Thermal Wall Analysis

Brandon S. Field, PhD
Associate Professor of Engineering
University of Southern Indiana
bsfield@usi.edu
812-464-1882

March 15, 2016

1 Introduction

The purpose of this report is to validate the calculations for the potential application of Thermal Wall Technology. At the heart of this technology is the use of insulated concrete forms (ICF) as a location for thermal storage, with a hydronic solar-thermal system to collect and distribute the solar energy. This combination of technologies has a good potential for energy savings.

It is not the intent of this report to validate the solar collector system, nor to produce a complete transient storage model. These should be done before the final design is developed, but none of the control systems being demanded by this project are more complex than existing commercially available systems. In this report, a one-dimensional, transient heat flux model is used to show the effect of storing thermal energy in the concrete walls and how the one-sided ICF walls will react when subjected to these heat fluxes. Radiation effects are not considered by the model, and neither are the potential for zoning the different walls to enhance the thermal storage. In addition, the model hydronic system is not extended to the concrete floors, which means that the advantages of the thermal storage are under-predicted by the model. This is because the maximum wall temperatures of the stored energy, discussed below in Section 4.2 are higher in the model than they would be in real life because the floors are neglected, and therefore the total heat loss is over-predicted. All of these simplifications can be accounted for in the future to better design the exact layout and control methodologies for the houses, but including a model of the thermal storage in the floor would involve including a model of internal space and at least a rudimentary control element, which is more complex than was needed for this demonstration.

In this report, it will be demonstrated that the Thermal Wall Technology has good potential to contribute to an energy-efficient design by using solar thermal collectors for space heating, even for extreme outdoor air temperatures. The outdoor temperature considered here (0 °F) was chosen to give the worst-case performance; on warmer days, the thermal performance would be improved.

2 Basic Equations

The mode of heat flow through a solid is known as thermal conduction. The ability of different solids to conduct heat is characterized in the material property of thermal conductivity, usually represented with the variable k. For insulating materials, the resistance of a material to thermal conduction is the thermal resistivity, or R-value of a material, which is the reciprocal of k:

$$R = \frac{1}{k} \tag{1}$$

The advantage of using R-values is that with multiple layers of different materials, the total thermal resistance, R_{tot}, is the sum of the R-values of all the different layers.

Even convection — the transfer of heat from a solid to a liquid or to air — can be given a thermal resistance, and this is commonly done in the process of getting a total thermal resistance that spans all the way from the interior air temperature to the exterior air temperature.

The rate at which heat moves through a material is given the variable $\dot{Q}$ and is measured in Watts or in $\frac{\mathrm{BTU}}{\mathrm{hr}}$, which are commonly denoted BTUh. The total heat flux through a wall of frontal area A is then:

$$\dot{Q} = \frac{A\Delta T}{R_{tot}\Delta x} \tag{2}$$

where ΔT is the difference in temperature across the two sides of the wall (air temperatures, if R_{tot} includes the air gaps on both sides) and Δx is the thickness of the wall. The amount of energy, Q, lost through the wall in the amount of time Δt would then be:

$$Q = \frac{A\Delta T}{R_{tot}\Delta x}\Delta t \tag{3}$$

As thermal energy is stored in a material, the temperature of that material will increase. The amount of thermal energy that causes a specified temperature increase depends on the material's specific heat, a material property denoted by the variable c_p. The thermal energy, Q, stored in a material is governed by the equation:

$$Q = mc_p\Delta T \tag{4}$$

where m is the mass of the material, and ΔT is the temperature difference of the material before and after the thermal energy is stored.

3 Thermal Model

3.1 Material Properties

The various materials that are used in this analysis are common ones to ICF construction.

