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Numerical study of the thermal behavior of bi-zone buildings

Étude numérique du comportement thermique des bâtiments bi-zones

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ABSTRACT

This work aims at studying the thermal behavior of bi-zone buildings by the nodal method (using the FORTRAN simulation: DIGITAL Visual FORTRAN 95) based on an electrical analogy. The building temperature is assumed to be variable with time or imposed at a setpoint temperature. The results show the influence of various parameters (weather temperature, setpoint temperature of the indoor air in each zone) and the effect of common wall, which is composed by the alveolar structure in two different senses (insulating and conducting ones), on the thermal behavior of a building.

RÉSUMÉ

L'objectif de ce travail est d'étudier le comportement thermique d'un bâtiment bi-zones par la méthode nodale (en utilisant la simulation FORTRAN : DIGITAL Visual FORTRAN 95) sur la base de l'analogie électrique. La température du bâtiment est supposée être variable dans le temps ou imposée à la température de consigne. Les résultats montrent l'influence de différents paramètres (température météorologiques, la température de consigne de l'air intérieur dans chaque zone) et l'effet de mur mitoyen, qui est composé par la structure alvéolaire en deux sens différents (sens isolant et passant), sur le comportement thermique du bâtiment.

1. Introduction

The control of the energetic consumption of buildings is a major priority. This control requires knowledge on the energy performance of the envelope of buildings and use of digital models. Many previous works concerning the study of the thermal behavior of mono-zone or multi-zone buildings have been carried out in recent decades.

B. Sommereux [1] studied the different connection methods, mainly the recovery method of coupling. This method is very useful in some applications. It primarily concerns the modeling of a multi-zone building. The purpose of this work is to develop a method of analysis for predicting the effect of coupling zones on the behavior of a building. This method

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Nomenclature

T_i	Real-time temperature	K
$(mc)_i$	Heat capacity	$J \cdot K^{-1}$
$C_{i,j}$	Conductive and/or convective coefficient between nodes i and j	$W \cdot K^{-1}$
$K_{i,j}$	Radiative coupling coefficient between nodes i and j	$W \cdot K^{-4}$
P_i	Solar flux absorbed at the time t by node i.	
Gr	Grashof number	$Gr = \frac{\beta g \Delta T L^3}{T_m \gamma^2}$
Nu	Nusselt number	$Nu = h\frac{L}{\lambda_m}$
h	Heat transfer coefficient	$W \cdot m^{-2} \cdot K^{-1}$
H	Height of the cavity's vertical walls	m
L	Length from the floor to the roof	m
T_m	Average temperature	$T_m = (T_c + T_f)/2$ (°C)
T_f	Cold wall temperature	°C
T_c	Hot wall temperature	°C
ΔT	Temperature difference (°C)	$\Delta T = T_c - T_f$

Greek symbols

α	Angle of inclination	
γ	Cinematic viscosity of air	$m^2 \cdot s^{-1}$
β	Dilatation coefficient	K^{-1}
g	Acceleration of gravity	$m \cdot s^{-2}$
λ	Thermal conductivity of air	$W \cdot m^{-1} \cdot K^{-1}$
μ	Dynamic viscosity of air	$kg \cdot m^{-1} \cdot s^{-1}$

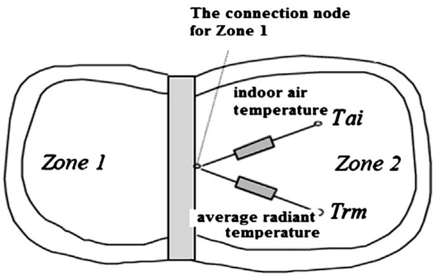

Fig. 1. Thermal coupling between zones [1].

identified three types of dynamic coupling (dynamic coupling to high and low inertia between two zones, coupling between a zone of high inertia and a zone of low inertia) by studying the time response of the temperature of each zone with different types of coupling.

Boyer [2] studied the thermal ventilation design of multi-zone buildings. He developed various coupling methods (coupling contact, coupling recovery, and coupling contact on fold). He established the thermal model of a building by offering a method of coupling recovery that is a numerical method of resolution to solve the involved equations. He considered two zones separated by a wall (Fig. 1). In the model system of equation describing zone 2, the node discretization surface in contact with the air in the second zone is going to play a special role. He qualified this type of node “a connection node”.

Mora [3] predicted the thermal flow and the airflow in buildings by associating the different models of simulation; this study consists in proposing a simulation platform to initially treat most areas of the building and its envelope and combine models of different levels of fineness for the representation of transport phenomena in buildings. In this approach, most areas are modeled by the nodal method. So the results show that the zonal approach is adapted to estimate the dynamic evolution of the temperature field for the prediction of thermal comfort.

2. The thermoelectricity analogy method

Boyer et al. [4] studied the thermal simulation of buildings and the numerical simulation of nodal models. This paper shows the adaptation of a method of thermal analysis, nodal analysis, related to the case of the thermal behavior of a building. They considered the case of conduction in a wall, coupling with superficial exchanges, and finally the formation of thermal models of the state of the building. This work is based on the electrical analogy. The author considered the analogy between Fourier's and Ohm's laws:

$$\vec{\phi}_t = -\lambda \overrightarrow{\text{grad}} T$$
$$\vec{j} = -\sigma \overrightarrow{\text{grad}} V$$

These two laws induce correspondence between the following groups: (ϕ, j), (λ, σ) and (T, V).

Mathews et al. [5] studied a first-order thermal model for building design. These works were the only ones that dealt with the modeling of buildings in ground contact for use in simplified RC-models.

They have validated their model in 53 existing buildings, covering a wide range of thermal characteristics. However, the model is a set of equations incorporating building parameters, which need to be calculated from the existing buildings properties.

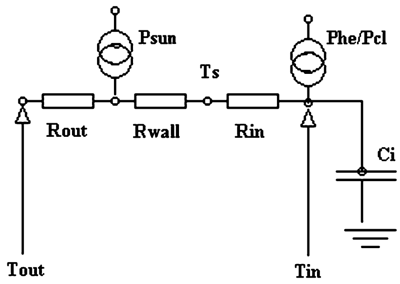

Fig. 2. Graphical representation of a lumped capacitance model [6].

