ADVANCED ZONE SIMULATION IN ENERGYPLUS: INCORPORATION OF VARIABLE PROPERTIES AND PHASE CHANGE MATERIAL (PCM) CAPABILITY

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ABSTRACT

EnergyPlus models follow fundamental heat balance principles very closely in almost all aspects of the program. However, the simulation of building surface constructions has relied on a transfer function transformation carried over from BLAST. This has all the usual restrictions of a transformation-based solution: constant properties, and fixed values of some parameters. As the energy analysis field moves toward simulating more advanced constructions, such as phase change materials (PCM), it becomes necessary to step back from transformations to more fundamental forms.

This paper describes the development of an implicit finite difference thermal model of building surfaces that has been incorporated into EnergyPlus. The model simulates the performance of PCM's using an enthalpy or heat content formulation so energy accounting is accurate, and the phase change enthalpy is included fully. The model also permits modeling temperature dependent thermal conductivity. The complete multilayer construction capability of EnergyPlus is retained, so simulations can be done with the PCM in any location within the surface structure. Because of the short time steps used in the finite difference solution algorithm, the zone time step can be reduced to correspond with the one minute minimum time step used by the integrated system in EnergyPlus.

Examples showing the effect of using PCM's in various locations within a wall construction, and examples of the annual energy performance changes caused by such materials are presented.

INTRODUCTION

The surface constructions in EnergyPlus are simulated as layers with one dimensional heat transfer paths through the layers. The traditional way of simulating the heat transfer uses Conduction Transfer Functions (CTF). These are the time series coefficients that describe the transient conduction process with an algebraic equation. The basic form of a conduction transfer function solution is shown by the following equations:

$$q''_{ki}(t) = -Z_o T_{i,t} - \sum_{j=1}^{nz} Z_j T_{i,t-j\delta} + Y_o T_{o,t} + \sum_{j=1}^{nz} Y_j T_{o,t-j\delta} + \sum_{j=1}^{nq} \Phi_j q''_{ki,t-j\delta} \quad (1)$$

For the inside flux, and

$$q''_{ko}(t) = -Y_o T_{i,t} - \sum_{j=1}^{nz} Y_j T_{i,t-j\delta} + X_o T_{o,t} + \sum_{j=1}^{nz} X_j T_{o,t-j\delta} + \sum_{j=1}^{nq} \Phi_j q''_{ko,t-j\delta} \quad (2)$$

For the outside flux.

The subscript following the comma indicates the time period for the quantity in terms of the time step d. Note that the first terms in the series (those with subscript 0) have been separated from the rest in order to facilitate solving for the current temperature in the solution scheme. These equations state that the heat flux at either face of the surface of any generic building element is linearly related to the current and some of the previous temperatures at both the interior and exterior surface as well as some of the previous flux values at the corresponding surface face. EnergyPlus uses a state space method to determine the CTF coefficients. [Seem (1987)]

The CTF solution form reveals both its advantages and its disadvantages. The advantage is that with a single, relatively simple, linear equation with constant coefficients, the conduction heat transfer through a complete layered building surface can be calculated. The coefficients (CTFs) in the equation are constants that only need to be determined once for each construction type.

These features also become the method's disadvantages. Because the coefficients are constants, it is not possible to include temperature dependent thermal properties, and thus behaviors such as a phase change enthalpy or a temperature dependent thermal

conductivity cannot be accommodated. It is also not possible to determine temperatures within the wall surface since the CTF solution spans the surface from the outside face to the inside face.

For high performance building designs, these disadvantages become more important, and the energy analysis of such designs needs to have the disadvantages overcome. In EnergyPlus, this has been done by addition a new solution algorithm that utilizes an implicit finite difference procedure. The implicit nature is necessary because the procedure follows the layer-by-layer formulation of the CTF formulation, and the variability of the layers makes an explicit procedure unacceptable. The iterative nature of the implicit solution also makes it possible to accurately account for the phase change enthalpy when simulating phase change materials. The temperature-enthalpy function for the material is followed exactly by updating the effective material specific heat during each iteration.

ENTHALPY MODEL DEVELOPMENT

The algorithm uses an implicit finite difference scheme coupled with an enthalpy-temperature function to account for phase change energy accurately. The implicit formulation for an internal node is shown in equation 3.

$$\frac{\rho c_p \Delta x \left(T_{i,new} - T_{i,old}\right)}{\Delta t} = \frac{k\left(T_{i-1,new} - T_{i,new}\right)}{\Delta x} + \frac{k\left(T_{i+1,new} - T_{i,new}\right)}{\Delta x} \quad (3)$$

Subscripts refer to nodes and applicable time step.