EPS plastic is to be the insulation layer, and several different types of EPS could be used. For this analysis, we will use EPS that has a specific heat of $c_p = 1500 \frac{\text{J}}{\text{kg K}} = 0.3583 \frac{\text{BTU}}{\text{lb-°F}}$, a thermal conductivity of $k = 0.0318 \frac{\text{W}}{\text{m K}} = 0.237 \frac{\text{BTUh-in}}{\text{°F-ft}^2}$, or a thermal resistance of $R = 4.22 \frac{\text{°F-ft}^2}{\text{BTUh-in}}$, and a density of $\rho = 2 \frac{\text{lb}}{\text{ft}^3}$.

The concrete layer will be poured at a density of $\rho = 150 \frac{\text{lb}}{\text{ft}^3}$, which gives a thermal conductivity of $k = 13.8 \frac{\text{BTUh-in}}{\text{°F-ft}^2}$, or $R = 0.0725 \frac{\text{°F-ft}^2}{\text{BTUh-in}}$, and has a specific heat of $c_p = 0.2 \frac{\text{BTU}}{\text{lb-°F}}$.

The thermal resistance for the exterior layer of air around the house is $R = 0.17 \frac{\text{°F-ft}^2}{\text{BTUh-in}}$, and for the air layer on the interior of the house $R = 0.68 \frac{\text{°F-ft}^2}{\text{BTUh-in}}$. These values are within the accepted range for convective losses — the exterior has lower thermal resistance to account for the outdoor winds that contribute to heat loss.

3.2 Model of ICF Wall

A transient, one-dimensional, finite-difference model was developed of the ICF wall in order to demonstrate the magnitudes of the heat flux through the wall. An exterior temperature of 0 °F was used to represent an extreme outdoor temperature that the house would experience. An interior temperature of 72 °F was used for comfort. Thermal resistances to convection were applied to the air flow on the interior and exterior of the wall.

In the two-sided model, the traditional ICF wall of 2.5 inches of EPS insulation on either side of an 8 inch poured concrete was used. In the one-sided model, 5 inches of EPS insulation was put on the outside and 8 inches of concrete was put on the inside of the wall.

To account for heat addition through the hydronic system, a heat flux was applied to the middle of the concrete layer. As will be shown, this is only helpful for heating the interior of the home when the one-sided ICF form is used.

For the finite difference model, the 13 inch wall is divided into 29 elements, with each element being $\Delta x = 0.464$ inches. The time-dependent aspect of the model was given a time step of $\Delta t = 0.1$ seconds, and the temperature profile was solved by using energy balance equations at each time step to model the transient response of the wall.

4 Analysis of Thermal Wall

4.1 Overall Heat Flow

Either configuration of the ICF wall (one-sided or two-sided) will result in the same overall heat flow through the wall, because the total thermal resistance is the same no matter what order the layers come in. The steady state temperature profiles in each wall configuration are shown in Figures 1 and 2. The total heat lost in these cases is 75.2 $\frac{\text{BTU}}{\text{ft}^2}$ over a 24-hour period. The discrepancy between this value and the 79.08 $\frac{\text{BTU}}{\text{ft}^2}$ per day in Section 1 of the provided Excel spreadsheet is from the addition in this model of the convection resistance on the interior of the wall.