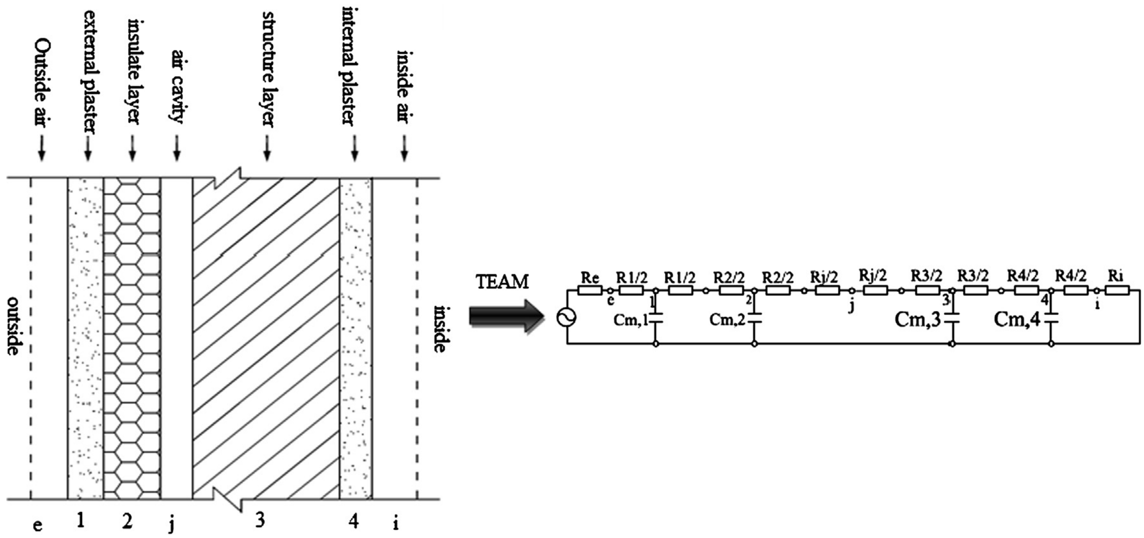

Fig. 3. Simulation of thermal conduction in a multilayer building through an electrical analogy. Left: thermal conduction mode. Right: electric conduction model.

Nielsen [6] developed a simple tool to evaluate energy demand and indoor environment in the early stages of building design. This work presents a simplified method based on RC-network model of thermal zone, it is able to assess the thermal environment inside and loads for heating and cooling a building. The model is based on a system of equations with two nodes: the first node representing the air temperature, and the second one the inside surface temperature. An electric analogy of the thermal model is shown in Fig. 2: where T_{out}, T_{in}, T_s, C_i, R_{out}, R_{wall}, R_{in}, P_{sun}, P_{he}, P_{cl} are respectively the outdoor air temperature, the indoor air temperature, the temperature on the internal surfaces, the internal heat capacity, the outdoor heat resistance, the thermal resistance of the wall, the indoor heat resistance, the solar flux, the heating load cooling loads.

Wang et al. [7] studied a simplified building model for transient thermal performance estimation using Genetic Algorithm (FORTRAN) based on the 3R2C model, which takes into account the orientation of the sun. The ceiling, the walls and the floor were modeled by their resistance and capacitance. The solar flux density was modeled by a current generator. To validate this model, the authors applied it on a real commercial office building under different weather conditions. Their results show that the model can provide a thermal performance prediction of good accuracy and robustness for practical applications.

Fraise et al. [8] developed a simplified and accurate building model based on an electrical analogy. They presented the various stages to propose the global analogical model of the building. Initially, they studied how to transform a multilayer wall into three resistance and four capacitance models (3R4C). They compared this model with other electrical ones thanks to time and frequency analysis.

J.H. Kämpf et al. [9] studied a simplified thermal model to support the analysis of urban resource flows. This article describes a simplified model to simulate heat flow in buildings considering a standard resistance–capacitance model with two nodes to study the energy exchange by radiation and convection, and the establishment of multi-layer capacity walls. These results show that the two-node model for a room gives good results for a variety of typical wall constructions.

C. Peng et al. [10] studied the thermoelectricity analogy method for computing the periodic heat transfer in external building envelopes. This paper, based upon the theory of thermoelectricity analogy, develops a new harmonic method, the thermoelectricity analogy method (TEAM) (Fig. 3(b)). This method makes it very easy and efficient to analyze periodical

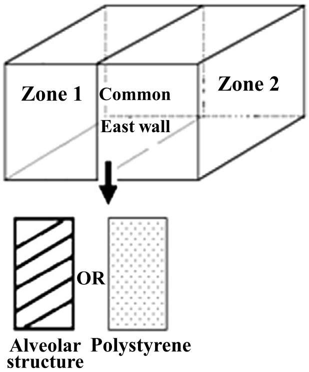

Fig. 4. Description of common eastern wall of the bi-zone model.

Table 1
Thermophysical properties of the common wall.

Common wall's eastern side	Thickness (m)	Conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
Polystyrene	0.057 [11]	0.041
Alveolar structure (cardboard) (Fig. 4, left)	0.063	The correlation including convection and radiation (see [14])

thermal conductions and estimate the performance of building envelopes and buildings' thermal comfort. Therefore, TEAM is suitable for the analysis of periodic thermal conduction through multilayer constructions (Fig. 3, left).

3. The thermal performance wall insulation in existing buildings

Daouas et al. [11] have studied the analytical periodic solution to the problem of thermal performance and optimum insulation thickness of building walls in Tunisia. Their results show that the most profitable case is the stone/brick sandwich wall associated with expanded polystyrene for insulation, with an optimum thickness of 5.7 cm. In this case, energy savings up to 58% are achieved with a payback period of 3.11 years. The thermal performance of the walls under optimal conditions was also investigated.

Marif et al. [12] studied the thermal performance of internal and external wall insulation in existing buildings in the South of Algeria. This study was validated by the work of Daouas et al. [11], who also found that the optimum thickness of polystyrene is 5 cm. The findings showed that the presence of insulation significantly reduces fluctuations of internal surface temperatures. The maximum internal surface temperature decreased from 32 °C to 26.6 °C for external insulation and 26.3 °C for internal insulation, thus providing a higher level of indoor comfort.

