AN ENERGETIC-ENVIRONMENTAL BUILDING SIMULATION MODEL IN TRANSIENT STATE AIMED AT COMFORT EVALUATIONS

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ABSTRACT

Through the paper a model simulating the thermal performances of an environment in transient state is presented. The model is composed by two codes that, used in sequence, concur to obtain evaluation, at a local level, of the most used comfort indexes, starting from the acquaintance of the external climatic conditions and of the thermal-physical characteristics of the building envelope. The model estimates, at the same time, energy consumption necessary to maintain prefixed environmental conditions.

A validation procedure, carried out according to a method proposed in a recent european standard, is also reported.

KEYWORDS

Building Simulation Model, Thermal Comfort, Energy Consumption

INTRODUCTION

The realisation of comfort conditions in indoor environments, the minimisation of related energetic consumption and the limitation of the consequent pollutant emissions into the atmosphere represent, in present days, the main task for planners, that can be obtained only through an appropriate energetic analysis of the building and plant configuration.

This results of primary importance above all considering that in the building sector a remarkable share of domestic energetic consumption and consequently of natural resources is gathered, especially in industrialised countries where about 40% of total energetic consumption is absorbed by buildings climatisation.

But the realisation of comfort conditions is strictly connected, apart from air conditioning system management, to the phases of planning and realisation of the building itself; particularly among building elements the envelope, constituting a separating element between the inside and the outside, shows to have peculiar importance in determining both comfort conditions and the related energetic consumption.

For the optimisation of the plan and the analysis of energetic consumption, in professional fields simple calculation methods in stationary state are generally used as support tools; nevertheless such methods, although easily manageable, can result limited as to precision (Marino et al. 2005).

For this reason software for the dynamic simulation of the building-plant system, such as DOE (Buhl et al. 1979), BLAST (BSL 1999), TRNSYS (SEL 2000), Energy Plus (Crawley et al. 2001), showing great precision in evaluating building energy performances, are becoming wide-spread; at the same time scientific literature is more and more enriching of new codes that are used not only for research purposes, but also for planning, management and verification of the system. Anyway these codes can frequently show appreciable differences among their results.

In the past years present authors have proposed a simulation code in transient state, the Building Simulation Model, based on the finite differences method and implemented in Excel™, also containing macro and routines in Visual Basic™ (Idone et al. 2003). Due to its modular structure, that can be easily integrated with external routines, the code constitutes a versatile simulation tool, able also to allow evaluation of different parameters connected to comfort conditions in indoor environments (radiant field, sensation indexes at punctual level, etc.).

In order to evaluate comfort conditions indoors, the code is integrated with a further one, completely implemented in Visual Basic™, that, using as input parameters the results provided by the first code, carries out the computation of the local values of PMV and PPD (Fanger 1970, ISO 2005) and provides the graphic restitution of iso-index curves.

The two codes, used in sequence, concur to obtain the evaluation, at a local level, of the most used comfort indexes, starting from the acquaintance of the external climatic conditions and the thermal-physical characteristics of the building envelope; at the same time, energy consumption necessary to maintain prefixed environmental conditions indoors is estimated.

The code is tested, as far as the thermal simulation of the building is concerned, using the validation procedures reported in prEN 15265 (CEN 2007).

Further comparison has been carried out in a previous work (Idone et al. 2003) between its results and those provided by Energy Plus (Crawley et al. 2001), a simulation code based on the response factors method, pointing out satisfying results.

STRUCTURE OF THE CODES

The structure of the simulation model, that evidences the relations existing between the two codes, is reported in Figure 1. It is possible to observe that the model is constituted by two independent blocks, the second of which, relative to comfort assessment, uses as input values the results previously elaborated from the first one.

In particular the first code realises the simulation of the building-plant system in transient state and, starting from the acquaintance of outdoor climatic conditions, allows determination of the wall surface temperatures and of indoor air temperature. These results, integrated with the microclimatic and subjective parameters on which the thermal-hygrometric comfort depends, are used by the second code in order to proceed to the calculation of the local values of the PMV and PPD indexes and to obtain the restitution in graphical format of iso-index curves.

Presently the model simulates the thermal behaviour in transient state of an environment delimited from six surfaces, each of which can be external or confine with other environments, climatised or not, and is in course of extension to more complex environments.

