quad (Predicted\ Mean\ Vote)$$

($Y$ stands for the PMV in order to have a simple algebraic notation)

Thermal sensation $Y$ is a scalar which is statistically associated with the expression of the ambient thermal perception. At the beginning of the 70s, FANGER defined its range for moderate thermal environments, and nowadays it is used all over the world on research sites where comfort criteria are relevant. In France, the national normalization establishment AFNOR has integrated it in its standard on the specification of thermal comfort conditions. The correspondence shown in Table 1 has been obtained:

<table>
<thead>
<tr>
<th>$Y = PMV$</th>
<th>Thermal sensation</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>very hot</td>
</tr>
<tr>
<td>2</td>
<td>hot</td>
</tr>
<tr>
<td>1</td>
<td>slightly hot</td>
</tr>
<tr>
<td>0</td>
<td>neutral</td>
</tr>
<tr>
<td>-1</td>
<td>slightly cool</td>
</tr>
<tr>
<td>-2</td>
<td>cold</td>
</tr>
</tbody>
</table>

Table 1: Correspondence between the scalar $Y$ ($Y=PMV$) and the thermal sensation perceived by the user
According to the French AFNOR standard, thermal comfort conditions are reached if:

\[-0.5 \leq Y \leq +0.5\]  

(7)

Then, the symbolic representation of the problem is:

1. Predicting process for the evaluation process of \(Y\):

\[E = (e_1, e_2, \ldots, e_8) = (T_a, T_r, V_{in}, H_d, m, m_{in}, R_v, F_v)\]

\[Y = F(E) = (y_1)\]

2. Predicting evaluation process of \(Y\) with the uncertainty \(\Delta Y\):

\[E + \Delta E \rightarrow \text{MODEL} \rightarrow Y + \Delta Y = F(E + \Delta E)\]

Given \(\Delta E = (\Delta T_a, \Delta T_r, \ldots, \Delta F_v)\), we want to calculate \(\Delta Y\), that is to say the uncertainty when obtaining the result with \(Y\).

2. COMPARISON OF THE MODELS

2.1 Preliminary Observation

In order to have a simple comparison of the results obtained, the models will be presented simultaneously, according to a defined thermal exchange type. For this purpose, we must bear in mind that the body uses 7 thermal exchange types:

- by convection (free or sometimes forced)
- by radiation (large infrared wavelengths)
- by skin diffusion (perspiration humidity transfer)
- by dry respiration (convection respiratory)
- by latent respiration
- by conduction
- by evaporation of sweat secretion (sudation)

Fig. 2: Scheme expliciting the second step of the study: evaluation and comparison of the output with its uncertainty \(Y + \Delta Y\) for different thermal comfort models of FANGER, DEVAL and SHERMAN

(Y represents the Predicted Mean Vote PMV. The occupant of the building is named “user”.)
However, the conduction heat exchange type is usually not taken into account because:

- when the person is standing up, the transfer is limited to his soles. In most current cases, it is not taken into account because it is negligible. Nevertheless, in case of cold floors or hot floors (heating floors), it requires specialized studies.

- when the person is sitting, the conduction analysis requires studies on coupled transfers where the thermal inertia of the chair should be taken into account.

As the position of the person is likely to change (standing up or sitting), an accurate simulation of these mechanisms would not be consistent either with the defined purposes or the accuracy of the evaluation methods allowing to calculate vector $A$.

Usually, the clothes resistance is artificially put at 20% to 40% in order to take the thermal insulation of the chair into account.

Generally speaking, no justification of the physical models presented and compared will be given in the following sections. On this subject, the authors’ original publications may be very useful [1-3]. A comparison protocol has been defined and consists in an operational situation, exploiting the models for pre-architectural projects. This leads to the simulation of the user’s thermal sensation $Y$ with each model, on different climatic sets, taking the example of a building.

Indeed, variations between models can only be properly observed on a climatic set. The study, once set, presents a limited interest, given the defined purposes. First, a numerical simulation of the building has been performed on two climatic sets (a warm summer climatic set and a hot summer climatic set), selecting one representative day. The following data was obtained in this simulation:

$$ A = (e_1, \ldots, e_4) = (a_1, \ldots, a_4) $$

depending on time $t$: $A = A(t)$. Then, considering a user in the building whose characteristics are:

$$ U = (e_5, \ldots, e_8) = (u_1, \ldots, u_4) $$

not depending on time $t$.

2.2 Description of the Models

In this section, the thermal exchange laws $E_{cv}(X)$, $E_{eh}(X)$, $E_{ps}(X)$,... correspond to the model no. $X$ with:

- head (marked $t$)
- hands (marked $m$)
- the rest of the body, the clothed part (marked $v$)

Each density of the composite heat flux density follows a rule corresponding to:

$$ e_{cv} = \alpha Fh_c (T_s - T_a) $$

where:

- $\alpha$ = coefficient corresponding to the heat flux density which runs through each zone of the body: head, hands, clothed part;
- $F$ = coefficient allowing to increase the thermal exchange: particularly for the clothed part, considering that clothes increase the exchange surface [1,2];
- $h_c$ = convection exchange coefficient, depending on: the type of convection process around the body of the user (laminar, turbulent), the relative air velocity, the surface temperature (clothes, skin) if the convection can be considered as natural;
- $T_s$ = surface temperature of the body involved in the exchange: clothes, skin;
- $T_a$ = dry temperature of the ambient air.