Using the experimental laws of Vullierme and Boukadida [14], the global density of heat transfer flux including convection and radiation (Fa) in the crossing and insulating senses through the realized alveolar structure, these measures allowed them to bring out laws for different distributions: low or high emissivity coatings of the inside faces of alveolar. These laws are defined by the following correlation:

$F_a = \sigma(\Delta T)^{1.25}$, where σ is a constant which depends of emissivity, transfer direction and the angle of inclination. Based on the work of [14], Lajimi and Boukadida [13] studied numerically the thermal behavior of the premises in which vertical walls are equipped with alveolar structure and/or simple glazing in east, south, and west faces. The temperature of the premises is assumed to be variable with time or imposed at a setpoint temperature. The results principally show that the simple glazing number has a sensitive effect through the alveolar structure on convection heat transfer and on inside air temperature. They also show that the diode effect is more sensitive during winter. The effect of alveolar structure and simple glazing on the power heating in the case with a setpoint temperature was also brought out.

4. Position of the problem

Based on this work, we were interested in studying the thermal behavior of bi-zone buildings in which walls of two zones (zone 1, zone 2) are identical ($S = 30$ m^2 and V = 300 m^3 with height, length and width of 3 m, 10 m, and 10 m respectively), and separated by a common wall on the eastern side. This wall may be the equivalent of a polystyrene layer or a honeycomb structure having a variable thermal insulation depending on the direction of the transfer (Fig. 4). To solve this problem, we based ourselves on the thermoelectricity analogy method (TEAM) (Fig. 5).

The thermophysical properties of the common wall are displayed in Table 1.

To calculate the global heat transfer coefficient inside alveoli, we have opted for the correlation including convection and radiation, determined experimentally by N. Boukadida and J.-J. Vullierme [14]:

$$h_t = \sigma \Delta T^{0.25}$$

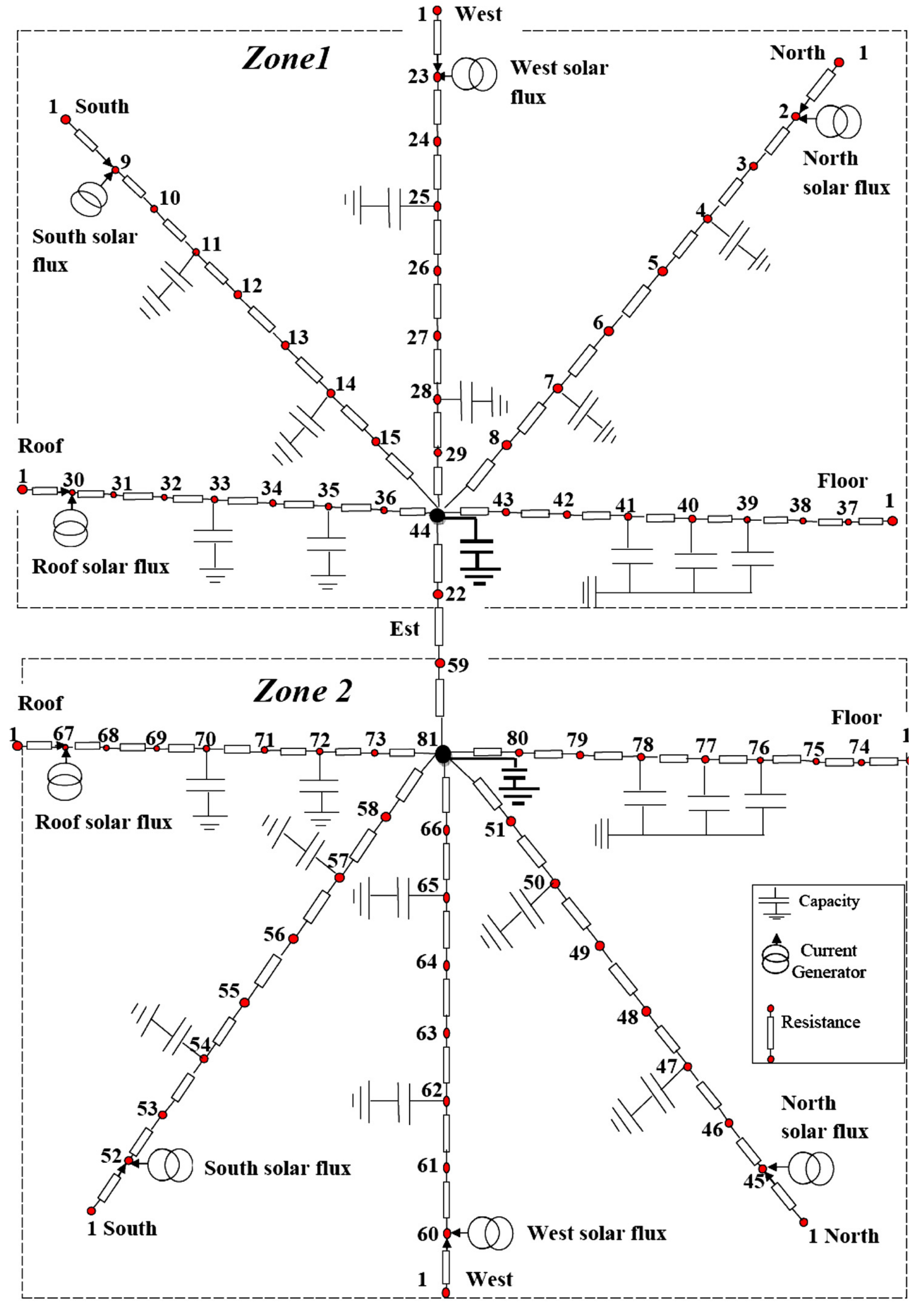

Fig. 5. (Color online.) Thermoelectricity analogy model.

where σ is a coefficient that depends on the heat's direction, the angle of inclination and faces emissivity of the lamellas (low or high emissivity). It is obtained for an angle of 60° and takes the value 2.950 in the spending direction and 1.388 in the insulating direction (Fig. 6).

5. Description of buildings walls

Fig. 5 depicts the kinds of different walls in the bi-zone building. Table 2 contains the description of each layer for the different walls.

An example of the description of the south and west side of the wall of model bi-zones is given in Fig. 7.

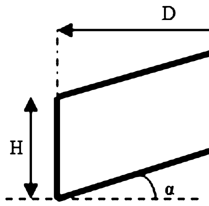

Fig. 6. Geometry of a lamella of the alveolar structure.