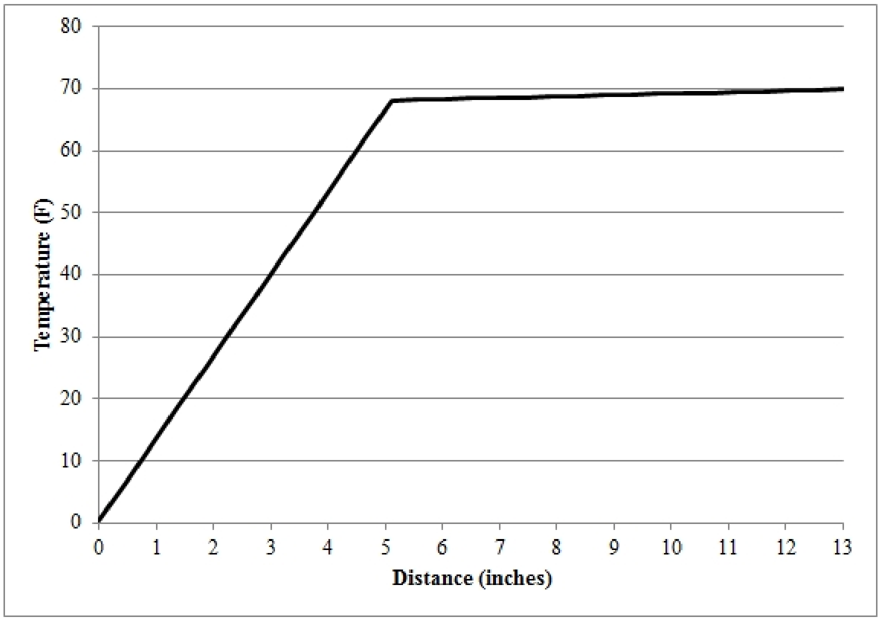

Figure 1: The steady state temperature profile of the ICF thermal wall with all 5 inches of EPS insulation on the exterior. Indoor temperature is 72 °F, outdoor temperature is 0 °F.

Over the entire 4440 ft^2 of wall area for the entire house, this would result in a total energy loss of 334000 BTU per day, which will be compared later on to the total energy available per day from the solar thermal collectors.

4.2 Solar Input

The calculations of solar energy collected by the hydronic collectors is shown in Section 2 of the provided Excel spreadsheet. A heat flux of 51,840 BTUh is collected by the solar thermal system during the six hours of available sunlight, and that amount is applied to the model

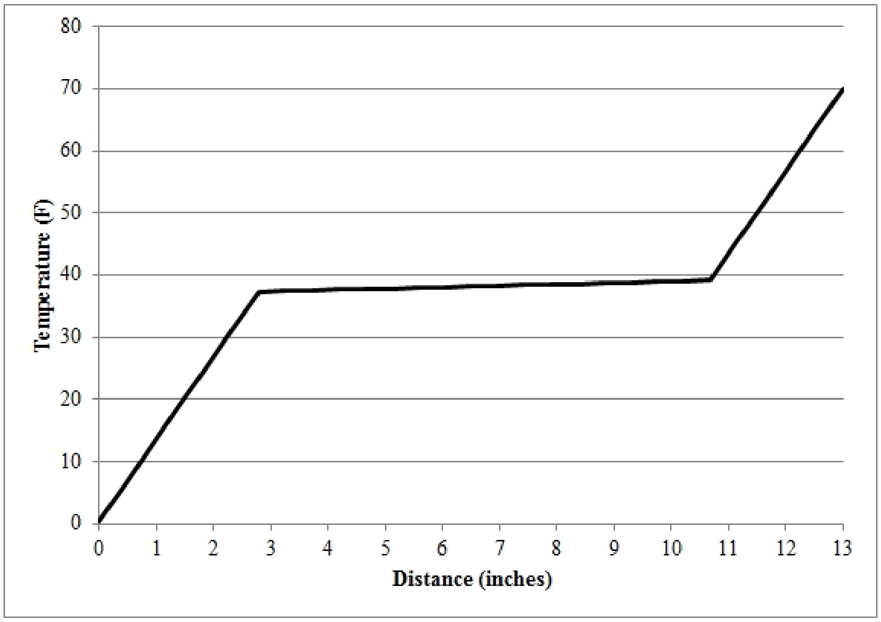

Figure 2: The steady state temperature profile of the ICF thermal wall with 2.5 inches of EPS insulation on the interior and exterior. Indoor temperature is 72 °F, outdoor temperature is 0 °F.

at the center of the 8 inch concrete layer of the walls. A simplification of this model is that this energy is applied throughout all the walls of the house, but not to any of the concrete floors. Another simplification is that the additional 413,831 $\frac{\text{BTU}}{\text{day}}$ of passive solar energy that enters the house through the south-facing windows is not applied to the walls at all, because the interior of the house is treated as a constant 72 °F. In reality, the passively-collected energy would contribute to maintaining the interior temperature of the house, and the floor would be used as a storage element. However, in order to model this, a more sophisticated model that includes the interior thermal mass of things like furniture would need to be run. With these simplifications, the heat loss from the walls will be over-predicted. For the final house design, the floor storage and control system will have to be modeled to develop the optimum mixture of floor and wall storage.

