



## CONDUCTION TRANSFER FUNCTIONS IN TRNSYS MULTIZONE BUILDING MODEL: CURRENT IMPLEMENTATION, LIMITATIONS AND POSSIBLE IMPROVEMENTS

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### ABSTRACT

The Conduction Transfer Function (CTF) method is used by many building energy performance simulation programs to calculate 1-D transient heat conduction through multi-layer envelope components. TRNSYS is one of these programs, and several authors have reported problems with the current CTF implementation in its multizone building model, known as Type 56. Reported problems are related to heavy and highly insulated slabs and short time-step simulations (less than 15-minute time-step). This paper documents the current implementation of CTF in Type 56. It then reports on our investigation of some issues with the current implementation and their causes. Workarounds and short-term solutions are assessed and longer-term improvements are discussed.

### INTRODUCTION

Transient conduction heat transfer through building slabs is one of the key aspects of space heating and cooling loads calculation. Several Building Performance Simulation (BPS) tools were developed to perform these calculations and address the dynamics of heat transfer through the building envelope. With the current interest for net-zero energy buildings and demand-side response to smart grids, a need is showing for accurate transient simulation of thick, highly insulated (and sometimes heavy) slabs with short time-steps (in the order of one minute). This sometimes represents a challenge for codes that were mainly developed with the objective of performing yearly energy load calculations, typically with a time-step of one hour. This is the case of TRNSYS building model, known as Type 56, which is known to have limitations with very thick, heavy, or highly insulated walls and with short time-steps (typically under 15 min).

At the same time, encapsulation of Phase-Change Materials (PCMs) in the building structure is becoming a reality for the building industry. Modeling tools must cope with this reality, but the current implementation

of CTF in TRNSYS Type 56 is not adapted to phase-changing wall layers. This has generated interest for external solutions, i.e. dedicated components that simulate the behavior of one particular wall and communicate with Type 56 to interact with the rest of the building model [5, 10, 14]. These solutions must be carefully setup by users and quickly become tedious if several PCMs walls are to be simulated.

### OBJECTIVES

The long-term goal of our project is to improve the transient conduction modeling in Type 56 to allow short time-step studies for demand-side management and to cope with encapsulated PCMs in the building structure.

As a first step, this paper reports on our work to assess the current implementation of CTF in Type 56 and explore possible improvements. The theory behind the CTF method and the different options to obtain CTF coefficients is briefly described and the current implementation of CTF coefficients generation in TRNSYS Type 56 is documented.

Some limitations of the current CTF modeling approach are investigated by comparing Type 56's response with a reference solution for three wall assemblies representing well insulated modern walls with different levels of thermal mass: Insulated Concrete Form (ICF), Structural Insulated Panel (SIP), and Double-Stud Wall with brick veneer (DST).

The tests performed to assess the current limitations of CTF in Type 56 are 1-min simulations of steps, periodic excitations, and an aggressive heating setback intended to represent demand-side management studies.

After assessing and quantifying the limitations with the current CTF implementation, workarounds are explored and future directions are discussed.

### CTF METHOD IN TRNSYS

The method implemented in TRNSYS to calculate the transient heat conduction through slabs is the CTF method. This method was introduced by Mitalas and Stephenson [20] and consists in determining transfer functions for 1-D conduction heat transfer through slabs by solving the conduction equation with Laplace and Z-transform theory.

The conduction transfer functions (CTF) are time series [21] allowing to calculate the inside and outside heat fluxes ( $q_{si}$  and  $q_{so}$ ) from current and previous values of the surface temperatures ( $T_{si}$  and  $T_{so}$ ) and the heat fluxes themselves:

$$q_{si} = \sum_{k=0}^{n_b} b^k T_{s,o}^k - \sum_{k=0}^{n_c} c^k T_{s,i}^k - \sum_{k=1}^{n_d} d^k q_{s,i}^k \quad (1)$$

$$q_{so} = \sum_{k=0}^{n_a} a^k T_{s,o}^k - \sum_{k=0}^{n_b} b^k T_{s,i}^k - \sum_{k=1}^{n_d} d^k q_{s,o}^k \quad (2)$$

Where:

$$\frac{\sum_{k=0}^{n_a} a^k}{\sum_{k=0}^{n_d} d^k} = \frac{\sum_{k=0}^{n_b} b^k}{\sum_{k=0}^{n_d} d^k} = \frac{\sum_{k=0}^{n_c} c^k}{\sum_{k=0}^{n_d} d^k} = U \quad (3)$$

a, b, c and d are the coefficients of the time series equations. There are several methods to obtain these coefficients for a particular wall type. The method used in TRNSYS Type 56 is the Direct Root Finding (DRF) method as performed by Mitalas and Arseneault [16].

