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Definition of Parameters Useful to Describe Dynamic Thermal Behavior of Hollow Bricks

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Abstract

Dynamic thermal behavior of hollow bricks is attracting much interest nowadays as there is much concern on energy performance of building envelope. In fact, high thermal inertia of outer walls provides mitigation of the daily heat wave, which reduces the cooling peak load and the related energy demand. Different approaches have been used to study dynamic thermal behavior within the papers available on unsteady heat transfer through hollow bricks. Actually, the usually employed methods for calculation of unsteady heat transfer through walls are based on the hypothesis that such walls are composed by homogeneous layers, so they are not suitable for many common building components. In this framework, a study on the dynamic thermal performance of hollow bricks is brought forth in the present paper. A critical review of available data from the literature is provided. Literature data are used to propose a parameter useful to predict dynamic thermal behavior. A finite-volume method is used to solve two-dimensional unsteady thermal fields in some standard bricks with different imposed temperature solicitations, with a numerical code developed by the authors. New results are used to check the effectiveness of the proposed parameters.

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Keywords: building envelope; thermal inertia; hollow brick; block response time;equivalent thermal diffusivity; time-lag

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1. Introduction

The fundamental "Nearly Zero-Energy Building (NZEB)" concept has been introduced by the latest updates in the European directive on energy performance of buildings [1]. Considering that in UE about 40% of total final energy consumption is attributed to civil sector, the analysis of the thermal performance of building, as well as the surroundings in which it is situated, has become a determining factor [2],[3],[4] and [5]. In this frame, a special focus needs to be addressed to building envelopes, especially on the role played by the thermal inertia on the energy requirements for heating and cooling applications.

Available methods to evaluate the attitude of building envelope to reduce the effect of daily heat wave are applicable only to homogeneous layers, as reported in [6] and [7]. Thus, they are not suitable for hollow bricks.

Dynamic thermal performance of walls may be shortly described through time-lag, which is the time that passes before the peak of the outer solicitation passes inside, and decrement factor, that is the reduction in heat flux in comparison to steady state heat transfer. In a previous paper by the authors [8], it has been shown that there is a straight correlation between these two, so the present study will be focused solely on time-lag.

As far as homogeneous multi-layered walls are considered, studies by Assan and Sancaktar [9], Assan [10], and by Lakatos [11] have shown that wall thickness is the main relevant parameter for time-lag of heat wave flux, even though wall composition is much important. These results are congruent with the common assumption that high masses per unit front area of walls lead to high time-lags, as it is linearly proportional to wall thickness.

Time lag of 24 hours long sinusoidal temperature solicitation on hollow bricks is provided in some papers. Sala et al. [12] experimentally studied multilayer walls containing hollow bricks, 40 mm thick, showing a 1.5 hours time lag. Arendt et al. [13] studied by numerical simulations the influence of cavities size on time-lag and decrement factor in a 300 mm thick clay brick. Their results show that time lag was in between 14 hours and 16.7 hours, with a maximum at an intermediate cavity concentration (that is the ratio of cavities volume to full block volume). Zhang et al. [14] experimentally studied heat transfer through a 190 mm thick layer of lightweight aggregate concrete with vertical cavities of two different sizes. They found a 4.4 hours time-lag.

Nomenclature

BRT	Block response time, ratio of the square of block thickness to equivalent thermal diffusivity, [s] or [h]
c_p	specific heat, [J/kg·K]
J	radiosity of the surface, [W/m^2]
k	thermal conductivity, [W/m·K]
L	dimension of integration domain perpendicular to main direction of heat transfer, [m] or [mm] as relevant
M	front mass, [kg/m^2]
q	specific heat transfer rate, [W/m^2]
s	block thickness, i.e. dimension of integration domain along main direction of heat transfer, [m] or [mm]
R	specific thermal resistance, [m^2·K/W]
T	temperature, [K] or [°C]
Greek symbols	
α	thermal diffusivity, [m^2/s] or [mm^2/s]
$\Delta\tau$	time-lag, [h]
ε	emissivity, non-dimensional
ρ	density, [kg/m^3]
τ	time, [s] or [h] as relevant
Subscripts	
1	hot side of block in steady state
2	cold side of block in steady state
a	referred to air
av	volume averaged value
c	referred to cavity

eq	equivalent
f	referred to block frame
j	other surfaces contributing to radiation within the cavity
R	radiating surfaces
st	steady state solution value

1.1. Literature data analysis

These analyses are done with front mass in the range from 20 kg/m^2 to 454 kg/m^2, using data from references [12], [13], and [14]. Plotting time-lag values versus front mass clearly shows that there is no straight correlation in between, as depicted in Fig. 1.

