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SIMPLIFIED MODELLING OF AIR MOVEMENTS IN A ROOM AND ITS FIRST VALIDATION WITH EXPERIMENTS

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SUMMARY

The need for increasingly sharp modelling of building energy behaviour allowing comfort to be evaluated within a heated, ventilated dwelling room lead Electricite de France ADE Department to develop a simulation model of air interior motion. This is a simplified modelling which it could be possible to integrate into a global building energy simulation software programme (CLIM2000). The design principle is the division of the air volume of the room into areas for which mass and energy balances are computed.

Room areas where air flows at very low velocities (standard areas) and dynamic area such as thermal plume are processed separately. A few computation results added to a first validation study based on a CFD code, and then on a series of real scale experiments, evidences the possibility of using simplified modelling to represent interior air motion.

NOMENCLATURE

C_p	: Specific heat at constant pressure ($W.kg^{-1}.K^{-1}$)
E_0	: Entrainement coefficient
Fr	: Froude number
g	: Gravitation constant (m/s^2)
h_c	: Surface exchange coefficient ($W/M^2/C$)
K_{ij}	: Permeability of the border between areas i and j ($m/s/Pa^n$)
L_{ij}	: Width of the border between areas i and j (m)
M	: Standard point of the border between areas i and j
n	: Flow nature characteristic parameter
P	: Air pressure (Pa)
P_{0i}	: Air pressure at area i lower level (Pa)
q_e	: Air entrainment mass flow rate in plume or jet (kg/s)
$qm_{i,j}$	: Absolute valve of the mass flow rate of air flowing from area i toward area j (kg/s)
$qm_{j,i}$	: Absolute valve of the mass flow rate of air flowing from area j toward area i (kg/s)
$Qm_{i,j}$	: Algebraic mass flow rate of air flowing from area i toward area j (kg/s)
$Qm_{j,i}$	: Algebraic mass flow rate of air flowing from area j toward area i (kg/s)
$Qm_{s,i}$	: Source mass flow rate (injected into area i) (kg/s)
$Qm_{p,i}$	: Negative heat source mass flow rate (taken from area i) (kg/s)
S_{ij}	: Surface of the border between areas i and j (m^2)
St	: Stanton number
T	: Air temperature (°C)
T_a	: Ambiant temperature (°C)
T_i	: Air temperature in area i (°C)
T_s	: Partition border surface temperature (°C)
U_m	: Maximum velocity in a plume (m/s)
V_M	: Velocity at the point M ($m.s^{-1}$)
z	: Standard level of an area (m)
z_i	: Standard level of area i (m)
z_j	: Standard level of area j (m)
z_n	: Neutral axis level (m)
β	: Coefficient of volumetric expansion (K^{-1})
ϕ_c	: Heat flow exchanged with the partition border (W)
$\phi_{i,j}$	: Heat flow from area i toward area j (W)
$\phi_{j,i}$	: Heat flow from area j toward area i (W)
ϕ_p	: Well heat flow (taken from area i) (W)
ϕ_s	: Source heat flow (taken from area i) (W)
$\phi_{cp}(z)$	: Heat flux to wall behind the plume ($W.m^{-1}$)
Φ_z	: Thermal energy flux in plume ($W.m^{-1}$)
ρ	: Air density (kg/m^3)
ρ_i	: Air density in area i (kg/m^3)
ρ_j	: Air density in area j (kg/m^3)

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INTRODUCTION

The numerical model became in a few years an ordinary, widely used tool in the building energy sector like in many other fields. The model components whether for heating systems or for building envelope (walls, windows, thermal bridges,...) now form the subject of complex modellings.

These models which often are developed to meet sizing and energy operating cost requirements, generally represent the final stage in its entire totality ie. the return of energy to the room. This means that the space or the volume of air in a room in which one lives, is regarded as being fully homogeneous from temperature and concentration viewpoint (humidity, pollutant, ...).

Thermal comfort requirements via (vertical or horizontal) temperature gradients or the quality of air relative to pollutant distribution will certainly not be satisfield with a simple air node to typify the whole room volume. Similarly, a sharp evaluation of energy losses through the room walls makes it necessary to take the differences in temperatures and exchange coefficients into account.