At the end of the six hours of sunlight, the thermal energy that was collected results in a wall temperature profile shown in Figures 3 and 4. This is for the one-sided ICF thermal wall; the inability of the two-sided configuration to work in this application is shown in the following section. Figure 3 shows the overall wall, and Figure 4 is a zoomed in graph that shows the temperature profile in only the concrete. The elevated temperature in the center of the concrete and the downward slope to the right side of the wall indicates that the thermal energy is delivering heat to the interior of the house.

Figure 3: The resulting temperature profile of the thermal wall after six hours of solar energy storage. Indoor temperature is 72 °F, outdoor temperature is 0 °F.

Since the thermal energy collected is not being applied evenly through the whole house, the maximum temperature within the wall is higher than the 77.12 °F calculated in Section 3 of the provided Excel spreadsheet which treated all the concrete as being a uniform temperature. In addition, the peak temperature is closer to the outside of the wall than it was in the calculations in Section 4 of the spreadsheet, which applied the elevated temperature to the interior surface of the wall and over-estimated the insulation. However, this only resulted in a 2% difference in the heat flux between the model and the spreadsheet.

Using the model, the heat flux from the wall that is fully-loaded with 6 hours of solar thermal energy is shown to be 86.64 $\frac{\text{BTU}}{\text{ft}^2}$ per day, instead of the 84.72 $\frac{\text{BTU}}{\text{ft}^2}$ per day calculated in Section 4 of the Excel spreadsheet. This represents a 15% increase in the total thermal loss, compared to the 75.22 $\frac{\text{BTU}}{\text{ft}^2}$ per day of the ICF walls without solar thermal energy collected. In order to estimate the amount of additional thickness of EPS insulation that would bring the heat loss back down to the level, the temperature of the concrete surface is considered. After six hours of solar flux, the exterior surface of concrete reaches 78.5 °F. In order to achieve a heat flux of 75.22 $\frac{\text{BTU}}{\text{ft}^2}$ per day, a thickness of 5.93 inches of EPS would be needed, or a 0.93 inch (18%) increase in the thickness of the insulation layer. This thickness is slightly more than actually would be needed, because in the actual case, the added insulation would also be applied to the wall during the collection phase, and would