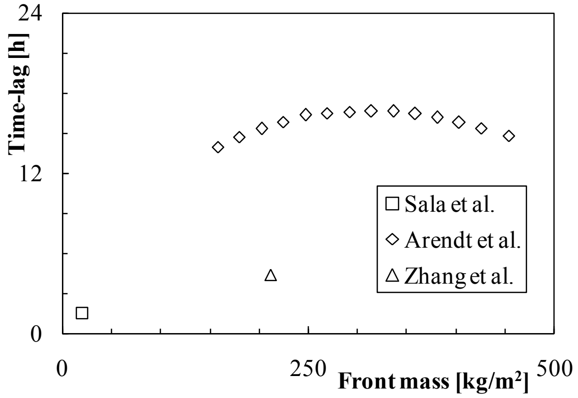


Fig. 1. Literature data on time-lag for 24 hour solicitation vs. front mass

Arendt et al. [13] defined an equivalent thermal diffusivity as the ratio of the equivalent thermal conductivity, defined from steady state heat transfer, to the product of the weighted mean specific heat capacity by weighted mean density. Thus, equivalent thermal diffusivity has been calculated for the other walls for which time-lag data are available, plotting data together, as shown in Fig. 2. Although it appears to be relevant, there is much scattering even with few data.

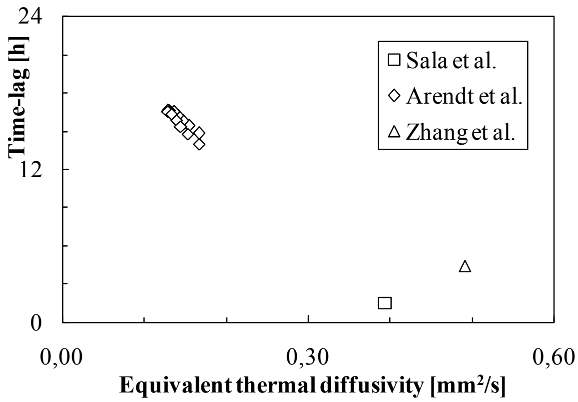


Fig. 2. Literature data on time-lag for 24 hour solicitation vs. equivalent thermal diffusivity

The analytic solution of Fourier equation for conduction heat transfer in slabs subject to sinusoidal solicitation depend on the ratio of square of thickness to thermal diffusivity [6]. It has the dimension of a time, so it may be called "Block response time" (BRT) and used to characterize dynamic performance of a wall layer. Plotting available data versus this parameter shows a straight correlation in between, as depicted in Fig. 3 (notice that BRT from [12] is 2 hours, much lower than the others, as wall thickness is only 80 mm).

In this framework, the aim of the present study is to verify this correlation by numerical simulations.

Although sinusoidal solicitation is a good approximation of daily heat wave, convergence to periodic regime requires a long time, even longer than 10 periods, as shown by Dos-Santos and Mendes [15]. Some numerical and experimental solutions have been done using triangular pulse temperature solicitation, [8], [12], and [16]. This solicitation is easier to handle as once the peak heat transfer is reached, time-lag is well defined and there is no need to simulate further.