According to the notation conventions adopted, model $X$ corresponds to:

$$ E_{cv}(X) = \alpha_{v,X} F_{v,X} h_{c,v,X} (T_{v,X} - T_a) + \alpha_{t,X} h_{c,t,X} (T_{c,X} - T_a) + \alpha_{m,X} h_{c,m,X} (T_{c,X} - 6 - T_a) \quad (10) $$

I) The clothes factor $F_{v,X}$

$F_{v,1} = 1 + 0.77 R_v$

$F_{v,2} = F_{v,1}$

$F_{v,3} = (1 + 0.23 I_{cle}) \sqrt{1 + 0.178 I_{cle} (h_{c,3} + h_{r,3})} \quad (11)$

where

$I_{cle} = 6.45 \left[ R_v + (1 - F_{v,1}) \right] \left[ (h_{c,3} + h_{r,3}) F_{v,1} \right] = 5.56 R_v$
II) Coefficients of exchanges division $\alpha_{v,X}$, $\alpha_{t,X}$, $\alpha_{m,X}$

These coefficients balance the convection heat exchanges of the different parts of the body. FANGER and SHERMAN do not take into account this balance which has just been introduced by DEVAL and BERGER [2]. It is:

$$\alpha_{v,1} = \alpha_{v,3} = 1 \quad \alpha_{v,2} = 0.94 \text{ clothed body area}$$

$$\alpha_{t,1} = \alpha_{t,3} = 0 \quad \alpha_{t,2} = 0.02 \text{ head area}$$

$$\alpha_{m,1} = \alpha_{m,3} = 0 \quad \alpha_{m,2} = 0.04 \text{ head area}$$

III) Convection exchanges coefficients

1) Clothed part:

$$h_{c,v,1} = (2.38 |T_{c,1} - T_a|^{0.25};10.1|V_a|)$$

$$h_{c,v,2} = (2.38 |T_{c,2} - T_a|^{0.25};10.1|V_a|)$$

$$h_{c,v,3} = \left[ 5.66 \left( \frac{m}{m_0} - 0.85 \right) \right]^{0.39} \times 83.3V_a^{0.53}$$

2) Head part:

$$h_{c,t,1} \text{ and } h_{c,t,3} \text{ are not defined: } \alpha_{t,1} = \alpha_{t,3} = 0$$

$$h_{c,t,2} = (2.38 |T_{c,2} - T_a|^{0.25};10.1|V_a|)$$

3) Hands part:

$$h_{c,m,1} \text{ and } h_{c,m,3} \text{ are not defined: } \alpha_{m,1} = \alpha_{m,3} = 0$$

$$h_{c,m,2} = (2.38 |T_{c,2} - 6T_a|^{0.25};10.1|V_a|)$$

IV) Temperatures $T_{v,X}$ and $T_{c,X}$

These temperatures correspond to the outdoor surface temperature of the clothes and to the skin temperature.

1) $T_{v,1}$ and $T_{v,2}$ (FANGER’s and DEVAL’s models) cannot be directly calculated, given that the transfers are coupled with the ambient parameters. However, a simple iteration which is usually very quick provides these results.

As for Sherman’s model which is studied further into the text, a fitting of its mathematical formula gives:

$$T_{v,3} = T_{c,3}$$

2) For skin temperatures:

$$T_{c,1} = 35.7 - 0.0275m_{th}$$

$$T_{c,2} = 29.55 + 0.196T_A - 1.064\frac{m}{m_0}(1 - 1.9R_v)$$

$$T_{c,3} = T_{c,1}$$

$T_A$ is a temperature defined by:

$$T_A = \frac{(h_{c,v,2}T_a + h_{r,v,2}T_r)}{(h_{c,v,2} + h_{r,v,2})}$$

It is to be noticed that $T_{c,1}$ and $T_{c,3}$ can be directly calculated from data while $T_{c,2}$ requires an iteration.

2.2.2 Heat exchanges by radiation $E_{ry}(X)$

Radiation exchanges between the body’s surface and the ambient are those which are the least intuitively perceived as they develop in the infrared field. The basic equation of these transfers is the expression of the net heat flux which are exchanged between the body’s surface and the whole other surfaces constituting the environment: partitions of the room if the user is in an habitation, walls, windows,.....

This exchange does not take into account the absorption of air radiation and depends on:

- the area and the relative position of surfaces exchanging radiation,
- the emittance and the absorption coefficient of each surface,
- their temperatures.

According to the models, they can be written as follows:

$$E_{ry}(1) = F_{p,1}F_{v,1}h_{r,v,1}\left[ (T_{v,1} + 273)^4 - (T_r + 273)^4 \right]$$

$$E_{ry}(2) = F_{p,2}0.02h_{r,v,2}(T_{c,2} - T_r) + 0.04h_{r,m,2}(T_{c,2} - 6 - T_r)$$

$$E_{ry}(3) = F_{p,3}h_{r,v,3}(T_{c,3} - T_r)$$

I) Position factor $F_{p,X}$

This factor is relevant to the body-ambient factor. It is an average value which is common to the standing position and to the sitting position. It is the ratio of the effective radiation area of the clothed body to the surface area of the clothed body [1]. This approximation is usually accepted by the different researchers.

II) Radiation exchange coefficients
2.2.3 Heat exchange by skin diffusion \( E_{ps}(X) \)
(perspiration humidity transfer)

Perspiration is an insensitive mechanism of vapour transfer through epidermic tissue. The vapour which is perspired involves a thermal power corresponding to the potential heat of evaporated water. In this way, the body releases an important heat quantity and forces the person to drink a minimum of liquid that is to say various beverages.