Thermal simulation model

The analysis of the thermal behaviour of the walls is performed by solving Fourier general equation for heat conduction, in mono-dimensional form, using the solution method based on finite differences in its explicit formulation. Such method presents the advantages not to require the solution, at each calculus step, of large equation systems, typical of the implicit formulation, to allow very small steps and to maintain in the code a modular structure.

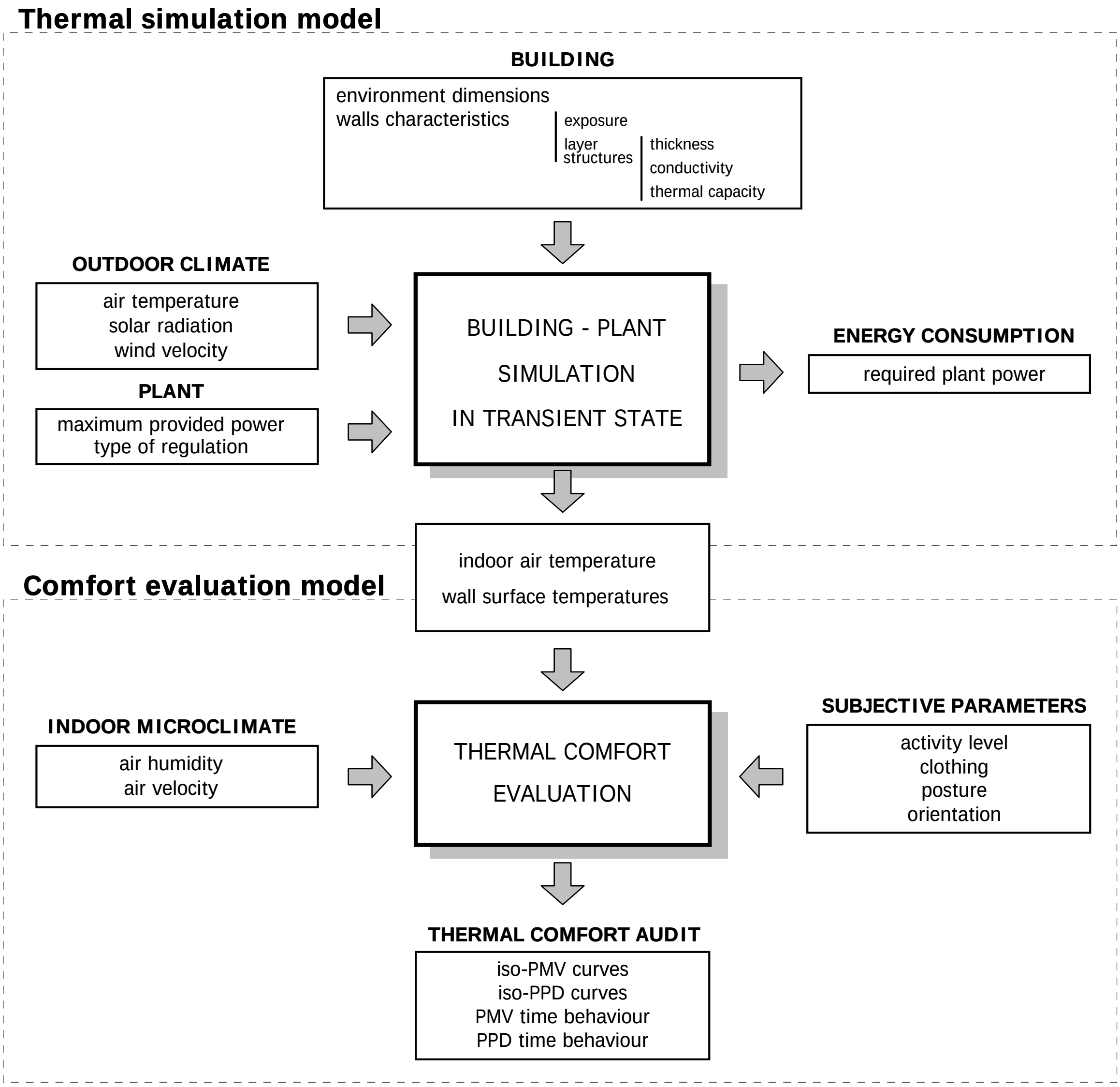


Figure 1 Structure of the code

In the following the main balance equations referring to opaque and transparent surfaces of the environment and to indoor air temperature will be described.