CTF are discrete time series and the selected time-step is referred to as the "timebase" in TRNSYS, to distinguish that CTF time-step from the main simulation time-step. TRNSYS simulations can run with a time-step that is smaller than or equal to the timebase, as long as the CTF timebase is a multiple of the simulation time-step. The lower the timebase, the more coefficients will be required to describe the dynamic response of a given wall.

The DRF method implemented by Mitalas and Arseneault in TRNSYS to calculate the CTF coefficients needs a fixed input signal (an excitation) for which these coefficients will be generated. This excitation will be a simple linear ramp input. This method was described previously by Giaconia and Orioli [8] and consists first in solving the heat transmission matrix for a slab, i.e. the matrix describing the thermal properties of the slab:

$$\begin{bmatrix} T_{so}(s) \\ q_{so}(s) \end{bmatrix} = \begin{bmatrix} A(s) & B(s) \\ C(s) & D(s) \end{bmatrix} \times \begin{bmatrix} T_{si}(s) \\ q_{si}(s) \end{bmatrix} \quad (4)$$

Where:

$$\begin{bmatrix} A(s) & B(s) \\ C(s) & D(s) \end{bmatrix} = \begin{bmatrix} 1 & -R_i \\ 0 & 1 \end{bmatrix} \times \begin{bmatrix} A(s)_1 & B(s)_1 \\ C(s)_1 & D(s)_1 \end{bmatrix} \times \dots \times \begin{bmatrix} A(s)_n & B(s)_n \\ C(s)_n & D(s)_{1n} \end{bmatrix} \times \begin{bmatrix} 1 & -R_o \\ 0 & 1 \end{bmatrix} \quad (5)$$

Where:

- s is the Laplace variable.
- $T_{so}$  and  $T_{si}$  are the outside and inside surface temperature [ $^{\circ}\text{C}$ ].
- $q_{so}$  and  $q_{si}$  are the outside and inside surface heat flow [W].
- $R_i$  and  $R_o$  are the inside and outside thermal resistance of the air film [ $\text{m}^2\text{K/W}$ ].
- $A(s)_n = D(s)_n = \cosh\left(L_n \sqrt{\frac{s}{\alpha}}\right)$
- $B(s)_n = -\frac{R_n \sinh\left(L_n \sqrt{\frac{s}{\alpha}}\right)}{L_n \sqrt{\frac{s}{\alpha}}}$
- $C(s)_n = -\frac{L_n \sqrt{\frac{s}{\alpha}} \sinh\left(L_n \sqrt{\frac{s}{\alpha}}\right)}{R_n}$
- n is the layer number.
- L is the layer thickness [m].
- R is the thermal resistance [ $\text{m}^2\text{K/W}$ ].

For a resistive layer, the transmission matrix becomes  $\begin{bmatrix} 1 & -R_n \\ 0 & 1 \end{bmatrix}$ .

After manipulation, the equation (4) becomes:

$$\begin{bmatrix} q_{so}(s) \\ q_{si}(s) \end{bmatrix} = \begin{bmatrix} G_x(s) & -G_y(s) \\ G_y(s) & -G_z(s) \end{bmatrix} \times \begin{bmatrix} T_{so}(s) \\ T_{si}(s) \end{bmatrix} \quad (6)$$

Where  $G_x(s)$ ,  $G_y(s)$  and  $G_z(s)$  are respectively the s-transfer functions of external, cross and internal heat conduction of the slab and are formulated as:

$$G_x(s) = \frac{A(s)}{B(s)} \quad G_y(s) = \frac{1}{B(s)} \quad G_z(s) = \frac{D(s)}{B(s)}$$

From these s-transfer functions (continuous-time system), z-transfer functions (discretized time system) can be evaluated:

$$G_x(z) = \frac{O_x(z)}{I(z)} = \frac{Z[G_x(s)B(s)]}{Z[B(s)]} = \frac{N_x(z)}{D(z)} \quad (7)$$

$$G_y(z) = \frac{O_y(z)}{I(z)} = \frac{Z[G_y(s)B(s)]}{Z[B(s)]} = \frac{N_y(z)}{D(z)} \quad (8)$$

$$G_z(z) = \frac{O_z(z)}{I(z)} = \frac{Z[G_z(s)B(s)]}{Z[B(s)]} = \frac{N_z(z)}{D(z)} \quad (9)$$

Where:

- z is the discrete Laplace variable.
- Z is the z-transform operator.
- I(z) is the linear ramp input and is formulated as:  $I(z) = \frac{\Delta}{z(1-z^{-1})^2}$  with  $\Delta$  being the sampling time.