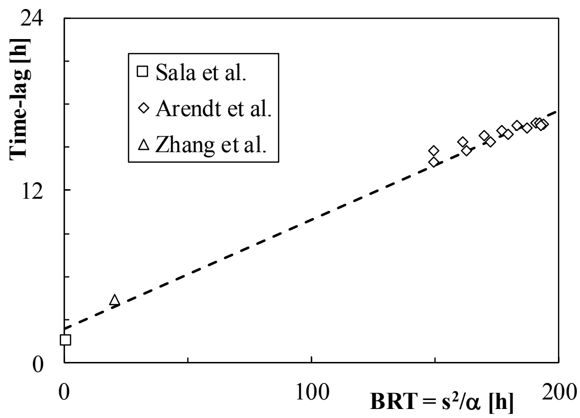
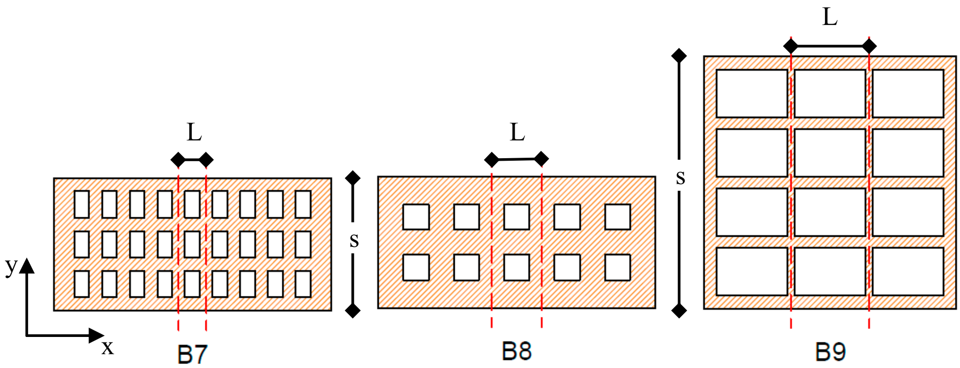


Fig. 3. Literature data on time-lag for 24 hour solicitation vs. block response time

Thus, a two dimensional numerical study is performed with triangular temperature pulse solicitation on one side while the other is kept at uniform temperature. Standardized blocks B7, B8, and B9, among those reported in EN1745:2002 [17] are chosen as much simplification of integration domain is possible. Cavity dimensions are modified to have different front masses and equivalent thermal diffusivities, with cavity to block ratios between 0% and 70%.

2. Mathematical Formulation

The reference masonry unit is depicted in Fig. 4. Bricks are made of clay, while cavities are filled with air. Simulation domain is limited to the central line of cavities.



	s [mm]	L [mm]
B7	105	22
B8	105	40
B9	200	62

Fig. 4. Sketch of the masonry unit and simulation domain, dimensions in mm.

Triangular pulse solicitation is used to check dynamic heat transfer characteristics. A 1 K high, 2 hours wide pulse was chosen. Along domain boundaries, defined by the dashed lines in Fig. 4, adiabatic condition is assumed, while the outer face that is not subject to the pulse is kept at constant temperature.

With the proposed solicitation, the highest temperature difference along opposite sides of a cavity is less than 0.33 K, 0.5 K, and 0.25 K, for B7, B8, and B9 bricks, respectively. Thus, Grashof numbers inside cavities are less than $5x10^2$, $6x10^2$, and $2x10^3$. According to Lacarrière et al. [18], these are in the conduction regime as aspect ratio is higher than 10 for the considered blocks. So, convection contribution to heat transfer may be neglected.

Thermal field equation is described by Cartesian two-dimensional Fourier's equation for conducting fields:

$$k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)=c_p\rho\frac{\partial T}{\partial \tau} \quad (1)$$

At cavity boundary, heat flux conservation is given by:

$$k_f\left.\frac{\partial T}{\partial n}\right|_f + q_R = k_a\left.\frac{\partial T}{\partial n}\right|_c \quad (2)$$

Radiation heat transfer is calculated through radiosity method, with Hottel's crossed-string method for view factors, assuming all surfaces to emit as gray-bodies:

$$q_R = \varepsilon_R\cdot\sigma\cdot T_R^4 - \varepsilon_R\cdot\sum F_{R\to j}\cdot J_j \quad (3)$$

$$J_R = \varepsilon_R\cdot\sigma\cdot T_R^4 + (1-\varepsilon_R)\cdot\sum F_{R\to j}\cdot J_j \quad (4)$$

A 20°C uniform temperature in whole integration domain is used as initial condition.