Opaque surfaces

All the walls can be constituted by one or more layers. The spatial discretization of each wall is carried out by subdividing an homogenous layer in sub-layers having thickness Δx depending on the total thickness of the layer itself. Each balance equation is written for the *n*-th node at the interface between two sub-layers.

For internal nodes the algebraic structure of the thermal balance that allows to obtain the temperature of the node *n* inside an homogeneous layer, showing density ρ and specific heat *c*, at the instant $\tau+\Delta\tau$, $t_n^{\tau+\Delta\tau}$, starting from the acquaintance of the temperature at the previous instant in the same node and in the adjacent ones, is the following:

$$\left(\frac{t_{n-1}^{\tau}-t_{n}^{\tau}}{R}+\frac{t_{n+1}^{\tau}-t_{n}^{\tau}}{R}\right)=\frac{\rho c\,\Delta x}{\Delta\tau}\left(t_{n}^{\tau+\Delta\tau}-t_{n}^{\tau}\right) \qquad (1)$$

where $R=\lambda/\Delta x$ is the conductive thermal resistance of the adjacent sub-layers (Figure 2).

The convergence of the solution requires verification of the stability condition, that assumes the following expression:

$$\frac{\lambda}{\rho c}\frac{\Delta\tau}{\Delta x^{2}}\leq\frac{1}{2} \qquad (2)$$

where λ is the thermal conductivity of the material.

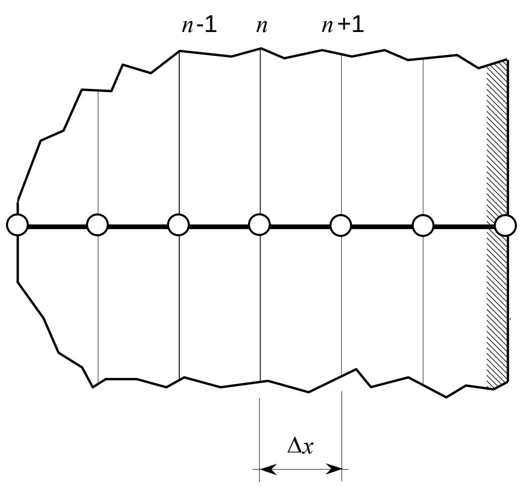


Figure 2 Example of discretization of an internal plane layer of material

The thermal balance on the border nodes laying at the interface between the wall and the environment must take into account the presence of the convective and radiative components of the heat exchange, apart from the component due to solar radiation. Anyway the presence of the first two contributions involves a considerable reduction of the temporal step that satisfies the stability condition, with a consequent increase of the number of iterations.

For the nodes in issue (Figure 3), therefore, the pure explicit method is abandoned in favour of the implicit one, in which some changes have been made following (Butera et al. 1984).

In this case the method introduces an approximation in the assessment of the temperatures, as the thermal balance is carried out using air temperature and convective, radiative and adductive coefficients evaluated at τ instant instead of $\tau+\Delta\tau$: anyway, as their variation in the time interval $\Delta\tau$ can be neglected, the approximation introduced is very small.

The two balance equations assume the following expressions in the case of wall-indoor environment interface:

$$\begin{aligned}&\frac{\lambda}{\Delta x}\left(t_{n-1}^{\tau+\Delta\tau}-t_{n}^{\tau+\Delta\tau}\right)+h_{ci}^{\tau}\left(t_{ai}^{\tau}-t_{n}^{\tau}\right)+q_{ri}^{\tau}+q_{si}^{\tau+\Delta\tau}=\\&=\frac{\rho c\,\Delta x}{2\Delta\tau}\left(t_{n}^{\tau+\Delta\tau}-t_{n}^{\tau}\right)\end{aligned} \qquad (3)$$

and in the case of wall-outdoor environment interface:

$$\begin{aligned}&\frac{\lambda}{\Delta x}\left(t_{n-1}^{\tau+\Delta\tau}-t_{n}^{\tau+\Delta\tau}\right)+h_{Ae}^{\tau}\left(t_{ae}^{\tau}-t_{n}^{\tau}\right)+q_{se}^{\tau+\Delta\tau}=\\&=\frac{\rho c\,\Delta x}{2\Delta\tau}\left(t_{n}^{\tau+\Delta\tau}-t_{n}^{\tau}\right)\end{aligned} \qquad (4)$$

