40. Improved method for 1D heat transfer calculation in multi-layered walls and application to refurbishment field cases

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Abstract A popular method to obtain the 1-D conduction heat transfer of multi-layered plane geometries is attributed to Stephenson and Mitalas (1971) and Mitalas (1968). It is applied in different forms known as; CTF (Conduction Transfer Functions) or RT (Response factors). Roughly his idea consists in sampling the temperature at each side of a wall at a certain fixed time step (usually one hour). Between sampling points, due to the lack of information, a linear profile for the evolution of those temperatures is imposed. A triangleshaping function is used to get such a piecewise linear profile. The paper proposes an improvement by extending the idea of a shaping function. Instead of assuming a linear evolution, a specially designed second order (parabolic) evolution is enforced.This paper describes the use of the methodology of transient 1D heat transfer in multi-layered walls with a hold element of 2nd order, and applies it to a specific situation with the most common constructive solutions used in Spain in the energy refurbishment field .The methodology is applied to several constructive refurbished solutions that include insulation as improvement. The results obtained are compared with traditional methods and the greater accuracy of the present method is shown. Finally it shows how the traditional 1ˢᵗ order holder presents worst approximations to reality when the enclosure has more inertia and the insulation is placed at the face where the disturbance is caused.

Keywords walls transmission heat, response factors, transfer functions, energy Simulation, Energy Refurbishment.
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1 Introduction

The purpose of this article is to analyze the application of a 2nd order holder for 1D heat transfer in multi-layered walls (Mitalas, G., & Stephenson, D., 1971) , and compare it with the traditional model which uses a first degree holder by Mitalas (Mitalas G. , 1968)..We also determine its influence in real applications to different typical constructive elements in the building renovation field (EPISCOPE Partners, 2014).The variables analized have been the insulation location and wall thermal inertia.

This work is an application of the model developed by the same authors, (Pinazo Ojer, Soto Francés, Sarabia Escriva, & Soto Francés, 2015),which details how to get the response factors for a 2nd order holder.

It should be noted that for obtaining the new response factors, besides the well-known balance of thermal power on both sides of the multi-layered wall , the energy balance within two sampling points must be done . Opposite to the traditional Mitalas' scheme, this ensures that the calculation scheme obtained is now conservative.

The superficial temperatures evolution imposed between sampling instants at both sides of the wall are showed in Figure 1. On the left the linear holder used by Mitalas while on the right Figure 1 shows the new 2nd order holder.

Our aim is to check the accuracies by its application to constructive elements that are representative in the existing residential building stock of Spain (Serrano Lanzarote, Ortega Madrigal, & García-Prieto Ruiz, 2011), and which it provides a Refurbishment Performance (EPISCOPE Partners, 2014).

The linear (1st order) and parabolic (2nd order) methods are compared for a typical time step of one hour used in energy simulation versus the linear with a time step of 5 minutes. This last short time step for the linear method is taken as the reference (notice although it still contains errors in energy conservation,).
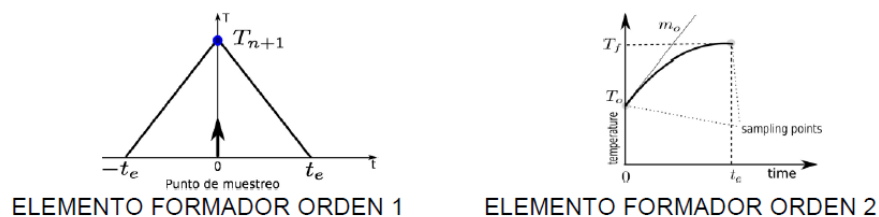

Fig. 1 Scheme temperature distribution according to the holder type. On the left 1st order holder. On the right 2nd order holder.

2 Input data with different holders

2.1 Linear Method

The Mittalas lineal Method (Mitalas G. , 1968).it is shown in Figure 2.
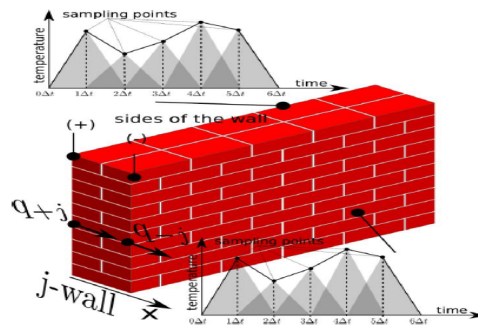

Fig. 2 Superficial temperature input signal at both sides, using a 1st order holder.

Figure 2 shows that the superficial temperature is linear between sampling points, and its continuity condition is expressed as:

(1)

Note: j means wall, and ± means each side of the wall.