The node arrangement within the surface layers is shown schematically in Figure 1.

Then, Equation (3) is accompanied by a second equation that relates enthalpy and temperature.

$$h_i = f_{ht}\left(T_i\right) \quad (4)$$

Where f_{ht} is an enthalpy-temperature function that uses data supplied as input.

Equations such as 3 and 4 are formed for all nodes in a construction. Because adjacent layers could consist of a phase change material and a regular material, the grid is set automatically layer by layer to make sure that the phase change enthalpy is accounted for properly. The grid is established with half nodes at each edge of the layer and equal sized nodes for the rest of the layer. The formulation of all node types is basically the same; there are four types: external surface nodes, internal surface nodes, internal nodes such as shown above, and then nodes occurring at the material interfaces. The material interface nodes are formulated to allow for a phase change material on either side or both sides, but are fundamentally the same as described above. Because the solution is implicit, a Gauss-Seidell iteration scheme is used to update to the new node temperatures in the construction. Because of this, the node enthalpies get updated each iteration, and then they are used to develop a variable c_p if a phase change material is being simulated. This is done with an additional equation for c_p.

$$c_p = \frac{h_{i,new} - h_{i,old}}{T_{i,new} - T_{i,old}} \quad (5)$$

The iteration scheme assures that the correct enthalpy, and therefore the correct c_p is used in each time step, and the enthalpy of the material is accounted for accurately. Of course, if the material is regular, the user input constant c_p is used. This effective specific heat procedure is a modification of an enthalpy based procedure (Pedersen 1972). This procedure overcomes the disadvantage of some simulation procedures that incorporate a variable specific heat that is based on the node temperature. In such simulations, it is possible to jump completely over the phase change temperature range and miss the phase change enthalpy altogether.

CONSTRUCTION SIMULATION DETAILS

The user is required to supply temperature enthalpy data for the phase change material. This is supplied in a tabular form as shown in table 1.

Table 1 Enthalpy Temperature Data

Temperature, C	Enthalpy, J/kg-K
-20.	0.
28.	58080.
28.4	127726.
100.	214362.

This represents the enthalpy for a polystyrene insulation filled with 30% encapsulated Octadecane (C18) Paraffin (Lee, 2005). The 0.4 C range for the phase change was used just to show the tabular function. Any small fraction of a degree could have been used.

The tabular data is interpreted within the program as shown in Figure 2.

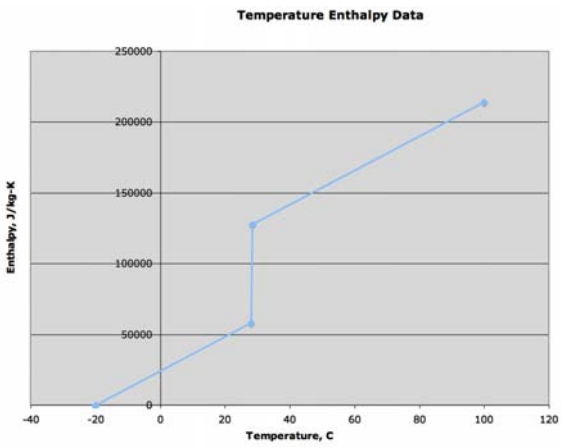

Figure 2, Temperatue-Enthalpy

BEHAVIOR OF WALLS WITH PCM

Phase change materials are incorporated into wall constructions either concentrated in a thinner layer at the surface of the construction or distributed throughout a thicker construction layer.

Looking first at the distributed layer configuration, a horizontal roof construction consisting of a single layer of polystyrene insulation with 30 % encapsulated paraffin pellets. Using the C18 paraffin described previously in a 20 cm thick wall, the temperature distributions throughout the layer with and without the PCM are shown in Figures 3 and 4. The simulation environment was a design day for Minneapolis MN, USA. The figures show the node temperature details in the layer, and it is easy to see the flat temperature profiles while the nodes are passing through the phase change. It is also interesting to note how the flattened temperature regions are communicated to the adjacent nodes.

