P1.10 IMPLEMENTATION OF A BUILDING ENERGY MODEL IN AN URBAN CANOPY PARAMETERIZATION.

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1. INTRODUCTION

The generation of heat in buildings, and the way this heat is exchanged with the exterior can play an important role in urban climate. In this contribution, a Building Energy Model (BEM) is developed to be implemented in an Urban Canopy Parameterization (UCP) for mesoscale models. BEM accounts for: diffusion of heat through the walls, roofs and floors; ventilation; radiation exchanged through windows; longwave radiation exchanged between the indoor surfaces; generation of heat due to occupants and equipments; air conditioning and heating. Buildings of several floors can be considered and, from the processes mentioned above, the time evolution of indoor air temperature and moisture are estimated for every floor. The links between BEM and UCP are as follows: UCP gives to BEM the outdoor air temperature and humidity, and the radiation reaching the wall for the computation of the amount of radiation entering in the building through windows. On the other hand, BEM gives to the UCP the wall temperature, the heat flux due to ventilation, and the heat flux due to processes linked with the generation of energy within the building (e. g. air conditioning).

Results obtained with BEM are compared to results obtained with a more sophisticated model usually employed in architecture. The expected future results of this study are to:

- Improve the capability of mesoscale models to simulate urban canopy climate (Urban Heat Island processes, etc.).
- Allow the estimation of meteorologically related building energy consumptions (e. g. due to air conditioning in summer, or heating in winter).

2. DESCRIPTION OF BEM MODEL

The model used here is similar to Kikegawa et al. (2003), the main difference being the computation of the solar radiation reaching the indoor walls. BEM is a box-type heat budget model in which a building in an urban block is treated as a box. In BEM, the time evolutions of the room air temperature T_r and room air humidity q_{Vr} are estimated solving the following equations:

$$Q_B \frac{dT_r}{dt} = H_{in} - H_{out} \tag{1}$$

$$lr V_B \frac{dq_{Vr}}{dt} = E_{in} - E_{out}, \tag{2}$$

in which $Q_B(JK^{-1})$ and $V_B(m^3)$ denote the overall heat capacity and the total volume of the indoor air in the building. The following equations are used for the computation of the total sensible heat load H_{in} and the total latent heat load E_{in} in the building, respectively:

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$$H_{in} = \sum_j A_j^{wind} h_{wind,j}(T_{wind,j} - T_r)$$
$$+ \sum_i A_i^{wall} h_{wall,i}(T_{wall,i} - T_r) + (1- b)C_p\, rV_a(T_a - T_r)$$
$$+ A_f q_E + A_f P j_{\,p} q_{hs} \tag{3}$$

$$E_{in} = (1- b) l r V_a (q_{Va} - q_{Vr}) + A_f P j_{\,p} q_{hl} \tag{4}$$

The first and second term (on the right hand side) in Eq. (3) represent the heat exchange between the windows and the indoor air, and between the walls, ceiling and pavement and the indoor air. The third term corresponds to the sensible heat exchange through ventilation. The fourth and the last terms indicate the internal sensible heat generation from equipments and occupants, respectively. The first right-hand term of Eq. (4) represents the water vapour intrusion through ventilation and the second term the evaporation from occupants. $H_{out}(W)$ and $E_{out}(W)$ indicate the sensible and latent heat pumped out from the building for cooling, respectively. If there is no air conditioning these two terms are zero.

3. COMPUTATION OF THE WALL TEMPERATURE

In order to compute the wall temperature, the heat diffusion equation is solved in several layers at the interior of the material:

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(K_s \frac{\partial T}{\partial x}) \tag{5}$$

where $K_s(m^2 s^{-1})$ is the thermal conductivity of the material and T is the wall temperature. At the indoor and outdoor surfaces, the boundary condition is defined by solving an energy budget equation (neglecting the latent heat flux),

$$HeatFlux \equiv \frac{(1- alb)Rs + eRl - e\, s T_{surface}^4 + H}{Cs} \tag{6}$$

where $Cs(JK^{-1}m^{-3})$ is the specific heat and H is the sensible heat flux. This budget equation is solved on both sides of the wall.