The expression of these latent thermal exchanges varies according to the authors. We have:

\[
E_{ps}(1) = 0.41 \left[ 43.2 - 0.052 m_{th} - p_v(T_a) \right] \\
E_{ps}(2) = 0.41 \left[ p_v(T_{c,3}) - p_v(T_a) \right] \\
E_{ps}(3) = 0.06 \left[ E_{max} - E_{sd}(3) \right]
\]

where

\( p_v(\ldots) \) = vapour pressure with mmHg unit
\( p_v(T_{c,3}) \) = saturated vapour pressure with mmHg unit
\( E_{max} = 2.2 h_{c,3} F_{v,c,3} \left[ p_v^*(T_{c,3}) - p_v^*(T_d) \right] \)
\( p_v^*(\ldots) \) = saturated vapour pressure with torr unit
\( T_a \) = due air temperature of air

SHERMAN shows that the variation of the saturating vapour pressure can be approximated by:

\[
\frac{p_v^*(T_{c,3}) - p_v^*(T_d)}{T_{c,3}} = \left[ T_{c,3}^2 - T_d^2 \right] T_{c,3}
\]

\[
F_{v,c,3} = \left[ 1 + 0.143 h_{c,3} \rho_{cle} \right]^{-1}
\]

\[
E_{sd,3} = 0.42 m_0 (a-1) \text{ and } a = m/m_0
\]

and \( E_{sd,3} \) is the quantity of heat exchange by evaporation of sweat secretion, a representing the activity level: \( a = m/m_0 \).

2.2.4 Heat exchange by latent respiration \( E_{hr}(X) \)

The water vapour released when breathing is considered as a small heat potential. As in the perspiration case, this vapour carries its vaporization heat and contributes to the slight cooling of the body.

\[
E_{hr}(1) = 0.0023 m \left[ 44 - p_v(T_a) \right] \\
E_{hr}(2) = 0.0023 \left[ p_v(T_{exp}) - p_v(T_a) \right] \\
E_{hr}(3) = 0.0023 \left[ T_{c,3}^2 - T_d^2 \right] T_{c,3}
\]

where:

\( T_{exp} = 32.6 + 0.066 T_a + 0.032 w_a \) expired air temp
\( w_a = \) absolute air humidity \((\text{kg/kg})\)

2.2.5 Heat exchange by dry respiration \( E_{cr}(X) \)
(convection respiratory)

These exchanges are the sensitive heat flow carried by the expired air and released by the lungs. It is a relatively minor exchange mode. It is easy to define quantities with this mode and the different authors consider that:

\[
E_{cr}(1) = 0.0014 m(34 - T_a) \\
E_{cr}(2) = 0.0014 m(T_{exp} - T_a) \\
E_{cr}(3) = 0.0014 m(T_{c,3} - T_a)
\]

2.2.6 Heat exchange by evaporation of sweat secretion \( E_{sd}(X) \)
(sudation)

Sudation is a particular thermo-regulator mechanism. The sweat secreted on the body’s surface uses some metabolic heat to evaporate. As for perspiration, it is a heat and mass transfer from the body to the room.

The accurate analysis of the sudation phenomenon (rythm, distribution on the body area...) is difficult and the worldwide physiologists’ community has not found an agreement on all the problems posed: resorption capacity of the room, inhomogeneous distribution of the liquid film, the body’s evaporating capacity, damping and running notions....

Regarding the context, the same sudation rule is used by the three authors studied:

\[
E_{sd}(1) = 0.42 (m_{th} - 58,1) = E_{sd}(2) = E_{sd}(3)
\]
This expression of sudation exchanges is appropriate to a user in a situation of thermal neutrality. The sudation problem is complex and elaborate studies on this subject show that it cannot be easily connected to the comfort notion.

Givoni (quoted in [4]) suggests that the situation of the person be considered as comfortable (given the other exchanges) if:

\[ E_{sd}(l) \leq 47/S_c \]  

(27)

In our work, we observed that it is possible for the persons to be in a situation of thermal imbalance when \( Y \) varies from -3 to +3. Then, the quantity \( E_{sd}(X) \) is an unexpended balance in the evaluation of the exchanges whose accurate formulation is therefore unnecessary. However that may be, as part of this comparative study, authors have adopted the same expression.

### 2.2.7 Thermal sensation

The evaluation of heat exchanges out of sudation for the models no. 1 and 2 will be:

\[ E(X) = E_cv(X) + E_{ry}(X) + E_{ps}(X) + E_{hr}(X) + E_{cr}(X) \]  

(28)

Sudation (or shivering) will start if:

\[ m_{sh} > E(X) \]

Then the thermal differential notion appears at a time \( t \) of the observation set:

\[ D(X,t) = m_{sh}(t) - E^*(X,t) \]  

(29)

\( E^*(X,t) \) is the algebraic sum of the exchanges calculated at a time \( t \) including the comfort sudation calculated in section 2.2.6.

\[ E^*(X,t) = E(X,t) + E_{sd}(X,t) \]  

(30)

The thermal sensation probably perceived by the person will be:

\[ Y(X,t) = L(m).D(X,t) \]  

(31)

\( L(m) \) is an adjustment experimental function:

\[ L(m) = 0.303 e^{-0.0362 m} + 0.028 \]  

(32)

SHERMAN’s model is original in the sense that it gives a direct evaluation of the sense (without iteration). Sherman found this formalism:

\[ Y(3,t) = Y_0 + \frac{Y_{ry}}{T_{c,3}} + \frac{Y_{cv}}{T_{c,3}} + \frac{Y_e}{T_{c,3}} + \frac{Y_{sd}}{T_{c,3}} \]  

(33)

where:

\[ Y_{ry} = F_{c,3}h_{r,3}T_{c,3}f(m)/m_0 \]

\[ Y_{cv} = [0.0014a + F_{c,3}h_{c,3}/m_0]T_{c,3}f(m) \]

\[ Y_e = [0.0024a + 0.132F_{c,3}h_{c,3}/m_0]T_{c,3}f(m) \]

\[ Y_0 = [0.4 + 0.6a][f(m) - Y_{ry} - Y_{cv} - Y_e] \]

\[ f(m) = 1.6 + 17.6 e^{-0.0362 m} \]

We can notice that if the metabolism \( m \) becomes a time function, which usually happens in reality, then the values \( Y \) and \( T_{c,3} \) also depend on time \( t \).