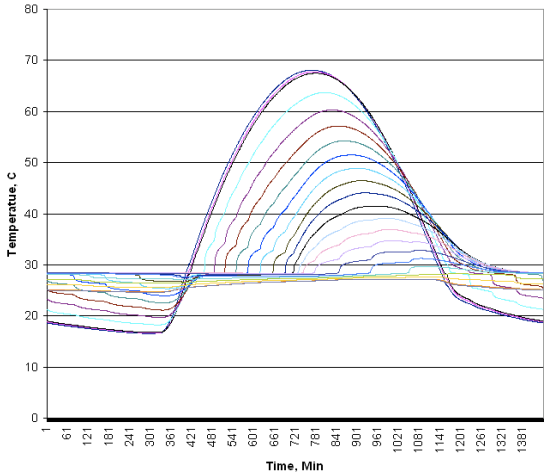

Figure 3, Node Temperatures With Distributed PCM.

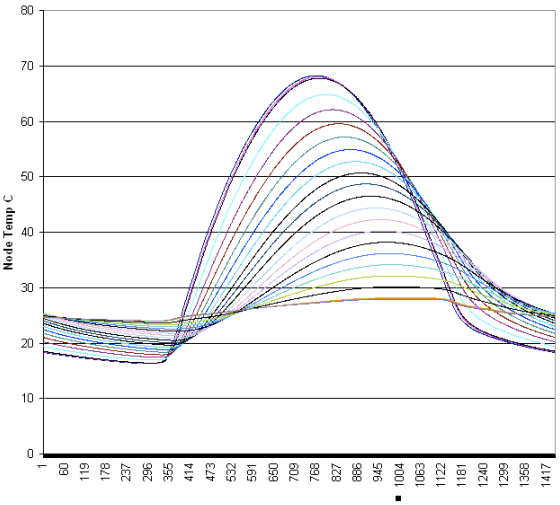

Figure 4, Node Temperatures Without PCM

To show the flexibility of the simulation, a case where only the outside layer of the wall surfaces was a PCM material. The resulting node temperatures are shown in Figure 5. The outside layer had three nodes, and their flat temperature profile while undergoing phase change is clear.

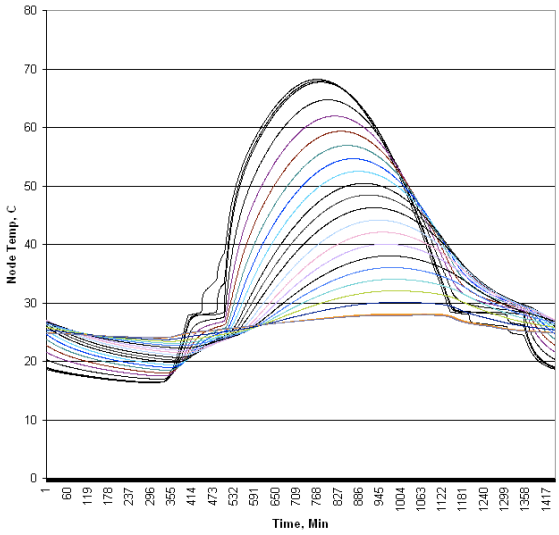

Figure 5, Node Temperatures with PCM in Outside Layer

Using a small building of 140 square meters having all surfaces of the same polystyrene layer construction , the simulation was performed with the traditional CTF solution algorithm, the finite difference algorithm, and the finite difference algorithm with the PCM layer replacing the polystyrene layers. The building had nominal gains, windows in all vertical surfaces, and a 24 C setpoint. The results are shown in Figure 6.

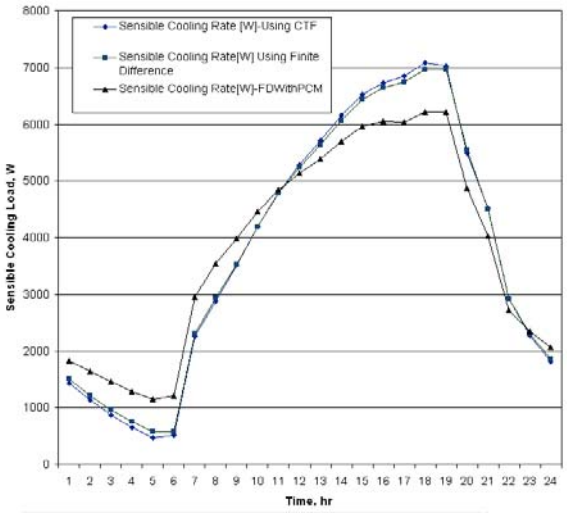

Figure 6, Comparison of Solution Algorithm and PCM Effect.