This paper presents a modelling which provides response data upon the aeraulic behaviour of room environment while restricting the complexity of our software which should remain a building "general" code. Examples of computation with their first experimental validation for a room equipped with an electric convector, made us think that the temperature stratification can be evaluated with the aid of a simplified modelling.

A SIMPLIFIED MODEL: "SAMIRA*"

The air motion inside a dwelling room is governed by the local equations for mass conservation, linear momentum, and energy. Integrating these equations after they have been rendered finely discrete, into a global science-of-heat software system would entail an unacceptable computation times. This is why we had opted for a simplified modelling allowing the air motion inside a room and the temperature distribution to be understood without using field models.

Though different types of simplified models exist, they all rest upon a division of the reference room into areas and they differ in the mode of computation used for inter-area mass and heat exchanges [ref. BOUIA].

The exchange laws may be deduced from serial experiments or from a degrading of fluid mechanics equations as is the case for our SAMIRA model.

Model hypotheses

In a dwelling room, heated and ventilated, the temperature and pressure vary from a place to another. These variations may be high between an area set near to a heat source or an air supplier, and the middle of the room. The division SAMIRA model uses consists in properly subdividing the room into parallelepipedic areas with vertical or horizontal generating lines. This division is based on visual qualitative observation by laser tomography [ref. AREFI]. The layout of heating and ventilation systems, and of the openings govern the choice of meshing to take into account the nature of areas (Figure 1).

SAMIRA is a tridimensional model which enables an evaluation of temperature distribution and of the flows exchanged for the whole volume.

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* Simulation Aéraulique des Mouvements d'air Intrazones en Régime Anisotherme.

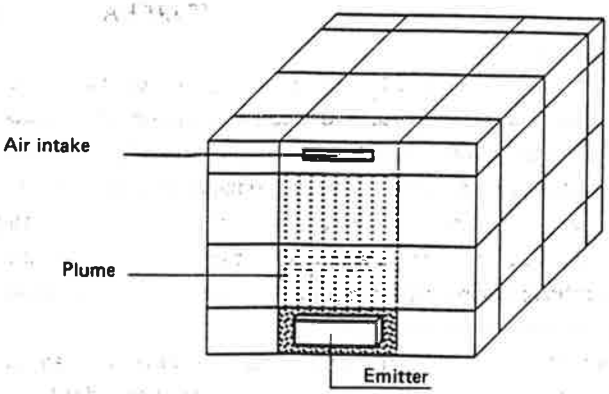


Fig. 1. Division of the room into areas

There are two types of areas (Figure 2):

- areas which belong to a plume every time a source of heat exists: Plume areas,

- the other areas will be called: standard areas.

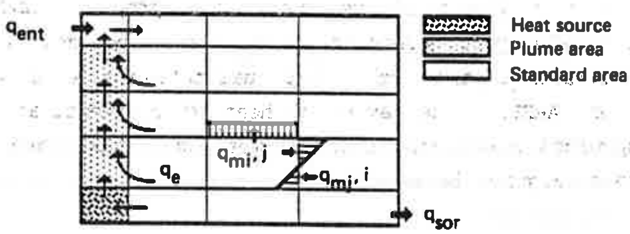


Fig. 2. Types of areas with associated flows.

This model is based on the drawing up of mass and energy balance equations for each area, making the following hypotheses:

Each standard area is supposed to be still at temperature T homogeneous given a hydrostatic pressure profile P.

The borders between these areas are assumed to behave as fictitious and fully permeable partitions.

The volume flow rates between two standard areas (i) and (j) comply with a power behaviour law resulting from BERNOULLI relation. They are function of pressures (P_{0I}, P_{0j}), temperatures (T_i, T_j) and area dimensions.

The flow conveyed from a standard area toward a plume area complies with an empirical entrainment rate law.

The balance equations

An area may exchange both mass and heat with its environment through six borders: 4 vertical and 2 horizontal. The mass and energy balances under steady-state operating conditions thus write as follows for each area (i):

$$\sum_{j=1}^{6} Qm_{i,j} - Qm_{si} + Qm_{pi} = 0$$

$$\sum_{j=1}^{6} \phi_{i,j} - \phi_{si} + \phi_{pi} = 0$$

The mass balances are expressed in a different way depending on whether the transfer takes place between two still areas or a plume area and the areas nearby (Figure 2).