Table 2
Description of each wall.

Layers thickness	
Outside layers	• Insulating coat: ∘ 2 cm (north, ceiling) ∘ 2 cm (south and west sides) ∘ 1 cm (floor)
Intermediate layers	• North and ceiling ∘ Brick (3 cm) ∘ Polystyrene (5 cm) • South and west sides ∘ Wood (2 cm) ∘ Polystyrene (5 cm) • Floor ∘ Concrete (6 cm) ∘ Polystyrene (5 cm)
Inside layers	• Wood: ∘ 2 cm (north, ceiling) ∘ 2 cm (south, east and west sides) • Concrete: ∘ 6 cm (floor)

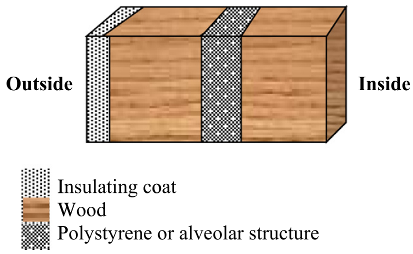

Fig. 7. (Color online.) Different wall elements.

6. Mathematical model

This mathematical model is based on the balance equation of element 'i', which can be written as:

$$(mc)_i \frac{\mathrm{d}T_i}{\mathrm{d}t} = \sum_{j=1,n} C_{i,j}(T_j - T_i) + \sum_{j=1,n} K_{i,j}\left(T_j^4 - T_i^4\right) + P_i \tag{1}$$

6.1. The working assumptions

- The heat transfer is unidirectional.
- The air is considered a perfect transparent gas.
- The thermo-physical properties of materials are constant and identical for two zones.
- The air temperature inside the two zones is uniform.
- The participation of the occupant's energy is negligible.

6.2. Discretization of the model and solving method

The numerical method used is nodal method; which is also known as multi-zone [4], consists in splitting the system into multiple elements. This model, divided into 81 nodes, includes 6 faces (south, east, west, north, roof and floor). The

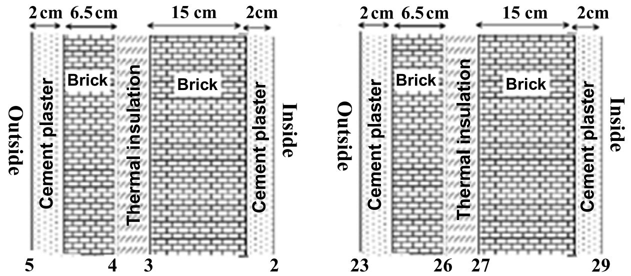

Fig. 8. Description of the west side of the wall in both cases. Left: case of configuration [11]. Right: case of the present study.

common wall [1] is between the two zones, which is to the east presented by one node (node 22 for zone 1 and 59 for zone 2) (Fig. 4).

The system of equation (1) is linearized by a Taylor development [13].

Developing in Taylor series limited to the first order, we get:

$$F_i(T_1, T_2, \dots, T_n) + \Delta T_1 \left(\frac{\partial Fi}{\partial T1}\right)_{T_1, T_2, \dots, T_n} + \dots + \Delta T_n \left(\frac{\partial Fi}{\partial Tn}\right)_{T_1, T_2, \dots, T_n} = 0$$

So, a linear system in ΔT_i is obtained; the implicit method is used to calculate the different temperatures. An iterative calculation is then performed at each time step (1 h) until the solution near the convergence criterion (0.1 °C) is reached. At each iteration, convective and radiative heat transfer coefficients, which depend on temperature, are recalculated. The solicitations correspond to periodic thermal conditions over 24 h; the calculation is repeated a sufficient number of times to obtain a periodic steady state. For two successive iterations, the convergence criterion over 24 h is 0.05 °C.

The implicit discretization equation (1) for each node leads to a system of linear equation that can be represented by the matrix equation:

$$\mathbf{M}\mathbf{T}^{*} = \mathbf{T}(t)\mathbf{A} + \mathbf{G}$$

with $\mathbf{T^*}$ the time derivative of the temperature vector, $\mathbf{T}(t)$ the temperature vector, $\mathbf{M}$ the vector containing the heat capacities, $\mathbf{A}_{i,j}$ the matrix including coefficients $C_{i,j}$ and $K_{i,j}$, $\mathbf{G}$ the oscillation vector.

6.3. Boundary conditions

6.3.1. Exterior conditions

For both zones, the considered values of convective heat transfer coefficients are respectively: 11 $W{\cdot}m^{-1}{\cdot}K^{-1}$ for a vertical wall and 14 $W{\cdot}m^{-1}{\cdot}K^{-1}$ for a horizontal one.

The outside metrological air temperature values are provided by local weather stations. The solar density flux direct and the diffuse radiation are calculated hourly, on the 15th day, which is considered as a typical day of the month [13].

6.3.2. Interior conditions

For both zones, the convective heat transfer coefficient between the indoor faces and the interior air are deduced using the following correlation: $Nu = A \cdot (Gr{\cdot}Pr)^B$, (A, B) takes as values (0.11, 0.33) for a vertical face, (0.27, 0.25) for the roof, and (0.14, 0.33) for the floor [16].

Concerning the temperature of the indoor air, we distinguished two cases:

- in the first case, it is assumed that the temperature of the indoor air is variable with time; we follow the evolution of the temperature for each zone;
- in the second case, two applications are made
  - application of heating type: we imposed a temperature of the indoor air at 19 °C in zone 2 and followed its influence on zone 1; we then calculated the heating power necessary to maintain this value in zone 2;
  - application of air-conditioning type: we considered the temperature of the indoor air to be 25 °C in zone 2 and followed its influence on zone 1 and calculated the supplied cooling power.

7. Validation of the model

In order to validate our results, we performed a comparison for a representative case characterized by a wall that is shown in Fig. 8. Its thermophysical properties are mentioned in Table 3. This configuration was simulated analytically by N. Daouas et al. [11] for a Tunisian city. In their simulation, the solar density heat flux on vertical surfaces is computed with the ASHRAE clear-sky model [15,16] for July. The inside air temperature is imposed at 25 °C, the surface's absorption coefficient of the outside wall is 0.4 and the heat exchange coefficients, including radiation and convection, are assumed to

Table 3
Thermo-physical properties of the wall (Fig. 11).