4. COMPUTATION OF THE RADIATION

4.1. Shortwave radiation

The method used to compute the radiation reaching the indoor surface of the walls is the same method used in the Urban Canopy Parameterization of Martilli et al. (2002). We suppose that when the solar radiation passes through the windows, the radiation is spread isotropically in all directions. The solar radiation captured by an indoor wall is the sum of the radiation coming from the windows and the radiation reflected by the others walls. This shortwave radiation reaching a wall is indicated by the Eqs. (7) and (8) (remember that the equations are for walls, ceiling and pavement):

$$Rs_i = Rs + \sum_{j \neq i} alb_j Rs_j y_{\,ji} \tag{7}$$

$$alb_j = albwall_j (1- window) + albwind(window) \tag{8}$$

The Eq. (7) is a linear system of six equations and six unknowns (the radiation received at each wall) easy to solve by a matrix inversion. The quantity of the solar radiation that passes through the windows Rs has two contributions: the direct solar radiation that reaches the window and the diffuse and reflected shortwave radiation that arrive at the window. The quantity of the direct radiation that passes through the window is a function of the angle of incidence and is computed with a polynomial approach based on the work of Roos (1997) and used by Karlsson et al. (2000) and others. The model employs a polynomial to fit the angle dependence of the direct solar transmittance and the total solar energy transmittance, ***g*** based upon the knowledge of the respective near-normal value. The general form of the polynomial is $g(z) = g_0(1- az^a - bz^b - cz^g)$, where $a + b + c = 1$ and $z = q/90$. The diffuse and reflected radiation that passes through the window is computed with the albedo of the window. This radiation when reaches the outdoor side of the window does not have a privileged direction, then we can obtain the albedo integrating the g expression supposing isotropy in all directions:

$$albwind \approx 1-\int_0^1 g(z)dz$$
$$=1-g_0(1-\frac{a}{a+1}-\frac{b}{b+1}-\frac{c}{g+1}) \tag{9}$$

4.2. Longwave radiation

The longwave radiation reaching an indoor wall is the sum of the longwave radiation emitted and reflected by the others walls. At this point is important to remember that the windows are opaque to the longwave radiation. In order to compute the radiation the following equations are used:

$$Rl_i = \sum_{j\neq i} s\, y_{ji}(\tilde{e}_j T^4_{wall,j} + \hat{e}_j T^4_{wind,j})$$
$$+\sum_{j\neq i}(1-e_j)Rl_j y_{ji} \tag{10}$$

$$e_j = e_{wall,j}(1-window) + e_{wind}(window)$$
$$\tilde{e}_j = e_{wall,j}(1-window) \tag{11}$$
$$\hat{e}_j = e_{wind}(window)$$

This is again, a linear system of six equations and six unknowns easy to solve (the incoming longwave and shortwave radiation at the outdoor surfaces are coming from the mesoscale model).

5. COMPUTATION OF THE WINDOW TEMPERATURE

We suppose that the differences in temperature between the two sides of the glass are small. In order to compute the window temperature we suppose that the absorption is negligible (glasses without coating or films) and the following budget energy equation is solved:

$$C_{wind}\frac{dT_{wind}}{dt} = f \tag{12}$$

where $C_{wind}(JK^{-1}m^{-2})$ is the heat capacity of the window and $f(Wm^{-2})$ is the total flux balance of energy,

$$f = H_{outdoor} + H_{indoor} + e_{wind}(Rl_{outdoor} + Rl_{indoor})$$
$$-2e_{wind}T^4_{wind}. \tag{13}$$

$H_{outdoor}$, H_{indoor} are the sensible heat flux on each side of the window, and $Rl_{outdoor}$ and Rl_{indoor} are the incoming longwave radiation for the two sides of the window.