- $N_x(z)$ ,  $N_y(z)$ ,  $N_z(z)$  are the numerators of z-transfer functions.
- $D(z)$  is the denominator of z-transfer functions and is formulated as follows:  

$$D(z) = \prod_{n=1}^N (1 - e^{-\beta_n \Delta} z^{-1}) = d_0 + d_1 z^{-1} + d_2 z^{-2} + \dots + d_N z^{-N} \quad (10)$$

Where:

- o  $\beta_n$  are the roots of B(s).
- o N is the number of roots.
- o  $d_n$  is one type of CTF coefficients (among 4 types). These coefficients can be calculated as follows:
  - $d_0 = 1$
  - $d_1 = -(h_1 + h_2 + h_3 + \dots + h_N)$
  - $d_2 = h_1 h_2 + h_1 h_3 + \dots + h_2 h_3 + h_2 h_4 + \dots + h_{N-1} h_N$
  - ...
  - $d_N = (-1)^N (h_1 h_2 h_3 \dots h_N)$
 With  $h_n = e^{-\beta_n \Delta}$
- $O_x(z)$ ,  $O_y(z)$  and  $O_z(z)$  are the output signals of z-transfer functions.  $O(z)$  is expressed as:

$$O(z) = \frac{C_0 \Delta}{z(1-z^{-1})^2} + \frac{C_1}{1-z^{-1}} + \sum_{n=1}^N \frac{d_n}{1-e^{-\beta_n \Delta} z^{-1}} = o_0 + o_1 z^{-1} + o_2 z^{-2} + \dots + o_N z^{-N} \quad (11)$$

Where  $C_0$  and  $C_1$  are coefficients and are different for  $O_x(z)$ ,  $O_y(z)$  and  $O_z(z)$ , i.e.:

- o For  $O_x(z)$ :  $C_0 = \left[ \frac{A(s)}{B(s)} \right]_{s=0}$  and  $C_1 = \left[ \frac{A'(s)B(s) - A(s)B'(s)}{B(s)^2} \right]_{s=0}$  with  $A'(s) = \frac{dA(s)}{ds}$
- o For  $O_y(z)$ :  $C_0 = \left[ \frac{1}{B(s)} \right]_{s=0}$  and  $C_1 = \left[ \frac{-B'(s)}{B(s)^2} \right]_{s=0}$
- o For  $O_z(z)$ :  $C_0 = \left[ \frac{D(s)}{B(s)} \right]_{s=0}$  and  $C_1 = \left[ \frac{D'(s)B(s) - D(s)B'(s)}{B(s)^2} \right]_{s=0}$

The coefficients  $o_n$  in equation (11) are computed as:

- o  $o_0 = C_1 + \sum_{n=1}^N d_n$
- o  $o_1 = C_1 + C_0 \Delta + \sum_{n=1}^N d_n e^{-\beta_n \Delta}$
- o  $o_2 = C_1 + 2 C_0 \Delta + \sum_{n=1}^N d_n e^{-2\beta_n \Delta}$
- o ...
- o  $o_n = C_1 + n C_0 \Delta + \sum_{n=1}^N d_n e^{-n \beta_n \Delta}$

After all these calculations,  $N_x(z)$ ,  $N_y(z)$  and  $N_z(z)$  can finally be computed to generate the three last CTF coefficients (a, b and c). Only the example for  $N_x(z)$  is developed. For the two others, the operations must be just repeated.

$$N_x(z) = \frac{z(1-z^{-1})^2}{\Delta} (1 + d_1 z^{-1} + d_2 z^{-2} + \dots + d_N z^{-N}) (o_0 + o_1 z^{-1} + o_2 z^{-2} + \dots + o_N z^{-N}) = (\bar{a}z + a_0 + a_1 z^{-1} + a_2 z^{-2} + \dots + a_{N+1} z^{-(N+1)}) \quad (12)$$