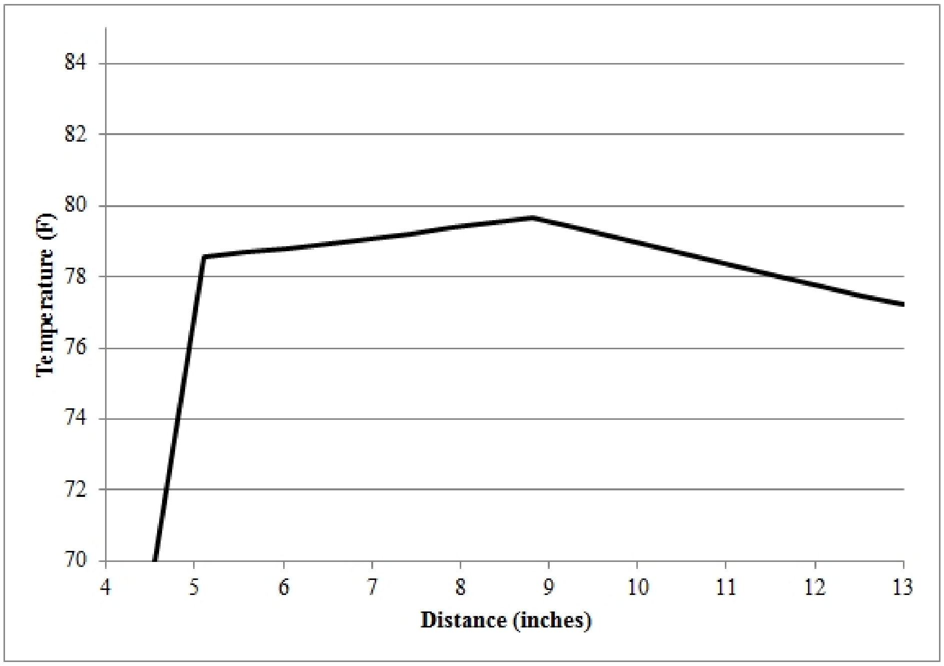

Figure 4: The portion of the temperature profile shown in Figure 3 that includes the concrete only. The elevated temperature profile indicates that the wall is providing heat to the indoor space (which is at 72 °F).

have contributed throughout the whole six hours of collection. Re-running the transient model with a new wall thickness was not done.

It is important to note that this increased thermal loss does not take away from the energy that is inside of the house, because this is energy that was collected from the solar thermal system. In other words, in the house without the solar thermal collectors *all* of the solar energy would be lost, whereas by storing the solar energy in the walls without an increase in the insulation layer, the energy loss increases slightly but none of that energy is being collected in the original case.

4.3 Two-sided vs. One-sided ICF

Sections 5, 6, and 7 of the provided Excel spreadsheet were intended to calculate the increased ability of the ICF wall to communicate with the indoor space by putting all the insulation on the exterior portion of the wall. In the spreadsheet, an increased temperature was calculated based on the premise that all the solar thermal energy was placed in the concrete uniformly and that heat was allowed to communicate back with the interior space through half of the wall. However, the assumption of a uniform temperature profile results in an error in this case. With half of the insulation layer placed between the concrete and the indoor space, the

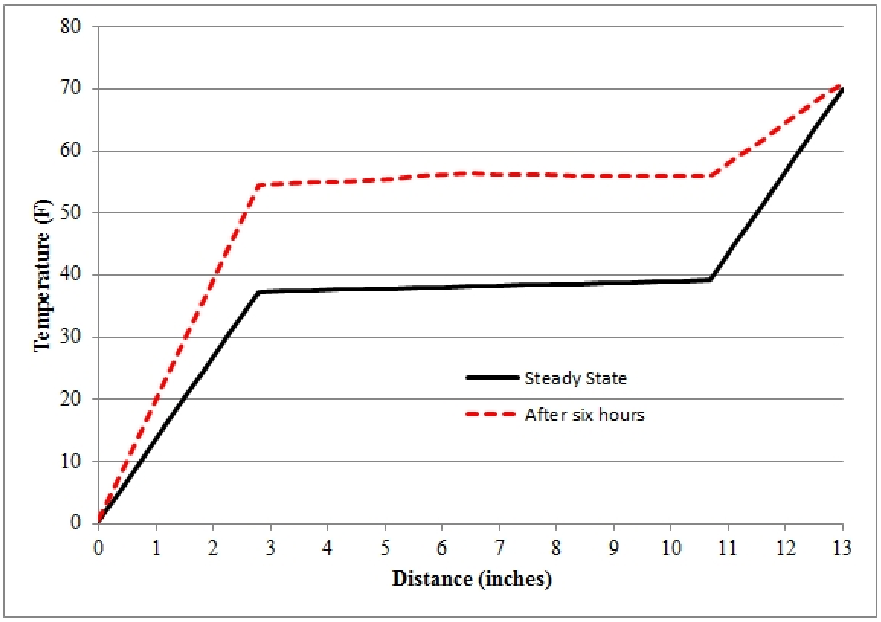

Figure 5: Temperature profiles for the traditional two-sided ICF wall configuration before and after six hours of thermal energy collection. Outdoor temperature at 0 °F, indoor temperature at 72 °F. The addition of the stored solar thermal energy into the concrete layer does not increase the temperature of the concrete layer sufficiently to transfer the stored heat into to the indoor space.