### 2.3 Exploitation Hypotheses - Definition of the Data Vector \( E \)

#### 2.3.1 Definition of vector \( A(t) \)

In the previous sections, it has been explained that our comparison of models had been realized by introducing the temporal variable \( t \).

We have considered a defined building physical system whose numerical simulation process leads to the definition of the ambience vector \( A(t) \) for each moment \( t = n \Delta t \).

Its definition is provided in Figs. 3 and 4.

Two climatic sets have been analyzed:

- the first climatic set corresponds to the month of July (selected in Test reference Year of Paris, France) which is relatively warm,
- the second climatic set also corresponds to the month of July, but this set is much hotter (it is marked hot set in the diagrams).

Air velocity shows variations of step type, as the \( A(t) \) component is not calculated with the thermal simulation program. We simply assume that when the windows are open, the user is subject to a uniform air velocity field of 0.25 ms\(^{-1}\) which is an average value calculated from crossing air flows. This is an approximation. However, the air speed seems appropriate because when this speed reaches 0.3 ms\(^{-1}\), the person reacts by the phenomenon of mechanical discomfort and manual regulation in limiting the opening of the windows. When the windows are totally closed, we assume \( V_a \approx 0.1 \) ms\(^{-1}\) (speeds being induced by a mechanical ventilation system).

These two climatic sets have been chosen during the same period in order to compare these models in rather different situations [5,6]. Moreover, the hot season has been selected because it is during...
this period that discomfort is likely to appear. The winter and the spring reduce the variations between the models, in terms of thermal sensation because in most cases it is a neutral situation \((Y = 0)\) due to the regulation of heating system.

2.3.2 Definition of vector \(U\)

The user vector is not dependent on time. Values chosen for its components are defined in Table 2, in section 3.2. In Fig. 1, \(U\) components are \(M, M_{th}, R_v, F_v\). Beyond the text, \(M_{th}\) is replaced by \(\eta\), with \(\eta = (m - m_{th})/m\) or \(\eta = (M - M_{th})/M\).

Fig. 3: Components of ambient vector \(A(t)\) - Warm climatic set
(a) indoor air and radiant temperature, (b) indoor air velocity, (c) indoor air relative humidity
Fig. 4: Components of ambient vector $A(t)$ - Hot climatic set
(a) indoor air and radiant temperature, (b) indoor air velocity, (c) indoor air relative humidity
2.3.3 Preliminary observations on the models

The three models exploited are rather similar:

- **FANGER’s model** is nowadays the most widely used model in the world for thermal sensation studies. A more advanced model exists and is especially used by the NASA for ambient prediction of moving habitable space [7,8]. Nevertheless, as the data vector A is determined with an accuracy as well as the simulations of the thermal behavior of buildings, it is coherent to evaluate thermal sensation with FANGER’s model. It is the reference model of this study.

- **DEVAL and BERGER’s model** is very similar and drawn from Fanger’s. Actually, it is a modified version of Fanger’s, including variations which are supposed to improve its accuracy. Thus, the body is divided into three parts (head, hands, clothed part of body), each of these having its own surface temperature while with Fanger’s model, the body is globally considered, with a unique surface temperature.

- **SHERMAN’s model** is also drawn from FANGER’s. Therefore, it is not a new model because thermophysiological mechanisms are treated in the same way. The innovation lies in the introduction of a new algorithm avoiding iterative calculations. The bibliography provides the reader with further information.

2.4 Comparison of Results on Thermal Sensation Y(t)

The diagrams in Fig. 5 show the evolution of the functions Y(t) for the three models studied.

With the warm climatic set, FANGER’s and SHERMAN’s models provide almost the same results: the predicted thermal sensations are almost always similar. However, the results obtained with DEVAL’s model are rather different.

For instance, at 7:00 p.m., the sensations obtained are opposed. It is also to be noticed that during this set, the difference \( \Delta Y_{1,2} \) is almost constant:

\[
\Delta Y_{1,2} = Y(2) - Y(1) \approx 0.5
\]

Thus, the model tends towards hotter sensation compared to the reference.

With the hot climatic set, the difference \( \Delta Y_{1,3} \) of the results are reduced and are included in a domain with amplitude 0.25 on the thermal sensation scale Y:

\[
\Delta Y_{1,3} = Y(3) - Y(1) \approx 0.25
\]

DEVAL’s model seems closer to FANGER’s. It seems more adapted to hot climatic sets if we accept the fitting principle with regard to FANGER’s. The objective quality of each model can only be discussed considering the experiment.

Thus, considering FANGER’s model as the reference can be argued because it has been conceived in ambiances corresponding to moderate climates. The hot climatic set belongs to this category. Nevertheless, the reference is maintained in terms of strict comparison.

A detailed analysis of the differences classified by thermal exchanges categories \( \Delta E_{cv}, \Delta E_{ry}, \Delta E_{ps}, \ldots \) could be undertaken. It would imply a detailed study of the model and an observation of possible balancing effects between heat exchange categories. This is not our working method and our study will be bound to the observation of differences on thermal sensation Y(X,t), only considering the models’ output. The detailed analysis of these differences would lead to discuss the types and the quality of the models which is not the purpose of our study.