Mass and energy exchanges between standard areas (BERNOULLI's law)

A fluid hydrostatically balanced complies with the law:

$$dP = -\rho.g.dz$$

In cases where the temperature is steady, and variations in pressure, low, we have:

$$P(z) = P_0 - \rho.g.z$$

Consequently, the pressure differential between two points of two adjacent standard areas (i) and (j) is:

$$P_i(z_i) - P_j(z_j) = P_{0i} - P_{0j} - (\rho_i.g.z_i - \rho_j.g.z_j)$$

There are two different cases:

- The border is vertical;

In this case assuming that the lower level is the same in all the areas, the pressure differential reads as follows at level $z_i = z_j = z$:

$$\Delta P(z) = P_{0i} - P_{0j} - (\rho_i - \rho_j).g.z$$

or $$\Delta P(z) = -(\rho_i - \rho_j).g.(z - z_n)$$

by introducing the level z_n of the neutral axis defined by $\Delta P(z_n) = 0$ (see Figure 3-b):

The differential pressure on each side of the bracket dz surrounding the point M at level z is represented by a flow with a velocity V_M in point M where prevails the pressure P_M taken equal to the pressure $P_J(z)$ by analogy with the flows through a submerged opening [ref. 2]. BERNOULLI's relation enables one to write (if $P_i(z) > P_j(z)$) (see Figure 3-a):

$$P_i(z) = P_M + \frac{1}{2}\rho_i.V_M^2 = P_j(z) + \frac{1}{2}\rho_i.V_M^2$$

that is:

$$\Delta P(z) = P_i(z) - P_j(z) = \frac{1}{2}\rho_i.V_M^2$$

$$V_M = \sqrt{\frac{2.\Delta P(z)}{\rho_i}}$$

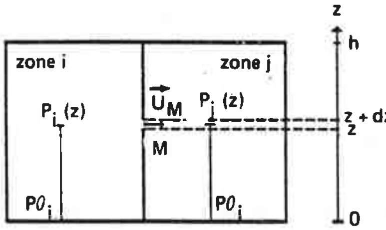


Fig. 3-a)
Flow through a submerged opening

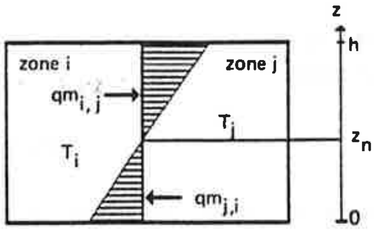


Fig. 3-b)
Flow exchange through a vertical border

The theoretical elementary mass flow rate flowing through dz then is:

$$\rho_i . V_M . L_{ij} . dz$$

but in reality this flow is:

$$dqm_{i,j}(z) = C_d . (\rho_i . V_M . L_{ij} . dz)$$

where C_d is the flow coefficient (C_d > or = 1) which gives the pressure drop. As a general rule, this flow rate is expressed as [ref. 8]:

$$dqm_{i,j}(z) = K_{ij} . L_{ij} . \rho_i . \Delta P(z)^n . dz$$

Where K_{ij} is the permeability of the border between areas (i) and (j), and n a parameter characterizing the nature of the flow (n ∈ [0.5;1]).

According to the position of the neutral axis Z_n and the values of P_i and P_j, the exchanged flow rate $Qm_{i,j}$ entering the area (j) and a flow rate $Qm_{j,i}$ entering the area (i) (see Figure 3-b), that is, after integration:

$$Qm_{i,j} = qm_{i,j} - qm_{j,i}$$

where, for the case represented in figure 3-b):

$$qm_{i,j} = K_{ij} . L_{ij} . \rho_i . [(\rho_j - \rho_i) . g .]^n . \left[\frac{(h - Z_n)^{n+1}}{n+1} \right]$$

$$qm_{j,i} = K_{ij}.L_{ij}.\rho_j.[(\rho_j-\rho_i).g.]^n.\left[\frac{Z_n^{\,n+1}}{n+1}\right]$$