The finite difference solution and the CTF solution show close agreement. The small differences arise because the CTF solution used a zone time step of ten minutes, and the finite difference algorithm used a one minute zone time step. Results were averaged over one hour intervals. The PCM lowered the peak cooling load by nearly 1000 W.

SEASONAL PERFORMANCE WITH PCM CONSTRUCTIONS

It is clear that the phase change material in walls changed the temperature profile behavior, and many times that is taken as a justification for incorporating the phase change material. However, the advantage of having this simulation capability in a detailed energy simulation program is that the energy effects and also other effects such as comfort calculations can be accessed.

If we first consider the same building described before, but move it to Denver CO where the daily temperature profile is more favorable for phase change materials, the average monthly cooling rate for the summer months as shown in Figure 7. It is interesting to see that the effect on cooling energy is negligible. This shows that it is important to evaluate such things as phase change materials over an extended period. It should be noted that this is just a simple example, with specific conditions, and in no way indicates that phase change materials will not have a positive energy effect in Denver. What it does mean is that the careful design of high performance buildings is essential, and just including some feature that looks favorable in a daily analysis may not have the desired effect.

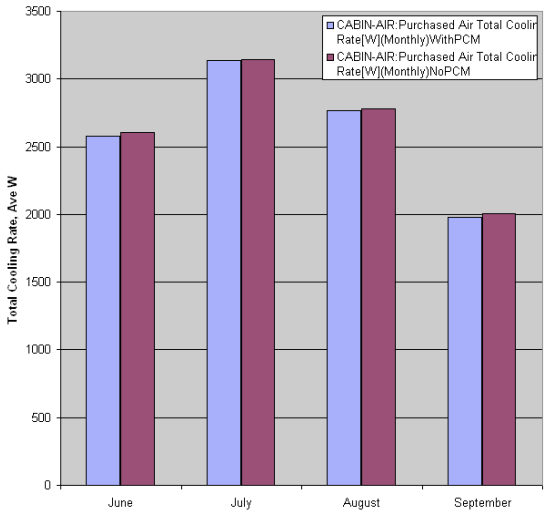

Figure 7, Monthly Average Cooling Rate

It is also interesting to look at the effect of PCMs on the comfort in the building. Figure 8 shows the monthly hours not comfortable for the summer months in Denver. Looking first at the months of July an August, it is clear that the PCM had a positive effect on reducing the number of hours not comfortable. In the cases of June and September, the hours not comfortable include some periods where the building was too cold since it had no heating system in this simulation. Again, it shows it is very important to perform a careful analysis of any simulation results, and not draw incorrect conclusions.

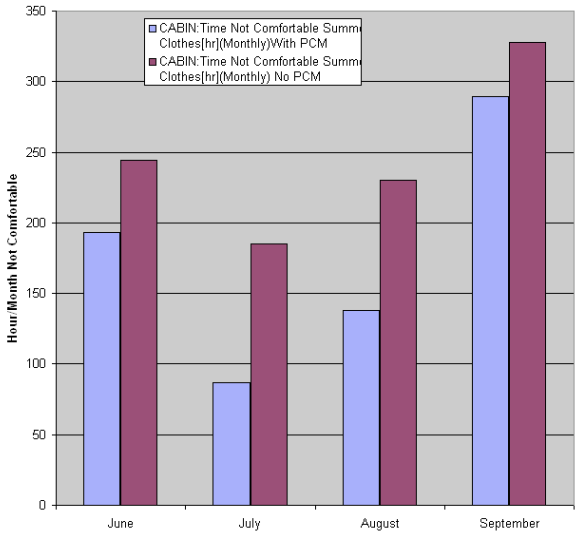

Figure 8, Monthly Hours Not Comfortable, Denver CO

DISCUSSION OF RESULTS

The results shown in this paper are only intended to show some of the capabilities of the finite difference solution algorithm that is now included in EnergyPlus. They are not intended to show proper application of phase change materials in building construction. However, it is clear that the application of a complete building simulation program is useful for obtaining an understanding of the interactions involved.

CONCLUSIONS

Current investigations of the effect of PCM layers are considering configurations with the PCM layer on the inside of the building structure surface and also with the PCM distributed through the structure surface. This paper has shown that the algorithm incorporated into EnergyPlus can simulate the PCM in any location while maintaining all the other aspects of a detailed energy simulation. The scheme of carrying the node enthalpy along with the simulation has proven to be very robust, and provides a completely accurate accounting for the phase change enthalpy. Because of the extreme variability of the layers of a building surface construction, the implicit numerical solution has been found to be the most flexible.

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