Where:

- $\bar{a} = \bar{m} o_0 = 0$
- $a_0 = m_0 o_0 + \bar{m} o_1$
- $a_1 = m_1 o_0 + m_0 o_1 + \bar{m} o_2$
- $a_2 = m_2 o_0 + m_1 o_1 + m_0 o_2 + \bar{m} o_2$
- ...
- $a_n = m_n o_0 + m_{n-1} o_1 + \dots + m_1 o_{n-1} + m_0 o_n + \bar{m} o_{n+1}$
- ...
- $a_{N+1} = m_{N+1} o_0 + m_N o_1 + \dots + m_1 o_{N-1} + m_0 o_N + \bar{m} o_{N+1}$

And:

- $\bar{m} = \frac{1}{\Delta}$
- $m_0 = \frac{1}{\Delta} (d_1 - 2 d_0)$
- $m_1 = \frac{1}{\Delta} (d_2 - 2 d_1 + d_0)$
- ...
- $m_n = \frac{1}{\Delta} (d_{n+1} - 2 d_n + d_{n-1})$
- ...
- $m_N = \frac{1}{\Delta} (-2 d_N + d_{N-1})$
- $m_{N+1} = \frac{1}{\Delta} d_N$

Once these coefficients are calculated, they can be used directly by TRNSYS with equations (1) and (2).

The CTF implementation in TRNSYS is in line with the general convention in the program that all the variables exchanged between components (Types) are averaged over the simulation time-step. This means, for example, that  $q_{si}^k$  is the average of the heat flux between ( $t = t_{k-1}$  and  $t = t_k$ ).

## TEST CASES TO ASSESS THE CURRENT CTF IMPLEMENTATION IN TYPE 56

### Selected wall types

We selected three wall types to represent well insulated modern walls with different levels of thermal mass: Insulated Concrete Form (ICF), Structural Insulated Panel (SIP), and Double-Stud Wall with brick veneer (DST). The three walls have approximately the same R-value:  $R_{SI} = 5.5 \text{ m}^2\text{-K/W}$ , or  $R_{IP} = 31 \text{ h-ft}^2\text{-}^\circ\text{F/Btu}$  (including standard inside and outside surface resistances). The following description of these walls is from inside to outside and the materials properties comes from ASHRAE Handbook [1]:

Table 1: Slabs description.

Slabs	L [m]	k [W/(m-K)]	$\rho$ [kg/m <sup>3</sup> ]	Cp [kJ/(kg-K)]	R [m <sup>2</sup> -K/W]
Wall-only U-value: 0.188 W/(m <sup>2</sup> -K)					
Gypsum board	0.016	0.16	800	1.09	0.100
EPS (expanded polystyrene) board	0.076	0.03	43	1.21	2.533
Heavy weight concrete	0.203	1.95	2240	0.9	0.104
EPS board	0.076	0.03	43	1.21	2.533
Stucco	0.025	0.72	1856	0.84	0.035

Slabs	L [m]	k [W/(m-K)]	$\rho$ [kg/m <sup>3</sup> ]	Cp [kJ/(kg-K)]	R [m <sup>2</sup> -K/W]
DST Wall-only U-value: 0.185 W/(m <sup>2</sup> -K)					
Gypsum board	0.016	0.16	800	1.09	0.100
Wood studs / insulation	0.089	0.06	56	1.00	1.583
Batt insulation	0.089	0.05	19	0.96	1.780
Wood studs / insulation	0.089	0.06	56	1.00	1.583
OSB panel	0.013	0.15	608	1.63	0.087
Wall air space resistance					0.150
Brick	0.100	0.89	1920	0.79	0.112
SIP Wall-only U-value: 0.197 W/(m <sup>2</sup> -K)					
Gypsum board	0.016	0.16	800	1.09	0.100
OSB panel	0.013	0.15	608	1.63	0.087
EPS board	0.143	0.03	43	1.21	4.767
OSB panel	0.013	0.15	608	1.63	0.087
Stucco	0.025	0.72	1856	0.84	0.035

### Test cases

Transient conduction through walls is tested by modeling a thermal zone with one wall type. The tested wall has a nominal area of 1000 m<sup>2</sup> (this area is actually split in two because Type 56 requires at least two walls per zone). Heating and cooling is implemented to keep the inside air temperature at the desired value (except during the setback phase of scenario 2, see below). Outside air temperature is imposed at a constant or periodic value. There are no internal gains or solar radiation. Outside long wave radiation is zeroed by defining the wall as a boundary wall and by setting the boundary temperature at the desired constant and periodic air temperature. The impact of inside long wave radiation is removed by using the simple long-wave radiation model with appropriate combined resistances. The detailed long-wave radiation mode introduced in TRNSYS 17 with the TRNSYS-3D interface could also be used, since that detailed mode allows modifying the emissivity of each wall.