Transfers between plume and standard areas

To study the plume, a series of tests has been carried out (jointly with CETIAT) on electric convectors having different configurations and powers. The measurement of velocities and temperatures at different levels of z in the plume enabled the mass flow rate q(z) and the heat flow conveyed X(z) to be calculated and a correlation to be made between these two variables:

$$q(z) = \int_0^\infty \rho.u.dy$$

$$\Phi(z) = \int_0^\infty \rho.C_p.U.(T-T_a)\ dy$$

that is:

$$q(z) = A.\phi^{1/3}(z).(z-z_o)$$

where :

A is a constant of about 0.01

zo is a fictitious origin corresponding to the level of a linear theoretical source producing an equivalent plume.

In other respects, assuming the velocity and temperature of gradients are equivalent for a wall plume (ref. LIBURDY AND FEATH), three adimensional numbers fully determine the plume.

The FROUDE number (Fr):

$$Fr^2 = \frac{\rho.C_p}{g.\beta}.\frac{U_m^{\,3}}{\phi(z)}$$

The STANTON number (St):

$$St = \frac{\phi_{cp}}{\rho.C_p.U_m(z).(T_m(z) - T_p(z))}$$

And the entrainment coefficient (E_o) defined by:

$$\frac{d\,q(z)}{dz} = \rho.E_o.U_m(z)$$

The measurements made in the plumes of electric convectors, in fact, show that the similitude is not perfect but these parameters however do not vary much from the given height above the convector. We have taken these average values to calculate the energy and the entrained airflow in the plume areas.

THE FIRST VALIDATION RESULTS

The validation of a numerical model is always a very critical task more especially as the model is based on largely simplified physical Laws.

To validate our model, we selected two working methods not equally complex but highly complementary:

- A fine validation based on the analysis of elementary phenomena met with the combined convection. This work rested on the use of a detailed field model taking into account the turbulence effects.

  This first phase has been carried out in two stages: first a validation of the field model using a fine, reduced-scale experiment and, then, validation of our SAMIRA model relative to the code.

- Lastly to confirm and complete this validation we have carried out a series of experiments in our laboratory cells.

Validation relative to a field model

This work which aims to reproduce medium and extreme conditions for the utilization of a room from a heating and ventilation viewpoint is currently in progress and we present only the first results, which are promising, in this document.

We have made a first series of 2D comparisons using a room with dimensions equivalent to those of our laboratory cell (ETNA*).

These comparisons are based on laser tomographic displays to define the grid of the SAMIRA model (see Figure 4).