3. PROPAGATION OF DATA UNCERTAINTIES ON THE RESULTS Y

3.1 Method of Study

Two methods have been used in order to define the uncertain domain \( \Delta Y \):

- the probabilist Quasi Monte Carlo method (marked QMC)
- the Finite Differences Differential Analysis (marked FDDA)

3.1.1 The probabilist Quasi Monte Carlo method (QMC)

Each datum \( D = E = (e_1,e_2,\ldots,e_8) \) is associated with a Gaussian probability density law, centered on the reference value \( e_j^0 \) and framed by the uncertainty, which is a priori known, of this datum. So for a simulation numero k and a datum \( e_i \), we have (see Fig. 6):

\[
e^k_j = e^0_j + (\delta e_j)^k \quad \text{with} \quad e^0_j - \Delta e_j \leq e^k_j \leq e^0_j + \Delta e_j
\]

(35)

The interval \( [e^0_j - \Delta e_j ; e^0_j + \Delta e_j] \), with an amplitude \( 2\Delta e_j \) is the uncertainty associated with
the datum $\epsilon_j$. The term $(\delta \epsilon_j)^k$ follows the selected probability law which is common to the whole data. Fig. 6 gives the principle of these computations allowing to reach the output $Y^k$.

The difference between the Quasi Monte Carlo method and the traditional Monte Carlo method lies in the random selection of data. Indeed, the use of the imperfect pseudo-random selection generators when using the Monte Carlo method implies an insufficient study of the selected field. Fig. 7 shows a better exploration of the domain with Sobol’s sequence. The main purpose of these quasi-random sequences is to avoid these difficulties by systematically producing points which are closer and closer to each other.

![Figure 5: Variation with time of output models $Y(t)$ - Results obtained with FANGER’s, DEVAL’s and SHERMAN’s model, for the warm and the hot climatic set](image)

(Y(t) represents variations of Predicted Mean Vote PMV.)
Fig. 6: Exploitation principle of the Quasi Monte Carlo method

\[ Y^0 \text{ is the "exact" solution, not perturbed: } Y^0 = F(E^0) \]

Fig. 7: Comparison between a pseudo-random sequence (left) and a traditional quasi-random sequence (right) in a unitary square (Each sequence consists of 1024 points.)
Several algorithms have been proposed. The most efficient is Sobol’s one [9] which has been transformed by Antonov and Saleev [10]. This algorithm has been chosen for this work. The principle of the quasi-random selection will not be described in detail. For further information, we can refer to reference [10]. In Fig. 6, two random sequences in a unitary cube illustrate the different results between these two kinds of selections.

The whole results $Y_k$, $k = 1, \ldots, N$, constitute the Monte Carlo cloud of the output, $N$ being the number of computations. In our study, $N = 1500$. The model studied in this work has a simple scalar output: $\text{dim}(Y) = 1$. The consequence is that the cloud is reduced to one dimension range. If we consider that the surface temperature of clothing, $T_{c1}$ is part of the outputs, then the Monte Carlo cloud is a cloud of dimension 2 (see Fig. 8).

The uncertainties associated with data can be found in Table 2 in section 3.2.

If the cloud in Fig. 8 is cast on the PMV axis ($= Y$), the uncertainty amplitude $\Delta Y$ on the PMV is obtained by:

$$\Delta Y = \sup(\delta Y)^k \quad \text{with} \quad (\delta Y)_k = \left| Y^k - Y^0 \right|$$

(36)

where $Y^0$ is the “exact” solution: $Y^0 = F(E^0, C^0) = F(c_1^0; \ldots; c_j^0; \ldots; c_8^0)$.

If the exploited values (Table 2) are taken into account, on either parts of the reference value $Y^0$, the uncertainty domains which can be found on the diagrams in Figs. 9 to 12 are obtained.

\subsection{The Finite Differences Differential Analysis method (FDDA)}

This study will only deal with general principles of the method.

Considering the function $F$ and the output vector $Y$, we have:

$$Y = F(E, C) \quad \text{in the most general case.}$$

If the function $F$ does not present any singularity on its fluctuation domain, near the reference solution, a first order analysis of each component $y_i$ of the output vector $Y$ in the tangential plan can be undertaken. By differentiating, we obtain:

$$\Delta y_i = \sum_{j=1}^{m} \left| \frac{\partial F}{\partial c_j} \right| \Delta c_j + \sum_{j=1}^{n} \left| \frac{\partial F}{\partial e_j} \right| \Delta e_j$$

(37)

where $Y = (y_1; \ldots; y_j; \ldots; y_p) \in \mathbb{R}^p$

with $\text{dim}(E) = m$ and $\text{dim}(C) = n$, $F^i$ corresponding to the expression of $F$ (given in its analytical form, or more often its numerical form) related to the output $y_c$.

With our model, $Y$ is reduced to a scalar, that is to say: $\text{dim}(Y) = 1$.

As we do not have any controlling variable, we obtain:

$$\Delta Y = \Delta(\text{PMV}) = \sum_{j=1}^{8} \left| \frac{\partial F}{\partial c_j} \right| \Delta c_j \quad \text{with} \quad Y \in \mathbb{R}$$

(38)

Fig. 8: The Monte Carlo cloud of dimension 2, with $Y = (\text{PMV}, T_{c1}) = (y_1, y_2)$
The calculation of the partial derivatives can be considered in an analytical way when the expression of F is not too complex (F must present an analytical form). Generally, an approximative calculation to the finite differences is used, each partial derivative being evaluated with the relation:

\[
\frac{\partial F_k}{\partial e_j} = \frac{F_k(e_j - h) - F_k(e_j + h)}{2h}
\]  

(39)

where \( h = 10^{-W} \), and \( 3 \leq W \leq 5 \), for the most traditional, linear or lower nonlinear functions F.

When F is strongly nonlinear, specific numerical problems appear, requiring a specific computation [11,12] which is not part of our work.

Then, the upper and lower frames of the output are:

\[
sup(Y) = Y^0 + \Delta Y \quad \text{and} \quad inf(Y) = Y^0 - \Delta Y
\]  

(40)

### 3.2 Exploitation Hypothesis of the Methods: Data Perturbation

The same perturbation \( \Delta e_j \), \( j = 1, 2, 3, 4 \) at every moment of the simulation has been used for the ambient data (vector A(t)). These values can be found in Table 2.