According to Mittalas (Mitalas G. , 1968),the conduction heat power exchanged in a given sampling instant, can be obtained by using the response factors named {X,Y,Z} . For a generic multi-layered wall, at the inside wall surface, it can be expressed as :

(2)

Note: obtaining the response factors {X,Y,Z} is a technique already known since (Mitalas, G., & Stephenson, D., 1971).

Therefore, to determine the thermal power transferred by conduction in wall j is necessary to determine two unknowns, the temperatures in the next sampling point n at both sides of the wall ($T_{-j,n}$ $T_{+j,n}$). In order to obtain these temperatures two thermal power balances (at both sides + and -) are established. In fact these balances are valid at any instant of time , however, the method uses a discrete sampling rate. The balance can be written as follows:

$$q_{cond,\pm j,n} + q_{rad,\lambda\uparrow,\pm j,n} + q_{rad,src,\pm j,n} + q_{rad,solar,\pm j,n} = q_{conv,\pm j,n} \quad (3)$$

, The new method needs new response factors named {XX,YY,ZZ}. They allow to get the energy transferred by conduction at a surface within the last time sampling period (Pinazo Ojer, Soto Francés, Sarabia Escriva, & Soto Francés, 2015). They are used similarly to the {X,Y,Z}:

$$(4)$$

The energy response factors can be obtained with the Laplace transform techique see (Pinazo Ojer, Soto Francés, Sarabia Escriva, & Soto Francés, 2015). These new response factors can be used with the 1st order holder as well as with the new 2nd order holder. Therefore they will provide us with a tool to meter the energy flows within time steps in both methods.

Since the 1st order holder uses a thermal power balance at the sampling points, no energy conservation is forced. In fact it is not conserved and part of the energy disappears at some sampling points and reappears latter, thus leading to a stable numerical scheme.

2.2 Parabollic holder (2nd order holder)

Figure 3 shows the reconstruction of the temperature profile obtained using a 2nd order holder.
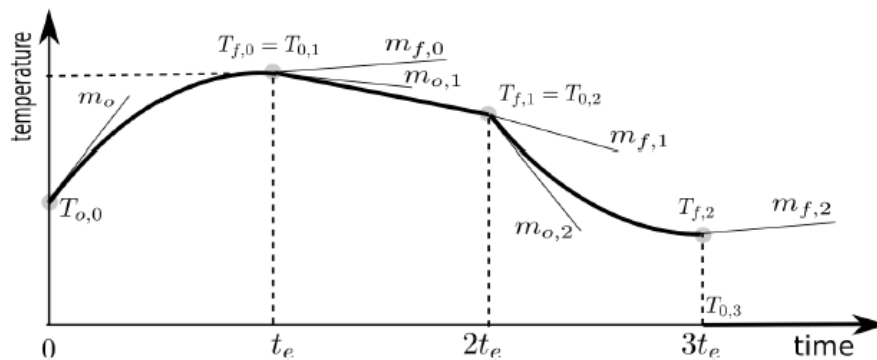
Fig. 3 Evolution surface temperatures with forming element 2nd order (Pinazo Ojer, Soto Francés, Sarabia Escriva, & Soto Francés, 2015)

The continuity of the temperature signal at the sampling points is also forced as with the 1st order holder.

The evolution of the superificial temperatures within a time range is given by:

$$(5)$$

In this case, two parameters are needed to determine the evolution of the temperature within a range, namely the temperature at end (T$_{-j,\,n}$) and the temperature semi-acceleration (p$_{-j,\,n}$).

Note that if p$_{-j,\,n}$ =0 then we recover the Mitalas method.

The 1D conduction heat power exchanged with this holder is obtained by the expression :

$$q_{-j,n} = \sum_{k=0}^{\infty}\left[T_{+j,n-k}\cdot Y_{T,j,k} + p_{+j,n-k-1}\cdot Y_{p,j,k}\right] + \sum_{k=0}^{\infty}\left[T_{-j,n-k}\cdot Z_{T,j,k} + p_{-j,n-k-1}\cdot Z_{p,j,k}\right]$$

$$(6)$$

, while the energy transferred in this interval by conduction through the surface is expressed as follows:

$$(7)$$

We would like to point out (Pinazo Ojer, Soto Francés, Sarabia Escriva, & Soto Francés, 2015) two facts:

1) We need to obtain the new response factors for heat power and energy to both temperature and temperature semi-acceleration signals. However it does not involve a much higher computational effort because the greater effort That is, the "computational cost" for determining these new response coefficients is basically the same.

2) The number of coefficients to be used in determining the power exchanged and transferred energy is twice that in the case of linearity.