### Scenario 1

For the first scenario, the time-step used is 1 minute and the following boundary conditions have been selected:

- 34.5 and 8.3 W/(m<sup>2</sup> K) for the outside and inside convection coefficients respectively.
- Outside air temperature is a sine wave (20 °C average value and 20 °C amplitude, 24-h period, no phase-lag).
- The inside temperature is maintained by idealized heating and cooling at 20°C.

### Scenario 2

Another scenario was developed to represent a typical use of short time-step simulations (1 min) to study peak-shaving control strategies. In this scenario, the simulated wall is in contact with an air node that represents the thermal zone. The air node has very little thermal mass (equivalent to 1 m<sup>3</sup> of air per m<sup>2</sup> of wall) and the tested wall is the only contact between the air

and the outside air which is kept constant at 0°C. No radiative flows are considered. The system is preconditioned by imposing a convective heating power adjusted to maintain exactly 20°C in the zone for a very long period. At time t=5 hours, the heating is stopped for 4 hours (simulating an aggressive setback strategy during peak period). After 4 hours in free-floating mode, convective heating is restarted with a power equal to 1.5 times the initial value (simulating a recovery period after the setback). This scenario keeps the same values of convection coefficients as the scenario 1.

### REFERENCE SOLUTION

Conduction heat transfer issue can be formulated with a state-space (SS) model by using finite-difference method [17] to spatially discretize building slabs. This method is presented e.g. by Jiang [12] and allows to link the inside and outside boundary temperatures  $T_i$  and  $T_o$  to the inside and outside surface heat flows  $q_{si}$  and  $q_{so}$  for each node of a multilayered slab. It can be formulated as follows:

$$\begin{bmatrix} \frac{dT_1}{dt} \\ \dots \\ \frac{dT_n}{dt} \end{bmatrix} = a \begin{bmatrix} T_1 \\ \dots \\ T_n \end{bmatrix} + b \begin{bmatrix} T_i \\ T_o \end{bmatrix} \quad (13)$$

$$\begin{bmatrix} q_{si} \\ q_{so} \end{bmatrix} = c \begin{bmatrix} T_1 \\ \dots \\ T_n \end{bmatrix} + d \begin{bmatrix} T_i \\ T_o \end{bmatrix} \quad (14)$$

Where:

- $T_1 \dots T_n$  are the temperatures at each node.
- a, b, c and d are matrices of coefficients that depend on material thermal properties and/or air film coefficients.

Waters and Wright [22] investigated optimized node placement in order to obtain accurate transient responses with a limited number of state variables (or nodes). The reference solution used in our tests is a state-space representation using the node placement method recommended by Waters and Wright with a large number of nodes (>100 for all walls). That solution was implemented and simulated in Matlab.

### RESULTS

#### CTF generation

CTF coefficients are generated by TRNBuild, the dedicated user interface and pre-processing program for TRNSYS Type 56 with the user-selected timebase. The Mitalas and Arseneault method implemented in the current version of TRNBuild is known to have

problems with very thick or highly insulated walls, especially for shorter time-steps. With the selected walls, the minimum timebase for which coefficients could be generated is 1 hour (ICF wall), 15 min (DST wall) and 9 min (SIP wall).

### Initialization

Type 56 walls are always initialized at a constant temperature, which is equal to the initial zone temperature specified by the user. A warm-up period is then necessary if the wall must be in a non-uniform condition at the beginning of a simulation. In our tests we always ran the model for a very long period (in the order of 1000 h) to suppress the impact of initial conditions.

The impossibility of specifying non-uniform initial conditions is a common limitation in BPS programs, which is usually addressed by running the building for a warm-up period. A commonly adopted strategy in TRNSYS when initial conditions are important is to run an extra month at the end of the simulation and to discard the results of the first month.