Walls	Thermal conductivity ($W{\cdot}m^{-1}{\cdot}K$)	Thermal diffusivity ($m^2{\cdot}s^{-1}$)
Cement plaster	0.72	$4.6{\cdot}10^{-7}$
Brick	0.69	$5.13{\cdot}10^{-6}$
Expanded polystyrene	0.037	$1.01{\cdot}10^{-6}$

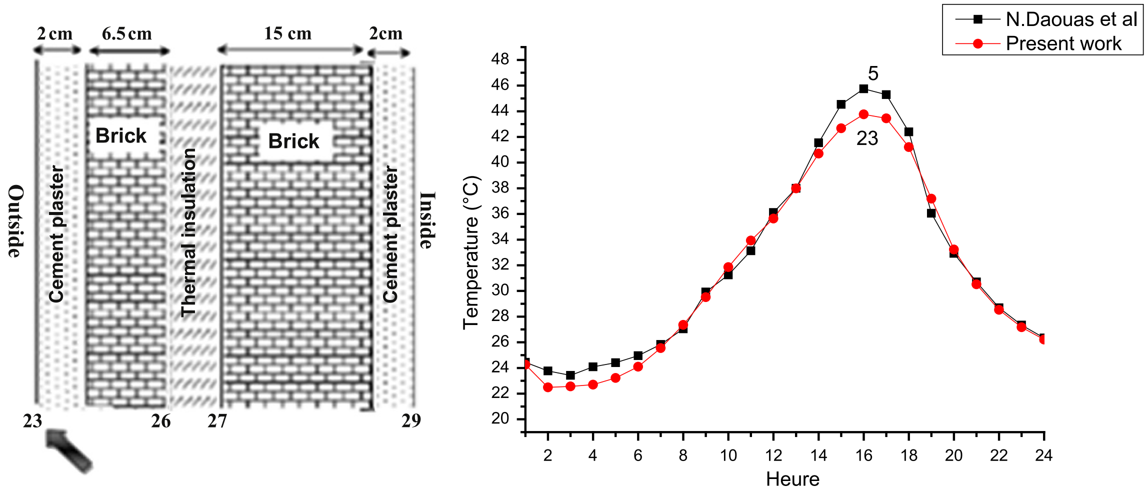

Fig. 9. (Color online.) Time evolution of outside surface for nodes (5, 23).

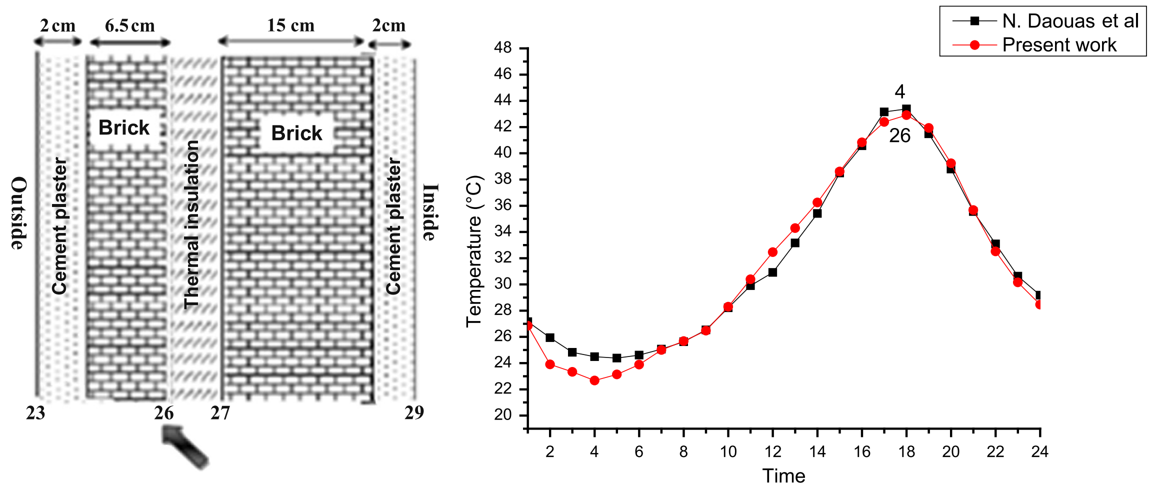

Fig. 10. (Color online.) Time evolution of the polystyrene surfaces for nodes (4, 26).

be constant (22 $W{\cdot}m^{-2}{\cdot}K^{-1}$ for the outside surface and 9 $W{\cdot}m^{-2}{\cdot}K^{-1}$ for the inside one). For the two studies, we compared the temperature profile of:

- the outside surface,
- the two faces of the polystyrene layer,
- the wall's inside surface.

We found, as was shown in Figs. 9–12, that the average relative gaps are respectively 2.44%, 2.40%, 2.8% and 1.25%. Accordingly, one concludes that they are in good agreement. Small differences are mainly due to the models used for the solar density heat flux.

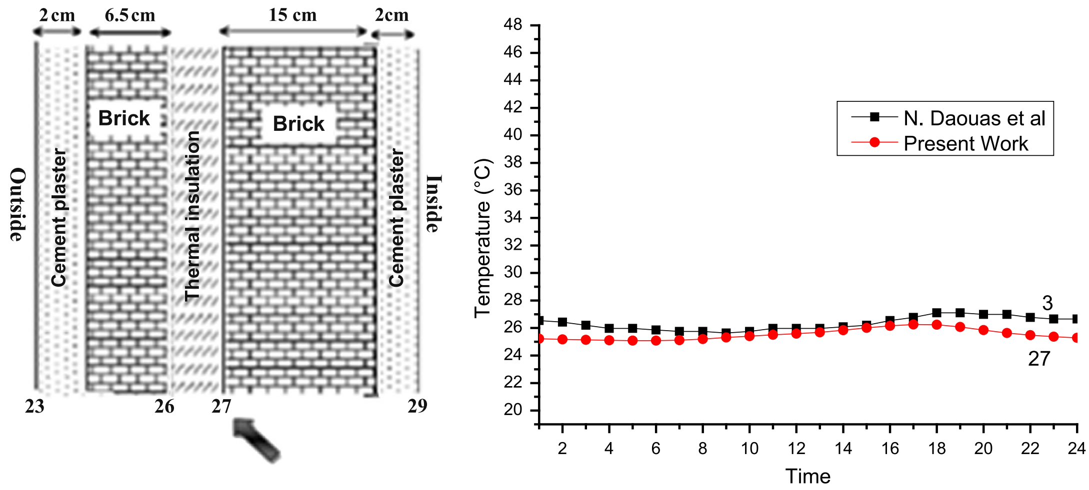

Fig. 11. (Color online.) Time evolution of surfaces of the polystyrene for nodes (3, 27).