6. NUMERICAL RESOLUTION

In order to compute T_r and q_{Vr}, we use the following procedure (Fig.1.).

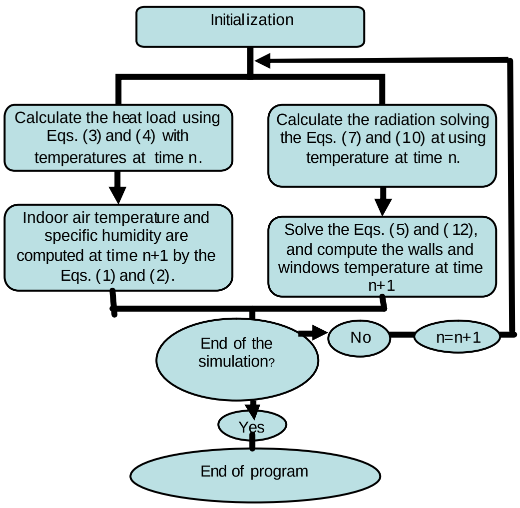

Fig.1. Flow-Chart of BEM.

7. VALIDATION PROCEDURES

The model validation is carried out following the procedure proposed by Zmeureanu et al. (1987). Following their work, BEM is compared firstly against analytical solutions and secondly against other, more sophisticated programs used in the thermal analysis of buildings, as CBS-MASS, THARP and BLAST. All the figures that not correspond to BEM are extracted from Zmeureanu et al. (1987).

The analytical validation was applied for a room 6.0 x 6.0 x 3.6 m^3 with four exterior walls, on an intermediate floor. Initially, the temperatures of the walls and the room air are assumed to be 20 ºC. Then, while the room air temperature is kept constant, the outdoor air temperature drops suddenly to 0 ºC (ΔT_0 =20 ºC). With the following assumptions, an analytical solution can be obtained:

- constant inside convective heat surface coefficient $h_{wall} = 8WK^{-1}m^{-2}$;
- no air infiltration ;
- no solar radiation .

For brick (thermal conductivity 0.78 W/mºC), the results of the comparisons between BEM the analytical solution and CBS-MASS predictions (Fig.2.) indicate good agreement.

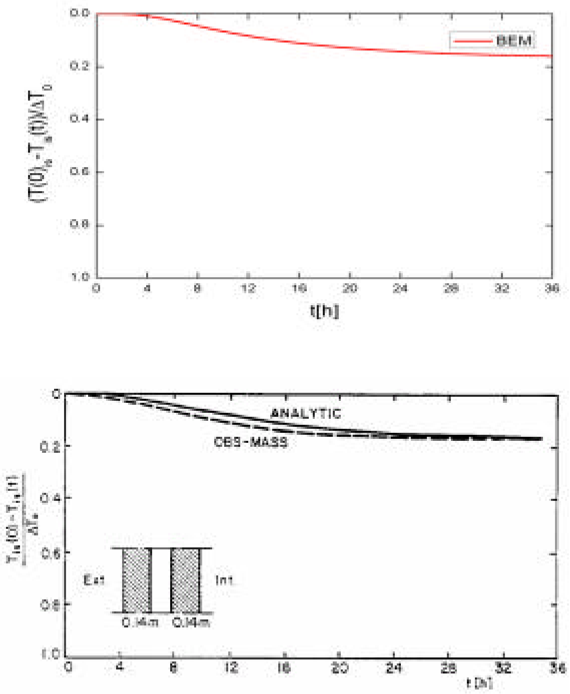

Fig.2. Comparison of the variation of the inside surface temperature of a 0.28 m brick wall due to a step change in outdoor air temperature.

The same room was analysed under different conditions accounting for the effect of internal mass and air infiltration. In this case (Fig.3.) BEM is compared with the analytical solution when the temperature of the internal mass is constant (equal to the room air temperature, $T_{im} = T_r$). Initially, the temperature of walls and air are equal to 20 ºC.