Therefore, our new scheme needs to determine four unknowns: the temperature wall (T$_{-j,n}$ T$_{+j,n}$) and the temperature semi- acceleration on both wall sides . In turn two energy balances, at each wall side , are needed to obtain these unknowns .

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These balances are written as:

$$q_{cond,\pm j,n} + q_{rad,\lambda\uparrow,\pm j,n} + q_{rad,src,\pm j,n} + q_{rad,solar,\pm j,n} = q_{conv,\pm j,n} \qquad (8)$$

$$Q_{cond,\pm j,(n-1)\rightarrow n} + Q_{rad,\lambda\uparrow,\pm j,(n-1)\rightarrow n} + Q_{rad,src,\pm j,(n-1)\rightarrow n} + Q_{rad,solar,\pm j,(n-1)\rightarrow n} = Q_{conv,\pm j,(n-1)\rightarrow n}$$

$$(9)$$

3 Application

3.1 Constructive elements analyzed

The analysis of the thermal behavior of a building can be solved by simulation programs which analyze the phenomenon of heat transfer. Because of the importance of energy rehabilitation to achieve the target objectives set in H2020 , the professionals need accurate methods.

Therefore, there has been a boom in employment and investment in   energy simulation tools.

Many energy simulations of buildings are performed to determine their behavior and estimate changes in energy consumption (Soto Francés, 2008).

Consequently, it seems logical that any action to improve the tools for analysis and decision making, would lead to an in improved energy efficiency of a building project will mean an increase in quality. Must therefore remain a global perspective workflow design. This flow, to be optimized, offers possibilities to improve the performance of a project without assuming an increase in workload.

The solutions tested are taken from the catalog Constructive Solutions Rehabilitation developed by the Valencian Institute of Building (Serrano Lanzarote, Ortega Madrigal, & García-Prieto Ruiz, 2011) which emerges as an aid to the technician who must face energy refurbishment of buildings. It focuses on the development of intervention proposals (EPISCOPE Partners, 2014),within the scope of passive measures, affecting the constructive elements of the thermal envelope of the building (walls, roofs, windows, etc.).
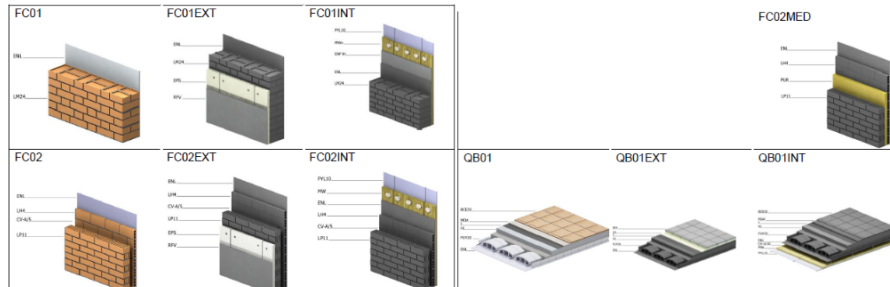
Fig. 4 Constructive elements analyzed. Nomenclatura elements type: EXT, exterior insulation; INT: insulation inside; MED: isolation in the middle of the enclosure.

3.2 Base case comparison

As implementation of the new methodology, this section determines the heat transferred by convection to air through a wall. The results are compared with the standard assumption of a linear evolution of surface temperatures. The time steps explored for the linear case and for the second order have been; 1 h Compared to the result to be considered valid: the linear case with passage of time of 5 minutes.

To determine the behavior of the enclosure and to perform simple calculations, the following calculation hypotheses are assumed:

• internal radiation source and people light impinging on the inner surface for 2 hours; PSRC = 10 [W / m^2]. (It is assumed that all incident radiation is absorbed)

• Rest of the internal surfaces of the enclosure are maintained at a constant temperature T_r = 22 [Cº].

• The temperature in the other side wall is also maintained at T_{-j} = 22 [Cº].

• The temperature of the dry air is also maintained T_a = 22 [Cº].

• The radiation coefficient equivalent (linearizing expression radiant exchange long wavelength) constant hr = 5 [W / m^{2}K] remains.

• The convection coefficient is constant; hc = 3 [W / m^{2}K].

4 Results

Table 1 shows the heat is transferred by conduction in each hour is represented when the calculations are performed with different methods of calculation time step raised and different calculation for the element FC01.