Considering the user data (vector U), they are constant with time; the amplitudes of the perturbations can be found in the right part of Table 2. The amplitudes of the perturbations have been arbitrarily selected, but correspond to the accuracy with which these data should be defined in the model.

### 3.3 Analysis of Results: Uncertainty Domains of the PMV \( (Y) \)

#### 3.3.1 Warm climatic set (Figs. 9 and 10)

#### 3.3.1.1 FANGER’s model

The first diagram in Fig. 9 shows that:

- the Quasi Monte Carlo method (QMC) allows to define an uncertainty field similar to that of the finite differences differential analysis (FDDA).
- The amplitude of this uncertainty domain is about 0.5 PMV units with the QMC method, and up to 0.6 units maximum with the FDDA method. It can be observed on this diagram that with the FDDA method, the uncertainty domain is slightly wider than that obtained with the QMC method. For the whole climatic set, that is to say for each time computation, the uncertainty field of the FDDA method includes that of the QMC method.

We notice that the uncertainty domain is not insignificant and is similar to the variation observed with the models (see section 2.4). This result can be expressed as follows:

\[0.35 \leq \Delta Y(1) \leq 0.51 \quad \text{QMC method}
\]

\[0.40 \leq \Delta Y(1) \leq 0.60 \quad \text{ADDF method}
\]

where \( \Delta Y(1) = Y(1) - Y^0(1) \) is the amplitude of the uncertainty field at a specific moment of the climatic set. \( Y^0(1) \) is the reference value of PMV, which has been calculated without any data perturbation of FANGER’s model; and \( Y(1) = Y^0(1) \pm \Delta Y(1) \).

#### 3.3.1.2 DEVAL’s model and SHERMAN’s model

The two other diagrams in Fig. 9 give the uncertainty domains provided by the QMC and FDDA methods, as with FANGER’s model. In the second diagram, it can be observed that DEVAL’s model is more sensitive to data uncertainties than FANGER’s one when using the FDDA method. The QMC method gives almost the same variations of uncertainty domains. DEVAL’s model has the particularity of slightly amplifying the uncertainties.

### Table 2: Reference values and uncertainties associated with data \( e_j \) for the study of the results \( Y = PMV \)

(Variations of the ambient data can be observed, depending on the numerical simulation moment. The user data are constant. With the warm climatic set, the thermal resistance of clothing is 0.155 m²KW⁻¹; with the hot climatic set, the thermal resistance is 0.077 m²KW⁻¹ (1clo = 0.155 m²KW⁻¹).)

<table>
<thead>
<tr>
<th>Units</th>
<th>( ^\circ C )</th>
<th>( ^\circ C )</th>
<th>( m/s )</th>
<th>( . )</th>
<th>( W )</th>
<th>( . )</th>
<th>( m^2,KW^{-1} )</th>
<th>( . )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data ( e_j )</td>
<td>( T_a )</td>
<td>( T_r )</td>
<td>( V_a )</td>
<td>( H_a )</td>
<td>( M )</td>
<td>( \eta )</td>
<td>( R_v )</td>
<td>( F_v )</td>
</tr>
<tr>
<td>Reference value</td>
<td>variable with time</td>
<td>variable with time</td>
<td>variable with time</td>
<td>variable with time</td>
<td>125</td>
<td>0</td>
<td>0.155</td>
<td>0.077</td>
</tr>
<tr>
<td>( \Delta e )</td>
<td>( \pm 0.5 )</td>
<td>( \pm 0.5 )</td>
<td>( \pm 0.01 )</td>
<td>( \pm 0.05 )</td>
<td>( \pm 5 )</td>
<td>( \pm 0 )</td>
<td>( \pm 0.008 )</td>
<td>( \pm 0.11 )</td>
</tr>
</tbody>
</table>
Fig. 9: Evolution with time of the PMV = Y and of the uncertainty fields, evaluated with the Quasi-Monte Carlo method (QMC) and the Finite Differences Differential Analysis (FDDA), for the three models: FANGER’s, DEVAL’s and SHERMAN’s. Case of the warm climatic set.
Fig. 10: Evolution with time of the amplitude of the maximum uncertainties $\Delta Y = \Delta \text{(PMV)}$ noted DY on diagrams, evaluated with the Quasi Monte Carlo method (QMC) and the Finite Differences Differential Analysis (FDDA), for the three models: FANGER’s, DEVAL’s and SHERMAN’s. Case of the warm climatic set.
On the contrary, SHERMAN’s model reduces the amplitude of the uncertainty domain as it is limited to 0.5 PMV unit. As in the case of FANGER’s model, we observe that with these two models, the FDDA method gives an uncertainty interval which is slightly superior to that of the QMC method. These results can be expressed in Table 3.

\[ Y(j) = Y^0(j) \pm \Delta Y(j) \]

with \( j = 1, 2, 3 \), for FANGER’s, DEVAL’s, and SHERMAN’s models.

\[ Y^0(j) = \text{reference PMV value, calculated without data perturbation}, \]
\[ \Delta Y(j) = \text{amplitude of the uncertainty domain}. \]

### 3.3.2 Hot climatic set (Figs. 11 and 12)

#### 3.3.2.1 FANGER’s model

The results obtained can be found in the first diagram in Fig. 11. We observe that:

- the uncertainty fields provided by the two methods reveal stronger differences, the FDDA method producing a slightly wider field. The first diagram in Fig. 12 shows that the variation amplitude can go up to 0.93 PMV units with the FDDA method. These uncertainty fields of high amplitude correspond to the colder moments during the night when the user keeps the same clothes on as during the day (\( R_v = 0.5 \) clo = 0.077 m²KW⁻¹).