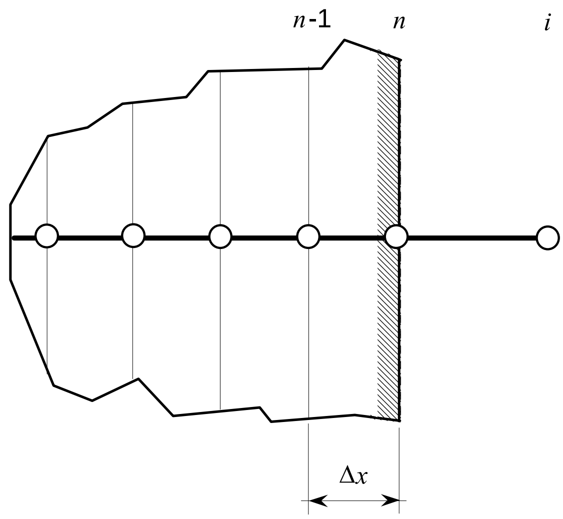


Figure 3 Example of discretization of a plane layer of material near the border surface

where h_{ci} and h_{Ae} respectively represent the indoor convective coefficient and the outdoor adductive coefficient, t_{ai} and t_{ae} indoor and outdoor air temperature.

For the evaluation of the infrared, q_{ri}, and solar indoor, q_{si}, and outdoor, q_{se}, radiative terms see Butera et al. (1984).

Transparent surfaces

Effecting the described assumptions concerning the convective and radiative exchanges and neglecting in the energetic balance both the material thermal inertia and thermal resistance, for a single glass window the following equation can be obtained:

$$h_{Ae}^{\tau+\Delta\tau}\left(t_{ae}^{\tau+\Delta\tau} - t_{v}^{\tau+\Delta\tau}\right) + h_{ci}^{\tau}\left(t_{ai}^{\tau} - t_{v}^{\tau}\right) + q_{ri}^{\tau} + q_{acc}^{\tau+\Delta\tau} = 0 \quad (5)$$

that allows calculation of the surface temperature of the glass, t_v, at instant $\tau+\Delta\tau$. For the evaluation of the radiative term q_{ri} and the accumulated solar power q_{acc} see Butera et al. (1984).

Indoor air temperature

Indoor air temperature is obtained, at each time instant $\tau+\Delta\tau$ by imposing the following thermal balance:

$$\frac{\rho_{ai}\, c_{ai}\, V}{\Delta\tau}\left(t_{ai}^{\tau+\Delta\tau} - t_{ai}^{\tau}\right) = \sum_{j=1}^{n} S_j\, h_{cj}^{\tau}\left(t_j^{\tau} - t_{ai}^{\tau}\right) + q_{ig}^{\tau} + q_{plant}^{\tau+\Delta\tau} \quad (6)$$

where ρ_{ai} and c_{ai} respectively represent the density and the specific heat of indoor air, V the volume of the environment and S_j the area of the j-th surface (either opaque or transparent) at temperature t_j, h_{cj} the corresponding convection coefficient, q_{ig} the thermal power due to internal gains (which is an input parameter) and q_{plant} the power demand to the plant; this latter is a function of air temperature at time $\tau+\Delta\tau$, depending on the indoor environmental conditions and the plant regulation system.

Comfort evaluation model

The second code (Nucara et al. 2000a), implemented in Visual Basic™, allows comfort verification, analysing its variability in space and time. To such extent the software proceeds to the calculation of PMV and PPD indexes, providing the respective iso-index curves, in different time periods; similar diagrams are produced in order to point out presence of discomfort due to asymmetry of the radiant field.

The software directly uses part of the results of the simulation code, but it demands further insertion of data concerning the indoor microclimate (air velocity and relative humidity) and the subject that makes use of the examined environment (its level of activity, the thermal resistance of its clothing, its orientation and posture).

As regards the determination of the space variation of the mean radiant temperature, the code uses simplified algorithms to calculate the view factors between the subject and the wall (Nucara et al. 2000b) and between the subject and a composite surface (Nucara et al. 1999).