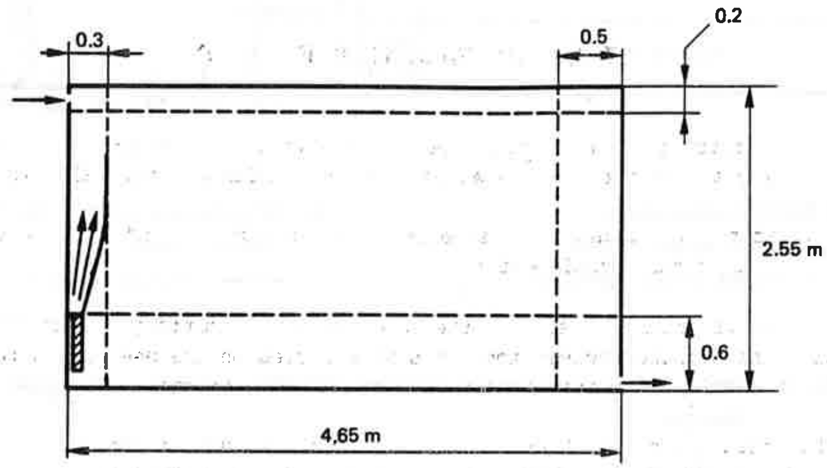


Fig. 4. Size and simplified grid of the cell

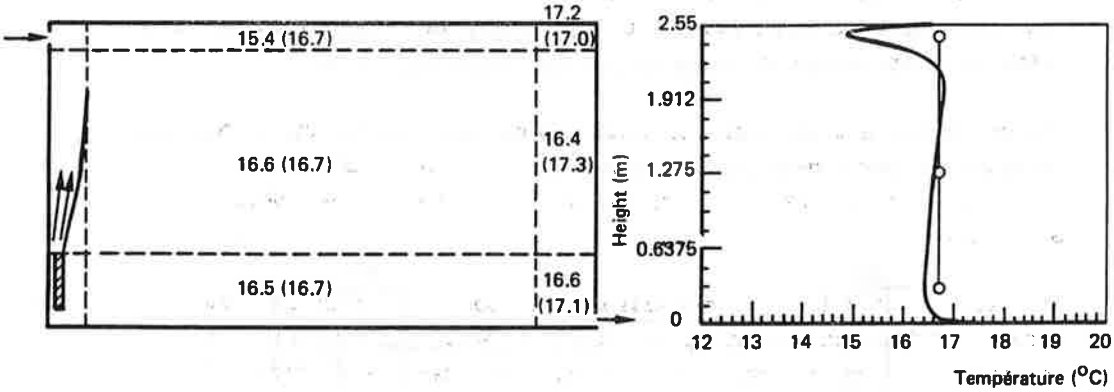
Among the hypotheses made for the simplified model, we find the temperature homogeneity per area and the temperatures computed with the aid of SAMIRA are therefore taken in the middle of the areas.

The first comparisons presented concern the air temperature gradient in the middle of the room and the average temperatures per ares (Figure 5).

ETNA* : Thermal test cells in natural or artificial climate.

In that case, the simulation conditions are:

- Emiter power : 500 W
- Surface temperature : 18°C
- Air inlet, speed : 2,5 m/s
  flow : 90 m^3/h/m
  temperature : 0°C.



a) Zonal temperature
   - Field model "SIMEC"
   - (Zonal model "SAMIRA)

b) Temperature profil on the central axis
   ——— Field model (SIMEC)
   —o— Zonal model (SAMIRA)

Fig. 5. Comparison between a field model "SIMEC" and the zonal mode "SAMIRA"

The principal temperature difference is observed in the upper zone and we assume that this probleme from the absence of jet model for the air inlet. This validation is in progress and we will be certainly obliged to modellise the jet and entrainment.

For the following global comparison, this problem is less important because the experiment and the computation are tridimensional and the air-flow is lower (1 vol/h against 7 vol/h). Furthermore, we think that the interaction of the plume and the inlet air flow is less important in real room configurations. Hence this weak-point of the SAMIRA model is not so negative.

A global validation

This second phase mostly consists of a comparison with a shorter but real-scale experiment.