The variation in time of the room air temperature, subjected to a sudden drop of outdoor air temperature to 0 ºC (ΔT_0 =20 ºC) is analyzed.

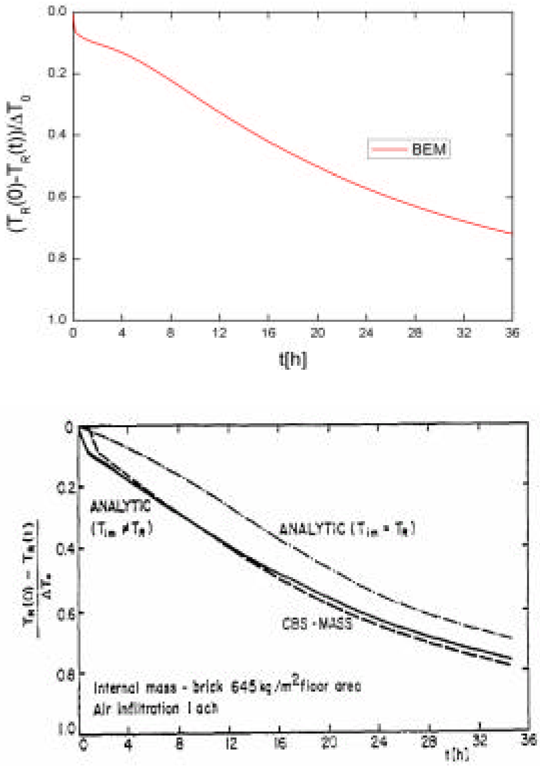

Fig.3. Comparison of the variation of the room air temperature due to step change in outdoor air temperature with air infiltration and internal mass.

The last comparison is performed on a winter design day, for an intermediate-floor office space 30 x 30 x 3.6 m^3, with four exterior walls and windows. The main characteristics and weather data are presented in Table 1. The air temperature of the adjacent rooms (above and below) is assumed to be equal to the air temperature of the analysed space. In this comparison we compare the thermal load obtained by BEM and the others models (since no analytical solution can be obtained for such a complex case). A good concordance is obtained as presented on the following Fig.4.

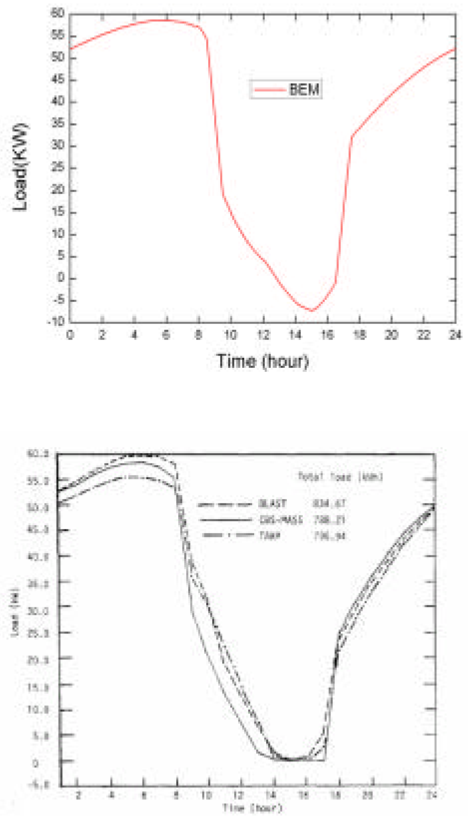

Fig.4. Comparison between the estimations of the CBS-MASS, BLAST, TARP and BEM programs for an office space on a winter design day.

The little differences observed may be also linked to uncertainties on the values of some parameters (e. g. exterior convective heat transfer coefficient, incoming longwave radiation at the outdoor surfaces, etc.) that were not explicitly mentioned in Zmeureanu et al. (1987).