VALIDATION OF THE PROPOSED CODE – CASE STUDIES

The code is tested, as far as the thermal simulation of the building is concerned, using the validation procedure reported in prEN 15265 (CEN 2007), that concerns the assessment of heating and cooling consumption for 12 case studies consisting of a mono-zone office environment (Figure 4) with prefixed thermal-physical characteristics. In Table 1 the thickness and the thermal capacities of the opaque components of the enviroment are reported.

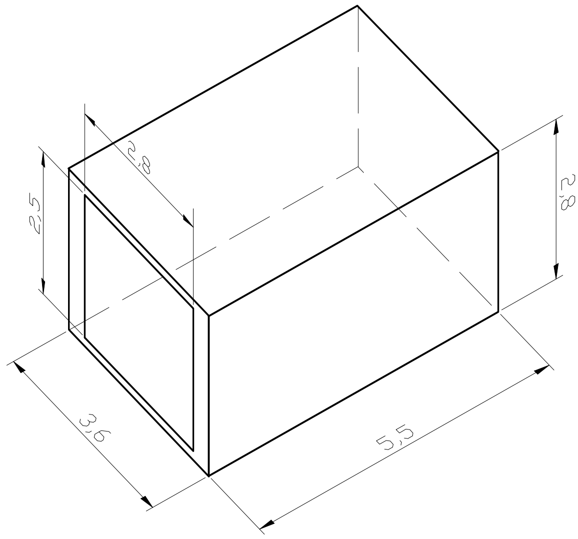


Figure 4 Environment used for the simulation

Table 1 Thermal capacities of the opaque components

TYPE	d (m)	C (kJ/m^{3}K)
1 - external wall	0.365	1187
2 - internal wall	0.124	169
3c - ceiling	0.284	1690
3f - floor	0.284	1690
4c - ceiling/roof	0.404	1215
4f - floor	0.404	1215
5 - roof	0.284	1476

The case studies are obtained using different combinations of glazed system, ceiling, floor, internal gains and climatisation system functioning (continuous or intermittent) (Table 2).

For each of the cases 1 to 12 the prEN 15265 standard provides reference values for heating and cooling yearly energy demand.

Table 2 Test cases

TEST N.	EXTERNAL OPAQUE WALL	GLAZING SYSTEM	VERTICAL INTERNAL WALL	ADIABATIC CEILING OR ROOF	ADIABATIC FLOOR	CLIMATISATION SYSTEM FUNCTIONING	INTERNAL GAINS
1	Type 1	SDP	Type 2	Type 4c	Type 4f	Continuous	yes
2	Type 1	SDP	Type 2	Type 3c	Type 3f	Continuous	yes
3	Type 1	SDP	Type 2	Type 4c	Type 4f	Continuous	no
4	Type 1	DP	Type 2	Type 4c	Type 4f	Continuous	yes
5	Type 1	SDP	Type 2	Type 4c	Type 4f	Intermittent*	yes
6	Type 1	SDP	Type 2	Type 3c	Type 3f	Intermittent*	yes
7	Type 1	SDP	Type 2	Type 4c	Type 4f	Intermittent*	no
8	Type 1	DP	Type 2	Type 4c	Type 3f	Intermittent*	yes
9	Type 1	SDP	Type 2	Type 5	Type 4f	Intermittent*	yes
10	Type 1	SDP	Type 2	Type 5	Type 3f	Intermittent*	yes
11	Type 1	SDP	Type 2	Type 5	Type 4f	Intermittent*	no
12	Type 1	DP	Type 2	Type 5	Type 4f	Intermittent*	yes

* Working hours: 8 - 18 from monday to friday.

The validation criteria consists in comparing the results provided by the proposed code to reference values by calculating the following parameters:

$$rQ_{heat} = \frac{\left|Q_{heat} - Q_{heat,ref}\right|}{Q_{tot,ref}} \quad rQ_{cool} = \frac{\left|Q_{cool} - Q_{cool,ref}\right|}{Q_{tot,ref}} \quad (7)$$

where Q_{heat} and Q_{cool} represent the energy demand respectively necessary for heating and cooling and Q_{tot} the total one, whereas $Q_{heat,ref}$, $Q_{cool,ref}$ e $Q_{tot,ref}$ are the corresponding reference values provided by the standard draft.

Referring to eq. (7), the standard draft provides three levels of accuracy, indicated as A, B, C and defined in dependence on the values assumed by the rQ_{heat} and rQ_{cool} parameters (Table 3).