- the results obtained with the FDDA method are not as close as those with the QMC method in the case of the warm climatic set. During certain night hours, the FDDA method is more pessimistic than the QMC method: the amplitude of the uncertainty domain is actually 23% superior in extreme cases. When the ambience of the building is hotter during the day, the amplitudes of the uncertainty domains of the two methods are almost similar, as in the warm climatic set.

- the most outstanding result is the great variability of the amplitude of the uncertainty domains according to the ambience data (see Fig. 12, FANGER), the user data being constant. This result can be expressed as follows:

\[
0.23 \leq \Delta Y(1) \leq 0.75 \quad \text{QMC method}
\]
\[
0.29 \leq \Delta Y(1) \leq 0.93 \quad \text{FDDA method}
\]

#### 3.3.2.2 DEVAL’s model and SHERMAN’s model

The observations made in the preceding part about FANGER’s model can also be applied to DEVAL’s model, with stronger variations. The amplitude of the uncertainty domain with the FDDA method is 33% superior to that obtained with the QMC method, during night hours. Apart from being stronger, an evolution of the amplitude of the uncertainty domain almost similar to that of FANGER’s model can be observed. On the other hand, like in the case of the warm climatic set, DEVAL’s model is more sensitive to data uncertainties than FANGER’s model, when using the FDDA method.

As in the case of the hot climatic set, SHERMAN’s model is really less sensitive to the variability of ambient data. The amplitude of the uncertainty field is relatively constant, and slightly weaker than that of the two other models. As with FANGER’s and DEVAL’s models, the FDDA method gives greater amplitudes of the uncertainty domains than those with the QMC method, the difference between the two here being really less sensitive.

As in the case of the hot climatic set, the results are expressed in Table 4.

### Table 3: Maximum and minimum amplitudes of the uncertainty domain on the PMV (marked \( \Delta Y \)) with the different models and with the two methods used QMC and FDDA

(With the QMC method, these results correspond to the upper value \( \Delta Y^+ \) only. The diagrams in Fig. 9 show that the \( \Delta Y^- \) shift from - 0.03 to - 0.15 units of PMV with time. Case of the warm climatic set.)

<table>
<thead>
<tr>
<th>Authors</th>
<th>Warm climatic set</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FANGER</td>
</tr>
<tr>
<td>QMC Method</td>
<td>( 0.35 \leq \Delta Y(1) \leq 0.51 )</td>
</tr>
<tr>
<td></td>
<td>( \Delta Y(1) \approx 0.43 )</td>
</tr>
<tr>
<td>FDDA Method</td>
<td>( 0.40 \leq \Delta Y(1) \leq 0.60 )</td>
</tr>
<tr>
<td></td>
<td>( \Delta Y(1) \approx 0.50 )</td>
</tr>
</tbody>
</table>
Fig. 11: Evolution with time of the PMV = Y and of its uncertainty domains evaluated with the Quasi Monte Carlo method (QMC) and with the Finite Differences Differential Analysis (FDDA) method, for the three models: FANGER’s, DEVAL’s and SHERMAN’s. Case of the hot climatic set.
Fig. 12: Evolution with time of the amplitude of the maximum uncertainties $\Delta Y = \Delta (PMV)$ noted $DY$ on the diagrams, evaluated with the Quasi Monte Carlo method (QMC) and the Finite Differences Differential Analysis method (FDDA) for the three models: FANGER’s, DEVAL’s and SHERMAN’s. Case of the hot climatic set.
Table 4: Maximum and minimum amplitudes of the uncertainty domain on the PMV (marked $\Delta Y$) with the different models and with the two methods used QMC and FDDA

(With the QMC method, these results correspond to the upper value $\Delta Y^+$ only. The diagrams in Fig. 9 show that the $\Delta Y$ shift from - 0.02 to - 0.1 units of PMV with time. Case of the hot climatic set.)

<table>
<thead>
<tr>
<th>Authors</th>
<th>Hot climatic set</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FANGER</td>
<td>DEVAL</td>
</tr>
<tr>
<td>QMC Method</td>
<td>$0.23 \leq \Delta Y (1) \leq 0.75$</td>
<td>$0.25 \leq \Delta Y (2) \leq 0.75$</td>
</tr>
<tr>
<td>FDDA Method</td>
<td>$0.29 \leq \Delta Y (1) \leq 0.93$</td>
<td>$0.32 \leq \Delta Y (2) \leq 1$</td>
</tr>
</tbody>
</table>

4. CONCLUSION

The purpose of this work has been to reveal the double effect of uncertainty implied by:

- the selection of the model
- the uncertainty corresponding to the data used by the model. This approach which has been proposed by several authors, including Tarantola [13,14], seems to be necessary in order to provide users of calculating codes predicting performance with a great number of information. This approach applied to the models predicting thermal sense is relevant to the uncertainty of the results obtained, which should then be used carefully.

The study of the models predicting thermal sense leads to two levels of conclusion:

- on the results obtained and the information the users of software predicting performance of building projects must learn from it.
- on the methods used to define the uncertainty domains of the results obtained.

4.1 On the Results Obtained

In the first step of the comparison of the models, slight differences in results have been observed according to the model used: FANGER’s, DEVAL’s, and SHERMAN’s. These differences can go up to 0.5 PMV unit depending on the climatic set analysed and cannot be considered as negligible. The observation of the PMV (= $Y$) of the two climatic sets (see Fig. 5) reveals that FANGER’s model which is our reference model gives results predicting an ever colder thermal sense than that of other models. So the first problem for the user of software predicting thermal sense is the choice of the model. The exploitation of models tested experimentally is recommended. Furthermore, as the calculating time is short for the three tested models, this parameter is not of great importance and cannot be a criterion for the choice of the model.