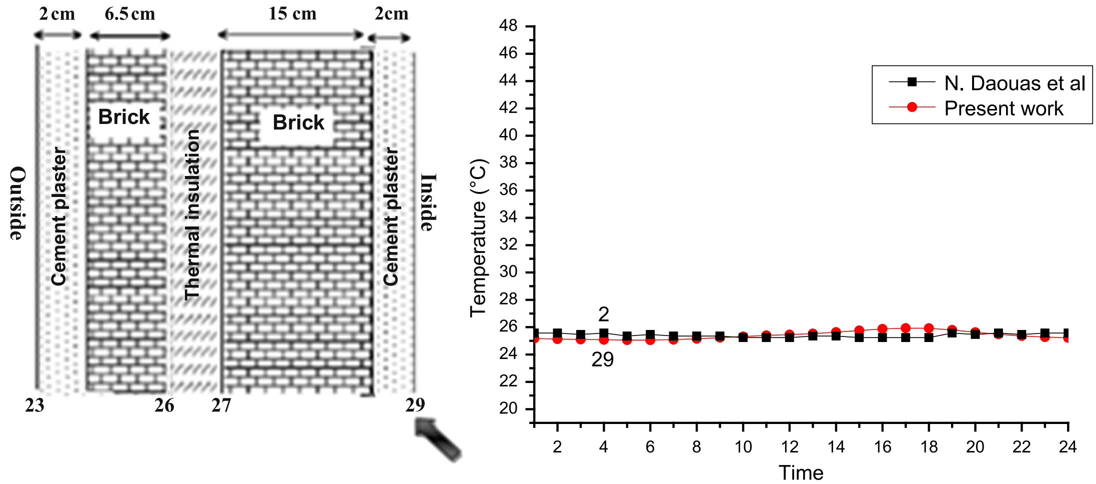

Fig. 12. (Color online.) Time evolution of the inside surface for nodes (2, 29).

8. Results and discussion

8.1. Case 1: The temperature of the indoor air is variable in accordance with time

Firstly we studied a representative case in which we took the same conditions of outside air temperature and solar flux for both zones. As it is shown in Fig. 13 (left and right), the temperature profiles of zones 1 and 2 are identical.

8.2. Case 2: The inside air is at the setpoint temperature

During one day, the temperature of the inside air in zone 2 is maintained at 19 °C (heating process), 25 °C (cooling process), and that of zone 1 is variable.

8.2.1. Case of heating

- *Insulating direction*

In case the common wall is composed of an alveolar structure with an insulating direction configuration, i.e. the wall of the alveolar from the inner side is in the high position, the natural convection is braked by the geometry of the alveolus, the heat flow transferred to the zone 1 is lower, the structure behaves as a strong resistance and the difference temperature between zones 1 and 2 is higher compared with the polystyrene wall (Fig. 14, left), and also the inside air temperature in zone 1 (Fig. 14, right) is lower than in the case when it consists of a polystyrene layer with a thickness of 5 cm, so that the lowest

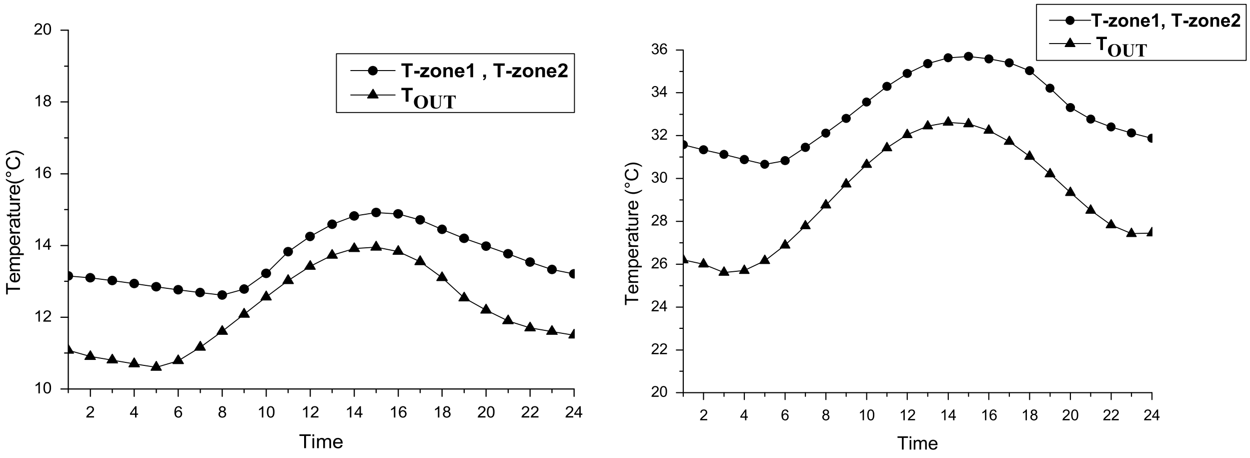

Fig. 13. (Color online.) Left: time evolution of inside and outside air temperature in January. Right: time evolution of the inside and outside air temperatures in July.