### Results for scenario 1

Figures 1, 2 and 3 below represent the evolution of the inside surface temperature calculated by the reference solution and TRNSYS for the 3 different walls described above. Each simulation was realized with a 1-minute time-step. The wall timebase is the smaller one that was achievable for each wall type.

The most obvious impact of the difference between the TRNSYS time-step (1 min) and the wall timebase (9 min to 1 h) is a stair-step effect in the simulated response, which is visible in Figure 1. This effect is also observed in Figures 2 and 3, although it is less visible. The stair-step phenomenon becomes more noticeable when the ratio between the time-step and the timebase becomes lower.

The results in Figures 1, 2 and 3 show that, even though the stair-step effect can be very visible and affect the 1-min simulation results, the behavior of the three wall types is simulated accurately, with no significant magnitude or phase error when the results at the end of each “stair step” are considered. This shows that the mechanism implemented in Type 56 to interpolate the results of CTF for time-steps that are shorter than the timebase is working correctly.

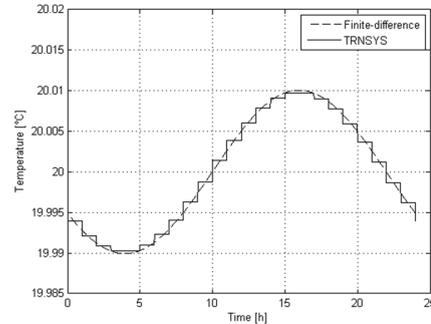


Fig.1: Evolution of the inside surface temperature for an ICF wall (1-hour time base – scenario 1).

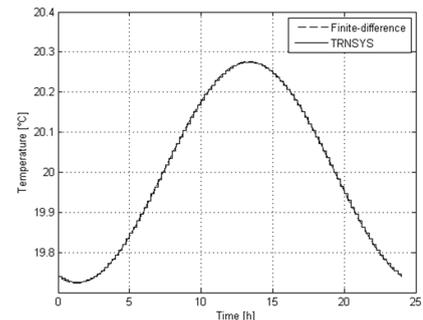


Fig.2: Evolution of the inside surface temperature for a DST wall (15-minute time base – scenario 1).

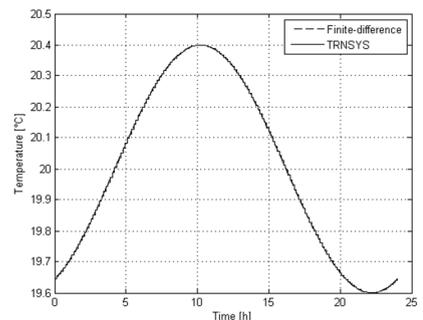


Fig.3: Evolution of the inside surface temperature for a SIPs wall (9-minute time base – scenario 1).

### Results for scenario 2

This scenario focuses on the results for ICF wall (1-hour timebase) because it is this wall that induces the greatest problem because of the stronger stair-step effect. The stair-step effect shown in Figure 1 is also noticeable in Figures 4 and 5, representing respectively the evolution of the inside surface temperature and the rate of heat storage into the wall for the scenario 2. The maximum temperature difference observed in Figure 4 is about 0.45 °C and occurs at approximately the third of the timebase, i.e at every 1 hour and 20 minutes. Figure 5 shows the heat transfer rate to or from the wall. This is the sum of the surface heat fluxes at both sides of the wall – a positive value indicates that heat is stored into the wall and a negative value means that heat is removed from the wall. The difference in heat

transfer rate peaks at the end of each timebase period with values of around  $1.5 \text{ W/m}^2$  (40% of the value when the heat is de-stored from the wall).

Figure 4 shows that the temperature is very close to the reference solution at the end of each timebase. This is confirmed by Figure 5 which shows, in spite of the spikes caused by the stair-step effect, the average heat transfer rate to and from the wall is correct when the average over the timebase is considered.

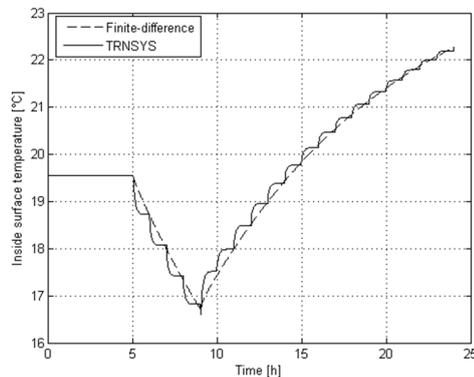


Fig.4: Evolution of the inside surface temperature for an ICF wall (1-hour time base – scenario 2).