3. Computational Procedure

Governing equation, along with boundary and initial conditions stated above are solved through a control-volume formulation of the finite-difference method. A first-order backward scheme is used for time stepping. Radiation heat transfer is solved using the same faces of control volumes. The discretized equations lead to a linear system for conduction and for radiation in each cavity (as unknowns are radiation heat transfer). Iterative Jacobi algorithm [19] has been implemented to solve each system. At each time step, the conduction field is solved with previous radiation heat transfer that is then calculated in relation to the newly calculated cavity boundary temperatures, iteratively, with a relative convergence limit of 10^{-3}.

The average heat flux through the constant temperature face is calculated as:

$$q = -\frac{1}{L}\int_0^L k_f\frac{\partial T}{\partial y}dx \quad (5)$$

The code was checked against simple analytic solutions, details can be found in [8] and [20]. Moreover, a self-consistency test was conducted to get the optimal mesh-size, time step and variance limit for iterations. A 5 s time step and 10^{-4} variance limit has been found to be a good balance between calculation time and solution accuracy with meshes with element numbers between 21x103 and 44x210, depending on cavity number and geometry.

4. Results and discussion

Masonry material is clay. Three different densities were considered among those proposed in [17], encompassing the least, the highest, and the mean value; properties are given in Table 1.

Thermal diffusivity of clay is just slightly increasing with density, while all other parameters are highly increasing. Air is one thousand times lighter than clay while its conductivity is ten times lower, so its thermal diffusivity is one hundred times higher. Notice that all materials share similar specific heat, thus heat capacity per unit volume is proportional to density.

Table 1. Properties.

	ρ (kg/m³)	c_p (J/kg K)	c_p*ρ (kJ/m³ K)	k (W/m K)	α (m²/s)
LWC – Light Weight Clay	1000	1000	1000	0.27	0.27 x 10^{-6}
MWC – Medium Weight Clay	1700	1000	1700	0.51	0.30 x 10^{-6}
HWC – Heavy Weight Clay	2400	1000	2400	0.84	0.35 x 10^{-6}
Air	1.20	1005	1.21	0.026	21.5 x 10^{-6}

Simulations of heat transfer through each block provide heat transfer rate on constant temperature face from eq. (5). Equivalent thermal conductivity of the block is defined from steady state heat transfer, as shown in eq. (6).

$$k_{eq} = \frac{s}{R} = \frac{s \cdot q_{st}}{T_1 - T_2} \tag{6}$$

The heat capacity per unit volume for each block may be easily calculated by volume weighted average of the product of specific heat to density, as shown in eq. (7). This is slightly different from that used by Arendt et al. [13], but it is the proper physical definition.

$$\left(c_p \cdot \rho\right)_{eq} = \frac{c_{p_f} \cdot \rho_f \cdot V_f + c_{p_c} \cdot \rho_c \cdot V_c}{V_f + V_c} \tag{7}$$

Equivalent thermal diffusivity is the ratio of these two values, calculated through eq. (8).

$$\alpha_{eq} = \frac{k_{eq}}{\left(c_p \cdot \rho\right)_{eq}} \tag{8}$$

Time-lags for different clay density and void fraction are plotted for each brick type versus Block response time, as reported in Fig. 5.