8. CONCLUSIONS

The analytical validation indicates the level of accuracy in simulating the basic phenomena, and indicates that the basic heat transfer phenomena are well simulated by BEM. The inter-program validation provides important information about the accuracy of BEM compared with well-known computer programs used in thermal analysis of buildings. We think that the results, for the tested cases, are good. These results show that BEM is able to capture the most important mechanisms governing heat generation within buildings and exchanges with the exterior. It is simpler and less CPU expensive than other building energy model and can be easily coupled with an UCP for mesoscale models.

In conclusion, this work is a step towards a modelling tool that can account for the complex interactions between urban climate, air pollutant dispersion, and energy demand of buildings. Such tool can be an important support to urban planners.

TABLE 1

Weather data for a winter design day

Hour	Outdoor temperature (ºC)	Direct normal radiation (W/m^2)
1	-18.05	-
2	-18.80	-
3	-19.40	-
4	-19.85	-
5	-20.00	-
6	-19.70	-
7	-18.95	-
8	-17.60	-
9	-15.65	398.1
10	-13.40	685.9
11	-10.85	794.5
12	-8.45	833.7
13	-6.65	830.0
14	-5.45	781.2
15	-5.00	652.7
16	-5.45	301.9
17	-6.50	-
18	-8.15	-
19	-10.10	-
20	-12.05	-
21	-13.70	-
22	-15.20	-
23	-16.40	-
24	-17.30	-

Main characteristics of the intermediate floor space

Exterior wall

0.10 m concrete

(thermal conductivity 1.73 W/mºC)

0.025 m air cavity

0.10 m insulation

0.02 m gypsum board

Glazing-to-wall ratio = 0.5

double glazing h=2.8 $(Wm^{-2\,o}C)$

Air infiltration

1 ach

Occupancy

09:00 to 17:00

Internal heat gains 30 Wm^{-2}

Room air temperature

$20 \pm 1^{o}C$

LIST OF SYMBOLS

A_j^{wind} surface area of window in the wall j (m^2)

A_i^{wall} surface area of the wall i (m^2)

$h_{wind,j}$ convective heat transfer coefficient between the indoor air and the window j $(WK^{-1}m^{-2})$

$h_{wall,i}$ convective heat transfer coefficient between the indoor air and the wall i $(WK^{-1}m^{-2})$

T_r indoor air temperature (K)

$T_{wind,j}$ temperature of the window j (K)

$T_{wall,i}$ indoor surface temperature of the wall i (K)

T_a outdoor air temperature (K)

b thermal efficiency of the total heat exchanger

C_p specific heat of air $(JK^{-1}kg^{-1})$

r air density (kgm^{-3})

V_a total ventilation rate (m^3s^{-1})

A_f floor area (m^2)

q_E sensible heat gain from equipments per floor area (Wm^{-2})

P peak number of occupants per floor area $(personm^{-2})$

j_p ratio of hourly occupants to P

q_{hs} sensible heat generation from the occupants $(Wperson^{-1})$

q_{hl} latent heat generation from the occupants $(Wperson^{-1})$

l latent heat of evaporation (Jkg^{-1})

q_{Va} specific humidity of the outdoor air $(kgkg^{-1})$

q_{Vr} specific humidity of the indoor room air $(kgkg^{-1})$

Rs solar radiation coming from the windows (Wm^{-2})

Rs_j total shortwave radiation flux received by the wall j (Wm^{-2})

$albwall_j$ albedo of the indoor surface of the wall j

$albwind$ albedo of the windows

$window$ % of window in the walls

y_{ji} view factor for the radiation emitted by the wall j and received by the wall i

s Stefan-Boltzmann constant $(Wm^{-2}K^{-4})$

$e_{wall,j}$ emissivity of the indoor surface of the wall j

e_{wind} emissivity of the windows

Rl_i longwave radiation flux received by the wall i (Wm^{-2})

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