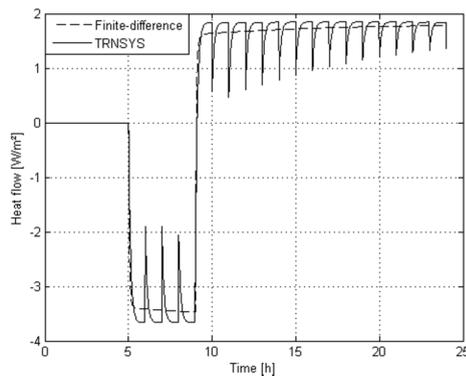


Fig.5: Evolution of the rate of heat storage into the wall for an ICF wall (1-hour time base – scenario 2).

## POSSIBLE IMPROVEMENTS

### Workarounds

A workaround can be used to allow the TRNSYS users to choose a lower timebase value when TRNBuild cannot generate CTF coefficients with the default method.

By changing the description of an insulation layer from “massive layer” to “massless layer”, the DRF algorithm is sometimes able to find the CTF coefficients for a shorter timebase. In the case of the ICF wall, replacing the two insulation layers by their

equivalent resistance (massless layers in Type 56) allows CTF coefficients to be generated for a timebase of 0.5 h (instead of 1 h with the “full” wall description). This introduces an approximation in the wall description, which can lead to differences in the transient response of the model. In the particular case of our ICF wall, a noticeable phase lag was observed between the simplified model (with massless layer) and the reference model (insulation as a normal layer with thermal mass). Although this result would need to be confirmed for various wall types and excitations, it shows that users should be careful before applying that workaround.

Another known workaround in Type 56 is to split the problematic wall into two or more walls that are connected through fictitious, infinitely thin, air zones with very high convection coefficients. Since the problems with CTF coefficient generation and numerical stability are always related to thick layers (insulation or thermal mass), the problem is alleviated when a slab is split into thinner parts. This solution is greatly facilitated since the introduction of “active layers” (thermally activated layers e.g. for floor heating). One side effect of adding an active layer into a wall is that the wall is effectively split into two walls on each side of the active layer. In that case Type 56 handles the combination of the two wall parts for output purposes so this represents a user-friendly way of splitting a heavy wall. That method is also compatible with the TRNSYS-3D detailed geometrical mode.

One last workaround is to use one of the dedicated components mentioned above to handle all heat transfer through a particular wall/slab in the building model [5, 10, 14]. This solution requires some intervention from the user to configure the dedicated component, as well as to define and connect the appropriate inputs/outputs of Type 56. It is however the most flexible of the workarounds mentioned here. In most cases it also allows to model special features in the walls that are extracted from Type 56, e.g. encapsulated PCMs. Its main downside is the amount of extra user interaction required if a large number of walls are at hand.

### Improvement to the CTF coefficients generation algorithm

Several solutions have been proposed to improve the CTF coefficients generation process in the literature, e.g. the Hittle and Bishop method [9], time-domain method [4], Seem’s method [19], state-space models [12] or frequency-domain regression [2]. Recent research efforts seem to focus on the last two methods. They tend to be more accurate [15] and could represent

an interesting option to replace the current implementation of the DRF method in Type 56.

In TRNSYS Type 56, CTF coefficients are generated by the building preprocessor interface known as TRNBuild. These coefficients are then stored in a dedicated text file, known as “TRN” file, which is used by Type 56 during the simulation. In order to investigate the potential of replacing or improving the algorithm which is used to generate the CTF coefficients, a set of simulations was run with modified TRN files. CTF coefficients were generated in Matlab by converting reference SS models into a transfer function representation and formatting the generated coefficients to be compatible with the TRN file format. Care was taken to use the corresponding functions in Matlab (c2d to convert the continuous-time state-space model and ss2tf to convert the model into a transfer function representation) with the correct settings to match the TRNSYS convention of calculating the average values over the time-step.