Table 3 Levels of accuracy

LEVEL	RANGE
A	rQ_{heat}, $rQ_{cool} \leq 0.05$
B	$0.05 < rQ_{heat}$, $rQ_{cool} \leq 0.10$
C	$0.10 < rQ_{heat}$, $rQ_{cool} \leq 0.15$

RESULTS

The results provided by the simulations are reported in Table 4 and Figures 5-6, together with the reference values.

As it can be seen, for 9 cases out of 12 the accuracy levels are included within level C; in particular, three cases show level A, three show level B and three level C.

Three cases are outside the range C. Probably this is due to a lower sensibility of the proposed code when combined effects of the horizontal structures thermic inertia and of the internal and solar gains are present.

A separate examination of rQ_{heat} and rQ_{cool} values corresponding to the above 9 cases points out, as concerns rQ_{heat}, 4 cases showing values ≤ 0.05, 4 cases showing values $0.05 < rQ_{heat} \leq 0.10$ and only one case showing values $0.10 < rQ_{heat} \leq 0.15$; as regards rQ_{cool}, 7 cases showing values ≤ 0.05 and only two showing values $0.10 < rQ_{cool} \leq 0.15$ are observed.

The above results indicate a good accordance between calculated and experimental results.

In addition, Figures 7-8 report an example of iso PMV and iso PPD curves provided by the software, evaluated for the winter solstice with reference to the assigned microclimatic and subjective conditions reported in Table 5.

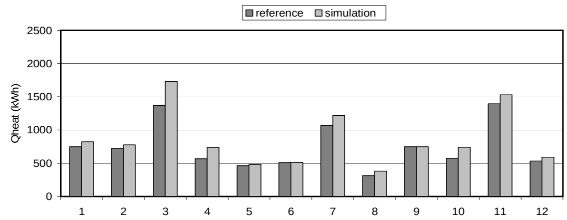


Figure 6 Levels of accuracy for the different test cases

Table 5 Subjective and microclimatic parameters

M (met)	W (met)	I_{cl} (clo)	v_{ar} (m/s)	RH (%)
1.2	0	1.0	0.10	50

CONCLUSIONS

A model simulating the thermal performances of an environment in transient state is presented. It is composed by two codes that, used in sequence, concur to obtain the evaluation, at a local level, of the most used comfort indexes, starting from the acquaintance of the external climatic conditions and the thermal-physical characteristics of the building envelope. The model estimates, at the same time, the energy consumption necessary to maintain prefixed environmental conditions indoors.

Table 4 Results of the simulation and reference values

TEST N.	$Q_{heat, ref}$ (kWh)	$Q_{cool, ref}$ (kWh)	$Q_{tot, ref}$ (kWh)	$Q_{heat,sim}$ (kWh)	$Q_{cool, sim}$ (kWh)	$Q_{tot, sim}$ (kWh)	rQ_{heat}	rQ_{cool}	LEVEL OF ACCURACY
1	748.0	233.8	981.8	823.0	238.5	1061.5	0.08	0.00	B
2	722.7	200.5	923.2	776.1	197.9	974.0	0.06	0.00	B
3	1368.5	43.0	1411.6	1729.3	21.5	1750.8	0.26	0.02	> C
4	567.4	1530.9	2098.3	737.5	1286.5	2023.9	0.08	0.12	C
5	463.1	201.7	664.8	478.0	173.4	651.4	0.02	0.04	A
6	509.8	185.1	694.9	511.6	162.6	674.2	0.00	0.03	A
7	1067.4	19.5	1086.9	1218.8	4.6	1223.4	0.14	0.01	C
8	313.2	1133.2	1446.4	379.4	868.7	1248.1	0.05	0.18	> C
9	747.1	158.3	905.4	747.2	155.4	902.7	0.00	0.00	A
10	574.2	192.4	766.6	741.9	156.5	898.4	0.22	0.05	> C
11	1395.1	14.1	1409.3	1529.4	3.9	1533.3	0.10	0.01	B
12	533.5	928.3	1461.8	590.9	761.1	1352.1	0.04	0.11	C