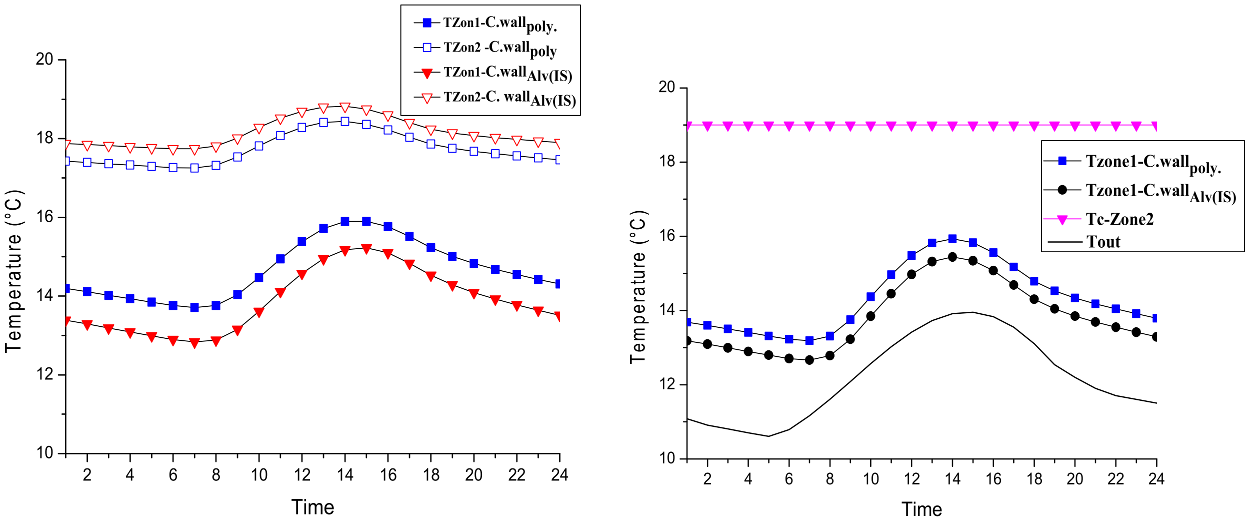

Fig. 14. (Color online.) Left: evolution versus time of the temperature of the common wall (C. wall) in the two zones in January. Right: evolution versus time of the inside air temperature of zone 1 in January.

Table 4
Average heat power required with different common wall (C. wall).

		Average power required by inside air temperature to maintain at 19 °C	
		Diurnal period	Nocturnal period
Wall composed by an alveolar structure	Insulating sense (IS)	433 W	1381 W
Wall composed of a layer of polystyrene (poly)		571 W	1537 W

value of the heat power required to maintain the inside air of zone 2 to 19 °C is obtained when an alveolar structure is used as the common wall (Fig. 15). This flux is minimum during the sunny period and maximum during the nocturnal period.

Table 4 summarizes main results concerning the insulation effect:

- *Conducting direction*

To increase the air temperature inside zone 1 (Fig. 16, right), the alveolar structure should be put in the conducting sense. The wall of the alveolar structure from the inner side is in the lower position, the natural convection is facilitated, the heat flux transferred to the zone 1 is more important, so the difference temperature of the faces between zone 1 and zone 2 (Fig. 16, left) is less important compared with the layer of polystyrene and therefore the power required to maintain the air temperature in zone 2 at 19 °C becomes higher (Fig. 17).

Table 5 summarizes the obtained results.

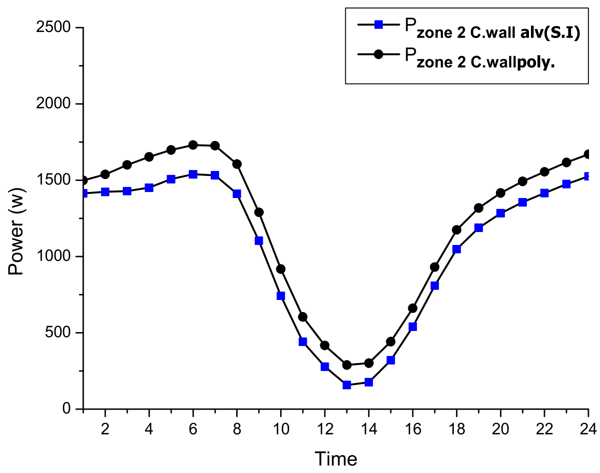

Fig. 15. (Color online.) Evolution versus time of heat power required in January.

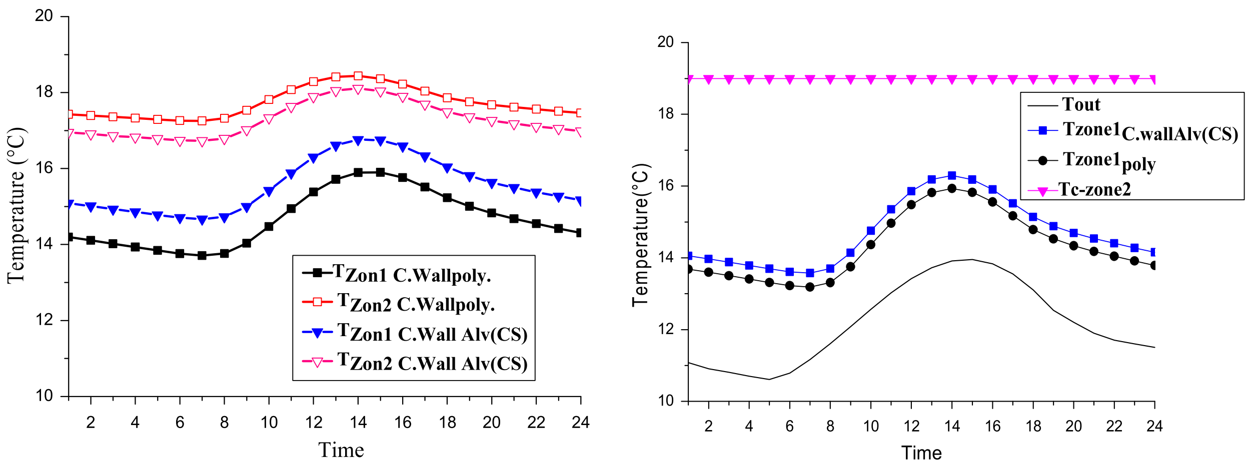

Fig. 16. (Color online.) Left: evolution versus time of the temperature of common wall (C. wall) in the two zones in January. Right: evolution versus time of the inside air temperature of zone 1 in January.

Table 5
Average power supplied in the case where the common wall is composed alveolar structure (conducting sense).

		Average power required to maintain at 19 °C the inside air temperature	
		Diurnal period	Nocturnal period
Wall composed by an alveolar structure	Conducting sense (CS)	748 W	1628 W
Wall composed of a layer of polystyrene (poly)		571 W	1537 W

8.2.2. Case of cooling

In the case of air conditioning application, we chose the month of July as a representative month in the summer season and we considered the conducting direction of the alveolar structure. The setpoint temperature is 25 °C, which corresponds to an acceptable thermal comfort.