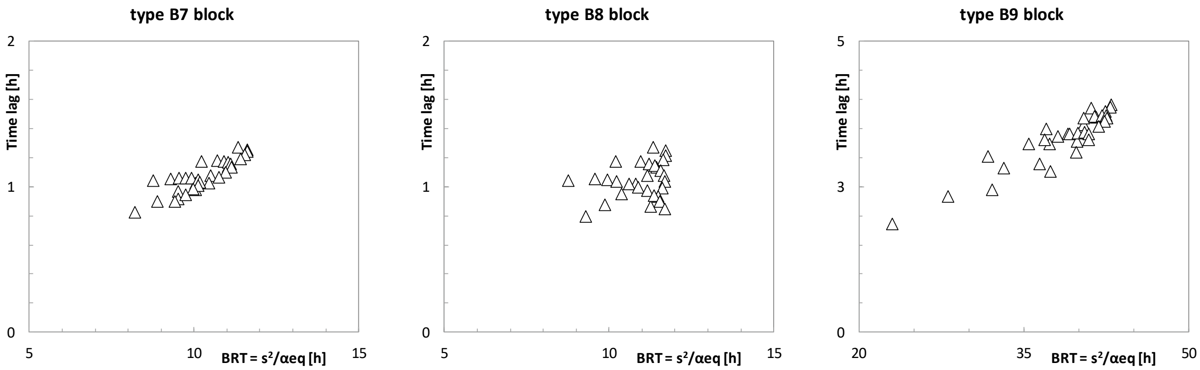


Fig. 5. Time-lag vs. Block response time (BRT)

Block response time is actually the specific thermal resistance multiplied by front mass and average specific heat, as shown in eq. (9):

$$BRT = \frac{s^2}{\alpha_{eq}} = \frac{s}{k_{eq}} \cdot s \cdot \rho_{av} \cdot \frac{\left(c_p \cdot \rho\right)_{eq}}{\rho_{av}} = R \cdot M \cdot c_{p_{eq}} \tag{9}$$

Where the volume averaged density is defined by eq. (10):

$$\rho_{av} = \frac{\rho_f \cdot V_f + \rho_c \cdot V_c}{V_f + V_c} \tag{10}$$

Plotting all available time-lag data versus BRT, the rightness of the latter to define block attitude to soften heat wave is confirmed, as shown in Fig. 6, where regression fit line is proposed with determination coefficient R^2=0.984.

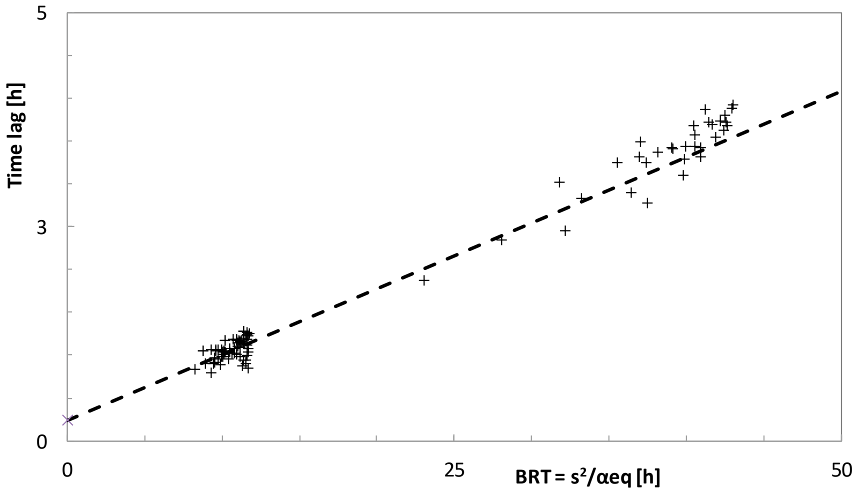


Fig. 6. Time-lag (in hours) vs. BRT

5. Conclusions

According to literature data and analytic solution of Fourier equation for conduction heat transfer through slabs, the Block response time (BRT) is proposed as the relevant parameter to evaluate the attitude of a block to soften heat waves. BRT may be expressed as the product of front mass multiplied by specific thermal resistance, and by mass averaged specific heat. So it is confirmed that wall thermal inertia increases with front mass for a given thermal resistance, but increasing thermal resistance lead to an increase in thermal inertia even without increases in front mass.

Heat transfer in hollow bricks for different materials and void fractions of three types of common bricks has been numerically studied in order to confirm the rightness of BRT to describe thermal inertia behavior.

This is just a first approach to a wide field of research. Much more work should be done to fully understand unsteady behavior of hollow and insulated blocks by analyzing different blocks and the influence of the other layers of the wall. Deviation from BRT predicted behavior are expected and should be analyzed. Moreover, the effect of combining BRT for different layers in a wall should be explored.

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