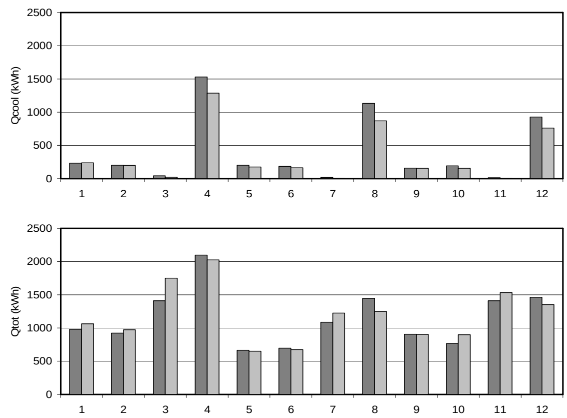
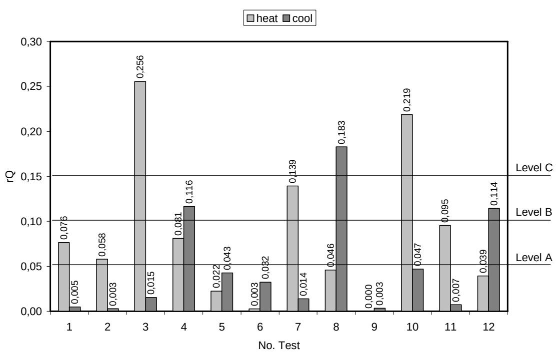


Figure 5 Comparison between reference consumption values and simulated ones for the different test cases



The code is tested, as far as the thermal simulation is concerned, using the validation procedures reported in prEN 15265 (CEN 2007).

The results indicate a good accordance between calculated and experimental results: for 9 cases out of 12 the accuracy levels are included within the level C of the reference table of the standard, showing in particular, in three cases level A, in three level B and in three level C.

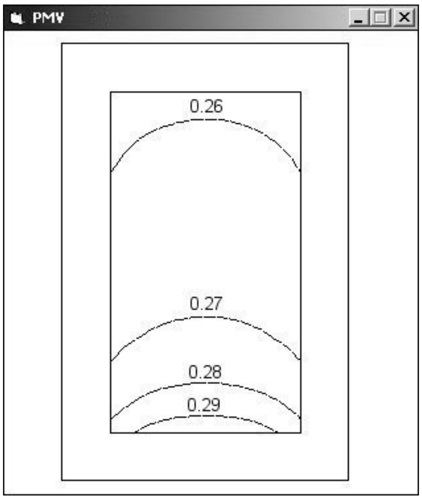


Figure 7 Example of iso-PMV provided by the code, evaluated for the winter solstice

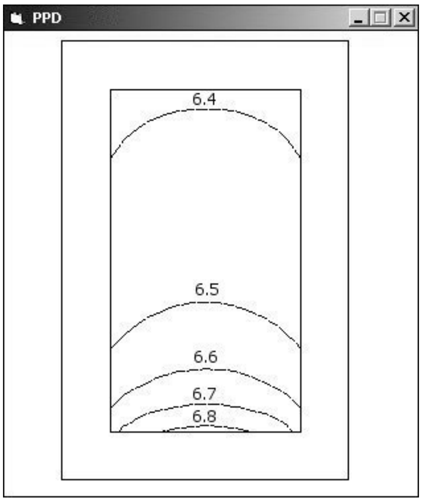


Figure 8 Example of iso-PPD curves provided by the code, evaluated for the winter solstice

NOMENCLATURE

c	specific heat	J/(kg°C)
C	thermal capacity	J/(m^3°C)
d	wall thickness	m
h	surface heat transfer coefficient	W/(m^2°C)
I_{cl}	clothing insulation	clo
M	metabolic rate	met
q	thermal power	W
Q	energy demand	kWh
R	conductive thermal resistance	(m^2°C)/W
RH	relative humidity	%
S	area of the surface	m^2
t	temperature	°C
V	volume of the environment	m^3
v_{ar}	relative velocity	m/s
W	effective mechanical power	met
Δx	layer thickness	m
$\Delta\tau$	time step	s
ρ	density	kg/m^3
τ	instant of time	s
λ	thermal conductivity	W/(m°C)

Subscripts

a	air
A	adductive
acc	accumulated
c	convective
cool	cooling
e	outdoor
g	gain
heat	heating
i	indoor
j	counter
n	internal node
o	border node
plant	plant
r	radiative
ref	reference
s	solar
tot	total
v	glass

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