Table 1 Heat transferred by conduction (J/m2) within several intervals. Errors are for the 1 (h) case referred to the linear 5 (min) case. FC01 solution

FC01					
Qconduction (J/m2)				Reference : linear shaping function (sampling rate 5 min).	
Time step	Parabollic 1h	Linear1h	Linear 15min	Linear5 min	Difference parab 1 h	Difference linear 1h
0-3600	-26621	- 15949	- 23431	- 25336	-1285	9387
3600-7200	-22002	-22341	-22455	-22292	290	-49
7200-10800	6430	-4834	3018	5045	1385	-9879
10800-14400	3171	2979	3461	3393	-222	-414
14400-18000	2413	2556	2507	2461	-48	95
18000-21600	1910	2059	1969	1939	-29	120
21600-25200	1579	1698	1619	1597	-18	101
25200-28800	1341	1435	1370	1353	-12	82
28800-32400	1160	1236	1182	1169	-9	67
32400-36000	1016	1078	1033	1023	-7	55
36000-39600	897	950	911	902	-5	48
39600-43200	796	842	808	801	-5	41
43200-46800	709	749	720	713	-4	36
46800-50400	633	669	643	637	-4	32
54000-57600	567	598	575	570	-3	28
57600-61200	508	535	515	510	-2	25
61200-64800	455	480	461	457	-2	23
64800-68400	408	430	414	410	-2	20
64800-68400	366	386	371	368	-2	18

68400-72000	328	346	333	330	-2	16
7200-75600	294	311	299	296	-2	15
75600-79200	264	279	268	265	-1	14
79200-82800	237	250	240	238	-1	12
82800-86400	213	224	216	214	-1	10

As shown in Table 1 errors relative to reference method (linear 5min) listed in the table are decreasing with time. In the case of parabolic method 1 h, the difference is very small as it evolves over time. This is an example for the FC01 solution and heat transferred by conduction, but can be verified in other solutions the trend and the order of magnitude are the same for the different types analyzed.

The evolution of the surface temperature of the enclosure according to the different methodologies used and the time step observed in Figure 5.
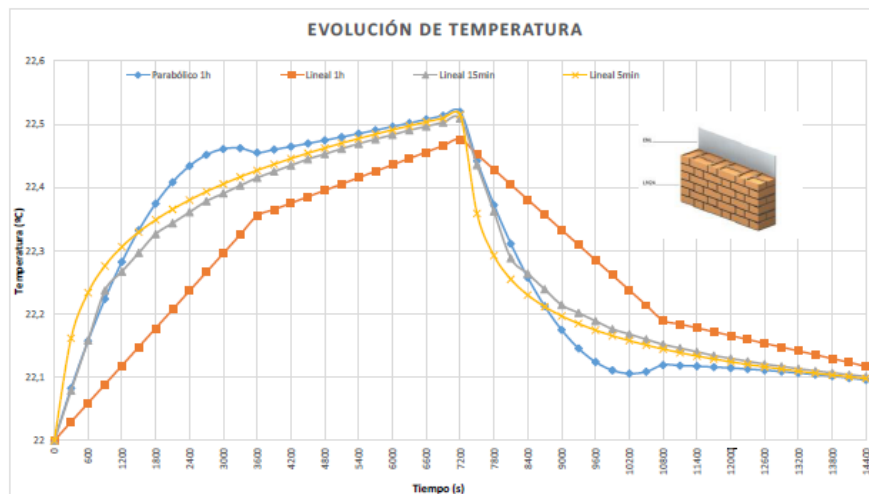

Fig. 5 The reconstruction of the temperature profile obtained using linear, parabolic shaping function in and different time steps

It can be seen that the closest values are represented by the blue dotted line (parabolic 1h) and crosses the yellow line (linear 5 min). It shows that the line corresponding to the linear method in red (1h) shows an evolution of the very

different and steeper temperature. The tendency of the parabolic fit between 1h
method and linear 5 minutes, occurs in all cases sampled.

5 Conclusions

It can be concluded:
The values of energy transferred to the air for a parabolic shaping
function with time step 1h are similar to those of linear shaping
function with a time step of 5 min. And clearly with a linear and time step 1h
profile results differ greatly from what could be considered acceptable.

It is important to emphasize that the purpose of the shaping
function in either case whether linear, parabolic or any other, is
to guess a profile about the evolution of the superficial temperatures between
sampling points. The actual evolution of the temperatures is actually unknown.

A parabolic profile could be thought at first sight, as non-physical or unnatural.
But, as it has been shown and explained, a linear profile should also be considered
so.
In short, the choice of one shaping function or another is an arbitrary decision. It
should be based on some criteria like; possibility of leading to stable schemes,
being computationally cheap, being compatible with certain forcing functions.
For the same sampling rate the parabolic shaping function gives better results than
the linear one. It gets a better accuracy in constructive solutions with greater mass
of the disturbance side and insulation position on the disturbance side.

The use of new shaping functions has a great potential to reach improvements
in accuracy and speed for the heat transfer applied calculations for new buildings
and especially existing and refurbishment strategies.

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