To decrease the air temperature inside zone 1, the alveolar structure should be put in the conducting sense, the cold air flow transferred to zone 1 is more important. It is observed that the faces of the difference in temperature of the common wall in the polystyrene layer between zones 1 and 2 is higher relative to the alveolar structure in the conducting direction, where it is about 5 °C (Fig. 18, left). As shown in Fig. 18 (right), the average air temperature inside zone 1 in the case where the wall consists of polystyrene is approximately 32.5 °C; it is higher than in the case where the wall is in the structure in which the cells are placed in the conducting direction, so that this power required to maintain the setpoint temperature in zone 2 is higher (Fig. 19) relative to the polystyrene layer.

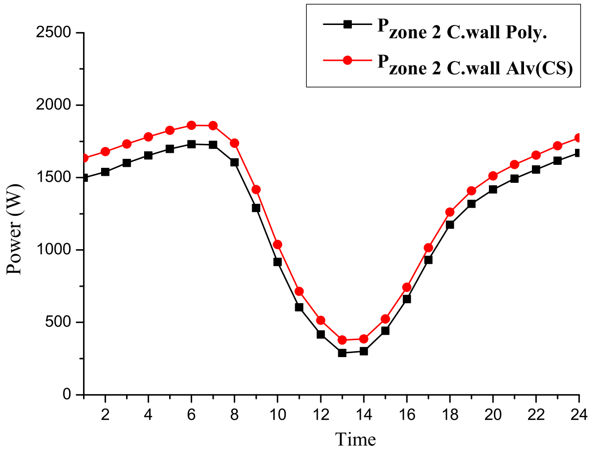

Fig. 17. (Color online.) Time evolution of the heat power required in January.

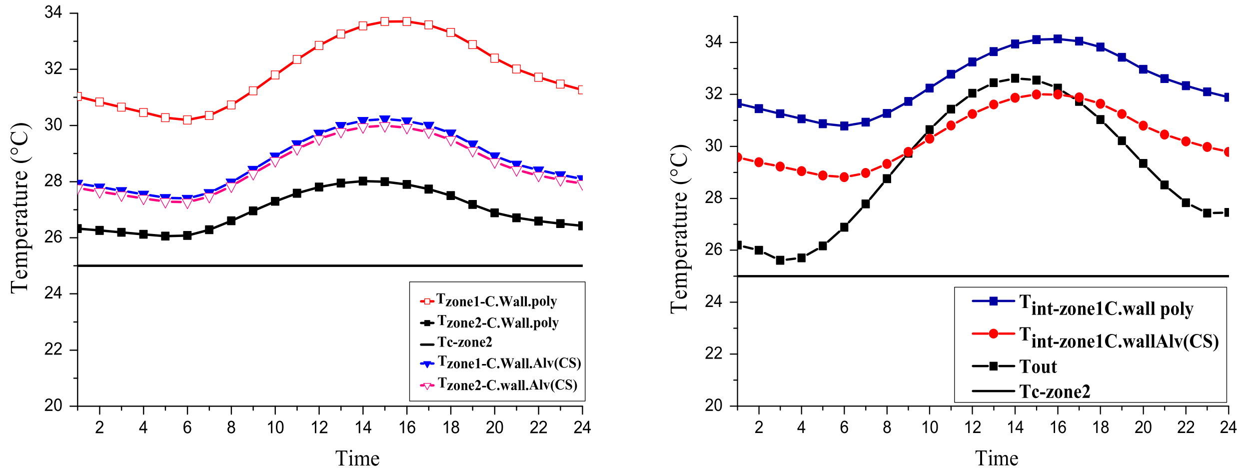

Fig. 18. (Color online.) Left: evolution versus time of the temperature of the common wall (C. wall) in the two zones in July. Right: evolution versus time of the inside air temperature of zone 1 in July.

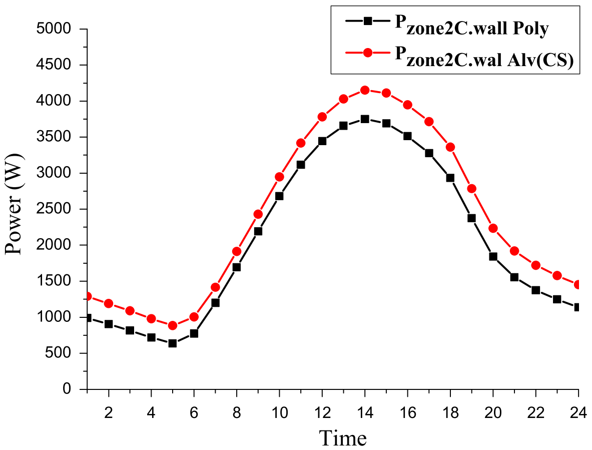

Fig. 19. (Color online.) Time evolution of the heat power required.

9. Conclusion

We studied the effect of the alveolar structure as being a common wall of two zones on the thermal behavior of bi-zones buildings. The results are as follows.

In case the common wall is composed of an alveolar structure, two simulations were made:

- in the heating case:
  - when the structure is placed in the insulating sense, it is equivalent to a strong insulating layer; the inside air temperature in zone 1 is lower compared with a polystyrene layer of 5.7 cm and the difference temperature faces of common wall between zone 1 and zone 2 is higher. The alveolar structure is equivalent to a layer of polystyrene having a thickness of 8 cm, so the power required for zone 2 drops;
  - when the structure is located in the forward direction, it is equivalent to a low insulation layer, hence the inside air temperature in zone 1 is higher and the difference temperature faces of common wall between zone 1 and zone 2 is less important. The alveolar structure is equivalent to a layer of polystyrene having a thickness of 6.3 cm; therefore the power required for zone 2 grows;
- in the cooling case, we compared with the previous case; we considered the conducting direction of the alveolar structure, we observed the same behavior as in the case of heating. The inside air temperature in zone 1 is lower compared with the case of a polystyrene layer and the difference temperature faces of common wall between zone 1 and zone 2 is small, hence the power required to maintain the indoor air in zone 2 at the set value is higher.

To modulate energy consumption and to achieve thermal comfort in one zone, it is advantageous and interesting to place this structure as a common wall between rooms.

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