The example developed below is for ICF wall with the scenario 2. The SS approach allowed generating CTF coefficients for a smaller timebase (0.2 instead of 1 hour). The method can be used in Matlab to generate transfer functions with an even shorter timebase, down to 1-min if desired, but the generated coefficients lead to numerical errors in the current version of Type 56. With a timebase slightly under 0.2 h, a bias is introduced in the transient response, and for even shorter values the simulation crashes with infinite surface temperature values.

Figure 6 shows a significant improvement of the stair-step effect when the timebase value is decreased from 1 to 0.2 hours. Figure 7 is a zoom on 3 hours of the simulation and shows that 1 previous stair-step is now divided in 5 smaller stair-steps, increasing in the same time the results accuracy.

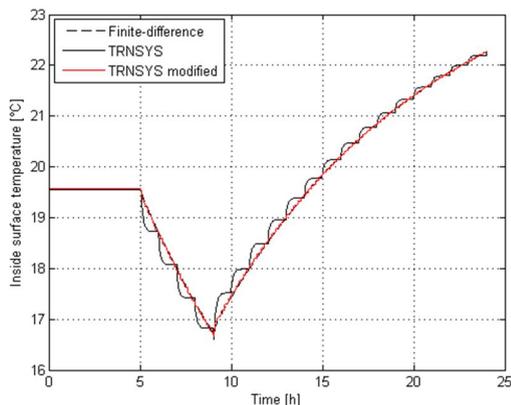


Fig.6: Evolution of the inside surface temperature for an ICF wall (1-hour and 12-minute time bases – scenario 2).

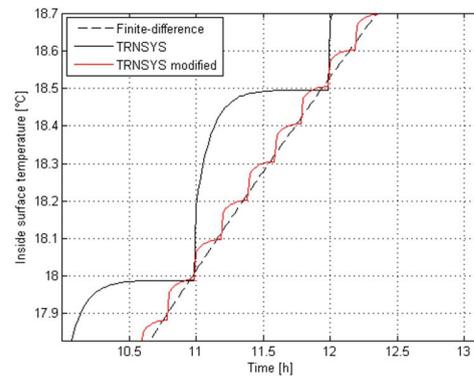


Fig.7: Zoom on the evolution of the inside surface temperature for an ICF wall (1-hour and 12-minute time bases – scenario 2).

The Root-Mean Square (RMS) of the error between the reference solution and the two sets of CTF coefficients values was calculated for both methods: 15.5 % and 2.2 % respectively. This shows that improved coefficients using a timebase of 0.2 h instead of 1 h lead to a reduction of the error RMS by a factor of 7.

## DISCUSSION AND CONCLUSIONS

The current implementation of the CTF method in TRNSYS Type 56 uses coefficients generated by the Direct Root Finding (DRF) method [16]. Our test have confirmed that this method must use relatively long discretization time-steps (known as “timebase” in TRNSYS Type 56) for very thick, or highly insulated walls. We were able to generate coefficients with an hourly timebase for the 3 tested walls in this paper, and reduce the timebase down to 15 and 9 minutes for the DST and SIP walls respectively.

Our results show that simulations using a time-step that is significantly shorter than the timebase lead to a “stair-step” effect in the wall response. This effect is more apparent for very short time-steps (e.g. 1 min) and longer timebase (e.g. 1 hour). The internal interpolation mechanism in Type 56 seems accurate and that simulated response and energy balance are correct at the end of each timebase period.

The stair-step effect can represent a problem for detailed control studies (e.g. demand-side setback strategies) that rely on detailed simulations with a short time-step in the order of 1 minute. Our results show that it is possible to generate improved CTF coefficients with the state-space method and use these coefficients in the current version of Type 56 to obtain a better dynamic response with short time-steps and alleviate the stair-step effect. However, numerical problems arise when the timebase is reduced even further. In the case of our ICF wall, the timebase can be reduced from 1 h to 12 min but not further.



Improving the Type 56 response further for heavy walls and short time steps would require to improve or replace not only the CTF coefficients generation algorithm but also the CTF implementation within Type 56. The state-space method, used e.g in ESP-r [3, 7] and more recently implemented in EnergyPlus [6, 18], is an interesting option that would also allow to represent Phase Change Materials (PCM) encapsulated within the building structure.

Our future work aims at exploring the options to improve the capabilities of Type 56 for short time-steps and modeling PCM within walls. Developed models will be validated against experimental data obtained at the Hydro-Québec facility in Shawinigan, where two identical cottages have been built and fully instrumented.

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