The second step of the study aiming at defining the amplitude of the uncertainty domain of PMV, shows that it is important and that the results must be used carefully. If we consider the results obtained with the probabilist Quasi Monte Carlo method and the reference model (FANGER’s one), amplitudes ranging from 0.23 to 0.75 can be noticed in the case of the hot climatic set. These amplitudes involve wide uncertainty domain about $0.23 + 0.75 \approx 1$ PMV unit, which is significant. The Finite Differences Differential Analysis method involves wider domains ($0.29 = 0.93 = 1.22$ PMV units) but which are very close to the probabilist method (QMC).

Given the values of uncertainties on the model data which seem correct, it can be concluded that these uncertainties are really representative. The observation of the results provided by the other models induce a great attention. We notice here that the accumulation of uncertainties due to the modelisation and to the data uncertainties (vector A and U) can provide important variations of results, about 1 PMV unit.

4.2 On the Methods Used to Define the Uncertainty Fields

This section deals with technical questions concerning scientific researchers who elaborate models predicting physical system behavior. The QMC method can be considered as the reference method. Indeed, this method allows to evaluate the perturbations of the results in a direct way as it consists in exploiting the model in a systematic way with perturbed data.

With our models, the calculating times are short and the repetition of numerous computations (15000) is not a problem. It will not be so with more complex models (thermal behavior of buildings, fluid mechanic simulation...) for which the
exploitation of the QMC method will be difficult as far as calculating time is concerned. Therefore, we have developed the FDDA method which has proven its reliability and its performance in our study.

As far as reliability is concerned, the interval described by this method includes almost systematically the Monte Carlo cloud. As for performance, calculating time rate is 1 to 100. The only precaution required by this method concerns the determination of the step h of partial derivatives calculation. We will demonstrate in more mathematically elaborate studies that h can be easily fixed for linear models. After analyzing the results from the simple models used here, the FDDA method seems to be an efficient method, easy to use in order to evaluate the uncertainty of the output calculating codes. Furthermore, this method allows the explicit evaluation of the sensibilities of the output Y compared to the data. Although this method requires the calculation of partial derivatives, it proves to be more economic than the probabilist Monte Carlo method whose calculating time is longer. The former is also more expensive given its complex configuration codes. Finally, the FDDA method does not impose any restriction with regard to the nature and the amplitude of uncertainties associated with the data of the model.

NOMENCLATURE

\( m \) total ratio metabolism, for 1 m\(^2\) of body area (Wm\(^{-2}\))
\( m_0 \) basic metabolism, for 1 m\(^2\) of body area (58.15 Wm\(^{-2}\))
\( m_{th} \) ratio thermal part of the metabolism, for 1 m\(^2\) of body area (Wm\(^{-2}\))
\( a \) activity level \( a = \frac{m}{m_0} \)
\( a_i \) components of the ambient vector A
\( u_i \) components of the user vector U
\( e_i \) components of the data vector E
\( w_a \) absolute air humidity (g/kg)
\( y_i \) components of the output vector Y
\( t \) time
\( F_v \) clothe factor ()
\( F_p \) radiative factor of the body ()
\( R_v \) clothe thermal resistance (m\(^2\)KW\(^{-1}\))
\( I_{sl} \) clothe thermal coefficient used by Sherman ()
\( S_e \) body area (m\(^2\))
\( h_c \) convective heat coefficient (Wm\(^{-2}\)K\(^{-1}\))
\( h_r \) radiation heat coefficient (Wm\(^{-2}\)K\(^{-1}\))
\( T_{rd} \) mean radiant temperature of the room (°C)
\( T_a \) mean air temperature of the room (°C)
\( T_c \) clothe surface temperature (°C)
\( H_a \) mean air humidity of the room (°C)
\( V_a \) relative air velocity of the room near the body (°C)
\( T_s \) mean skin temperature (°C)
\( T_d \) mean air due temperature of the room (°C)
\( p_a \) atmospheric pressure (mmHg)
\( p_v(T) \) vapour pressure with T temperature (mmHg)
\( p_{sv}(T) \) saturated vapour pressure with T temperature (mmHg)
\( p_{sv}*(T) \) saturated vapour pressure with T temperature (torr)
\( Y \) predicted mean vote, PMV (.)
\( Y(X,t) \) predicted mean vote, PMV, evaluated by author no. X, time t (.)
\( Y_{ry} \) radiative coefficient of Sherman’s PMV (.)
\( Y_{cv} \) convective coefficient of Sherman’s PMV (.)
\( Y_c \) humidity coefficient of Sherman’s PMV (.)
\( Y_o \) coefficient of Sherman’s PMV (.)
\( E_{cv}(X) \) convective heat flux density, evaluated by author no. X (Wm\(^{-2}\))
\( E_{ry}(X) \) radiative heat flux density, evaluated by author no. X (Wm\(^{-2}\))
\( E_{dp}(X) \) skin diffusion heat flux density, evaluated by author no. X (Wm\(^{-2}\))
\( E_{dr}(X) \) dry respiration heat flux density, evaluated by author no. X (Wm\(^{-2}\))
\( E_{lr}(X) \) latent respiration heat flux density, evaluated by author no. X (Wm\(^{-2}\))
\( E_{cd}(X) \) conduction heat flux density, evaluated by author no. X (Wm\(^{-2}\))
\( E_{sd}(X) \) evaporation sweat secretion heat flux density, evaluated by author no. X (Wm\(^{-2}\))
\( \Delta X \) uncertainty amplitude domain of the quantity X (scalar or vector)
\( \delta e_j \) random uncertainty value of the data \( e_j \) (scalar)
\( \alpha \) coefficients balance
\( \varepsilon \) emittance of the surface
\( \eta \) external mechanical efficiency \( \eta = \frac{(m-m_{th})}{m} \)

REFERENCES