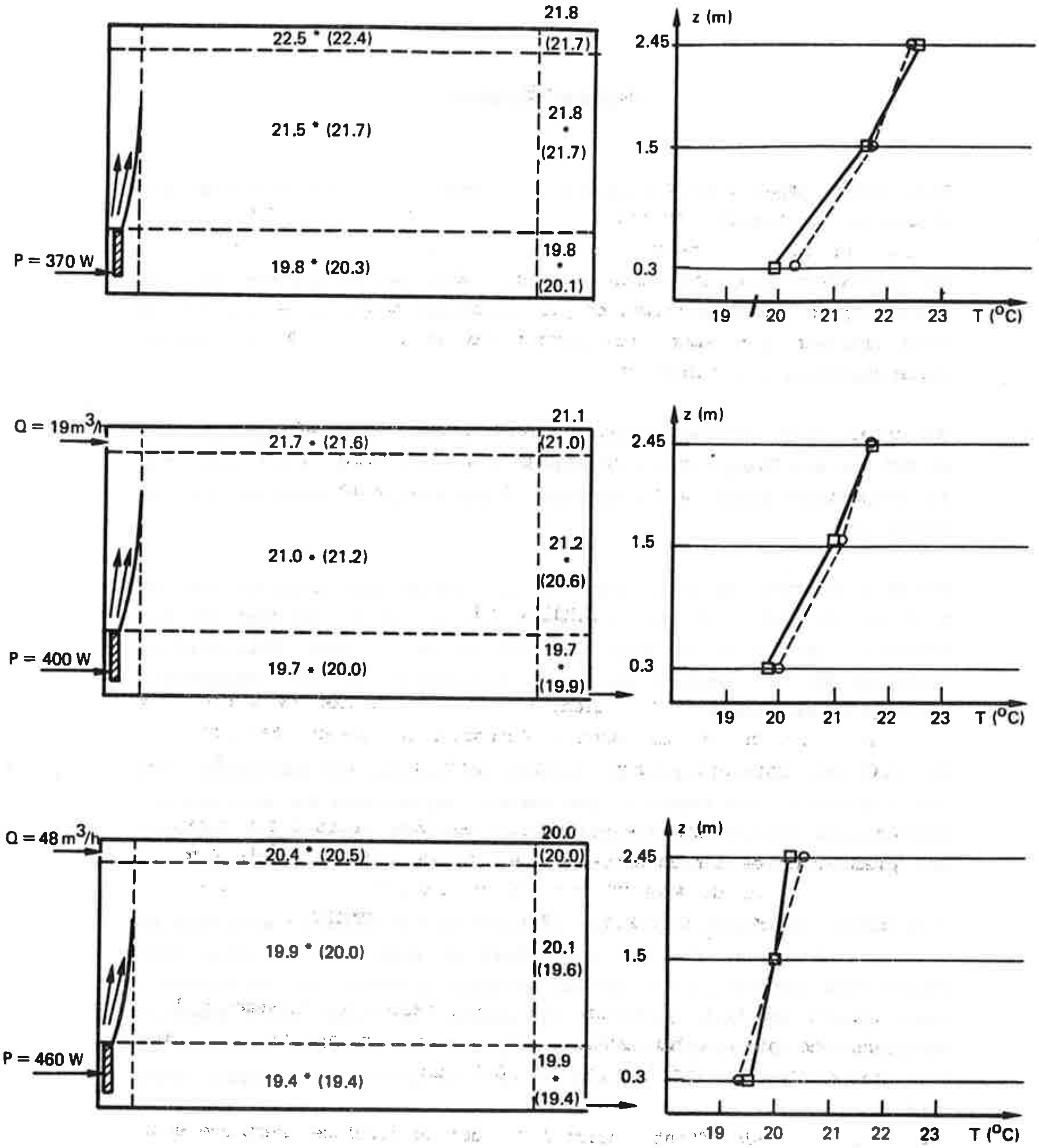
The cell (ETNA) with which the tests have been carried out has the same dimensions as above and each of its six faces opens on a seal volume which has been air conditioned at 10°C (these are tests under steady-state operating conditions).

The convector is located on the wall through which air is introduced and we had the air change rate vary from 0, 0.5 and 1.0 volume per hour. The air temperature probes are positioned in the middle of areas defined for SAMIRA model.

The grid selected for this comparison is a pseudo-tridimensional one, as much as the width of the plume area is equivalent to that of the convector and not to the room like for the other areas. This grid is justified by the adequate horizontal homogeneity of the temperatures recorded by experiment.

You will find below (Figure 6), comparisons between the measurement and the computation with regard to the average temperatures for area and for temperatures measure on a central axis. The area temperatures measured are average values in several points of a same plane within this area.

This global comparison with a set of full-scale experiments show that in this concrete case, the air temperature of each zone is quite well represented. Concerning the central vertical gradient, the measurements (very local) are not perfectly represented by those mixed computed temperatures, but the differences are quite small, and the evolution of this gradient against the ventilation rate is correct. This result seems more important for us.



a) Mixed zone temperature
- Experiment
- (SAMIRA modèle)

b) Temperature Profil on the central axis
□—□ Experiment
○---○ (SAMIRA modèle)

Fig. 6. Comparison simplified model (SAMIRA) and a full-scale experiment (ETNA Cell)

CONCLUSIONS

The first computation results and their validation approach make it obvious that the air motions on the temperature gradients in room environment can be represented with the aid of a simplified model. Such models are advantageous in that they are easy to integrate into a global software programme for thermal computations in a building (CLIM 2000) and also enable the air temperature distribution in a room to be assessed as a function of the heating mode.

The model validation must be considered more thoroughly and we still have to model the behaviour of a room equipped with a heating floor or an air conditioner according to such an approach, and to validate it.

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