concrete portion of the walls are no longer at the indoor temperature. When the solar energy is placed in the concrete forms, the temperature rises, but unless the outdoor temperature is warm enough, that amount of energy will not be sufficient to raise the wall to a sufficient temperature to communicate with the indoor space at all.

This is illustrated in Figure 5. The initial temperature profile (shown as the solid black line) is the same seen previously in Figure 2, with an outdoor temperature of 0 °F. The dashed red line shows the temperature profile after six hours of stored energy. It can be seen from this plot that the interior surface of the wall (at 13 inches) never increases above the 72 °F indoor temperature, and therefore the heat stored in the two-sided ICF wall will never communicate with the interior space. If the outdoor temperature were less extreme, the temperature profile would not be so steep, and there would be a point at which the stored heat *would* be able to communicate inward. The model can be used to determine this point, but from just a linear displacement it appears that an outdoor temperature of 32 °F would be more than sufficient. However, it is clear from comparing the temperature profiles that the one-sided ICF wall would be the desired configuration for the purposes of energy storage.

5 Conclusion

5.1 Findings

A model of the Thermal Wall Technology has been developed to map the transient temperature profiles of the wall resulting from a solar thermal collection system. The results of the model are slightly more sophisticated than the calculations performed in the provided Excel spreadsheet, however the overall conclusions are the same.

The addition of the solar thermal energy would result in an increased energy loss of 15% in the extreme case of an outdoor temperature of 0 °F. Using a simplified calculation, an addition of 0.93 inches of EPS insulation would reduce that level to an equivalent level without the stored energy, however that amount of insulation would be overkill unless the outdoor temperatures are regularly that low.

The one-sided configuration of the ICF wall, with 5 inches of insulation on the exterior of the wall, would be desired to enable the stored energy to be transferred back into the indoor space. With the traditional two-sided ICF wall configuration, an outdoor temperature of 0 °F is too low for the stored energy to be used to heat the indoor space.

The final design of the thermal wall will need to include the amount of tubing, the tube spacing within the wall, the desired location of the tubes in the wall, the effect of radiative heating and cooling to and from the wall, and transient effects of things inside the house. These can be easily considered by making the current model slightly more sophisticated.

5.2 Observations about Thermal Wall Technology

I feel as though a few observations should be made about the potential of this configuration for energy savings in houses. The use of solar thermal energy is advantageous for space heating, and based on the simple models presented here, the stored thermal energy in the walls from the active collection system is delivering energy to the interior of the house for about least 5 hours with this extreme outdoor temperature. Including the passive collection, which would double the total thermal energy collected directly contributing to the temperatures of the internal space, and by storing some of the actively-collected thermal energy in the floor of the house, where it is not lost to the outside, this amount of time should be more than double the model results.

A simple unit conversion reveals that the 311040 $\frac{\text{BTU}}{\text{day}}$ energy that the solar collectors will deliver to the house each day is equivalent to 91 kWh, or 3.1 therms, of energy.

Including the additional 413,831 $\frac{\text{BTU}}{\text{day}}$ of passively-collected thermal energy into the home, the home has the potential of being heated completely by solar energy, especially in areas with less-extreme temperatures, because of the storage capacity of the thermal wall. A portion of the thermal energy collected from the active system could also be used for other heating purposes, such as domestic hot water. The use of solar energy always depends on the ability to store that energy for use when the sun goes down, and this thermal wall system, especially in conjunction with thermal storage in the floor, where it not lost to the outdoors and with a hydronic system that can control where the thermal energy is going and being taken from, is an exciting development in home energy.