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ABSTRACT

The modeling of the three-dimensional heat transfer characteristics of thermal storage walls and the effect of nonuniform irradiation is investigated. Depending on how much of the wall is irradiated, a small error in energy storage is introduced with the one-dimensional, uniform irradiation assumption. The results show that these assumptions, currently used in most passive design codes, are adequate to predict the thermal energy storage characteristics. However, the temperature distribution along the surface of the wall is much different when the nonuniform irradiation case is considered. The addition of a highly conductive metal cover on the front surface of the wall does not significantly improve the thermal energy storage characteristics of the wall when the wall is partially irradiated. A selective radiation coating reduces front losses and improves the energy storage capacity of the wall 9-13%.

1. INTRODUCTION

Thermal storage walls are important and common in passive solar building designs. They have been examined using a number of simplified heat transfer models. These models generally treat the wall as a one-dimensional heat transfer problem with uniform heat input and use constant heat transfer coefficients over the entire surface area of each face of the wall. It has not been shown that such simplifying assumptions are justified.

This paper numerically investigates the three-dimensional heat transfer characteristics of both conventional and composite thermal storage walls. The effects of nonuniform heat input and convective film coefficients that vary both with position and wall temperatures are examined. Also, in an attempt to reduce energy losses from the front surface during charging, a highly conductive metal front cover attached to the wall is investigated with and without selective radiation coatings. The analysis of the multimode, three-dimensional heat transfer phenomena that this study addresses is made possible by the use of the generalized heat transfer program MITAS [1], developed by the aerospace industry.

The results of the investigation indicate that the conventional one-dimensional, uniform irradiation assumptions made by currently available passive design codes are adequate to predict the thermal energy storage characteristics of mass walls. However, the temperature distribution between the uniformly and nonuniformly irradiated cases studied are quite different. This indicates that three-dimensional analysis may be necessary in cases where realistic temperature distributions are necessary. Addition of a highly conductive metal front cover to the wall does not significantly reduce energy losses from the front surface, nor does it improve the thermal storage characteristics of the wall. However, addition of a selective radiation coating reduces the front losses off the wall and improves its energy storage capacity by about 9-13%.

2. DESCRIPTION OF THE MODEL AND SIMULATION METHOD

The 152-node thermal network model used to investigate the behavior of a mass storage wall is depicted in Fig. 1, along with a resistance/ capacitance network schematic of a general node on the wall surface. The network is described using three types of nodes: diffusion, arithmetic, and boundary. Diffusion nodes have thermal capacitance and have the ability to store energy. The future temperature of these nodes are computed by a finite-difference routine representing the diffusion partial differential equation. The arithmetic nodes have no thermal capacitance and thus no ability to store energy. Their future temperatures are computed by a finite-difference routine representing Poisson's partial differential equation. MITAS has three transient execution routines available to solve the finite-difference network: forward, backward, and central differencing. The explicit forward differencing technique is used for this study because it has the least energy imbalance and smallest computer run time for the number of nodes and the solution time step chosen. The time step used for the solution is three minutes. This is well below the minimum time step necessary to satisfy the forward differencing stability criteria of 12 minutes for the cases involving a metal front cover. Radiation conductors are not linearized. The execution routine solves an explicit quartic equation on nodes with radiation conductors. Both the small time step and manner in

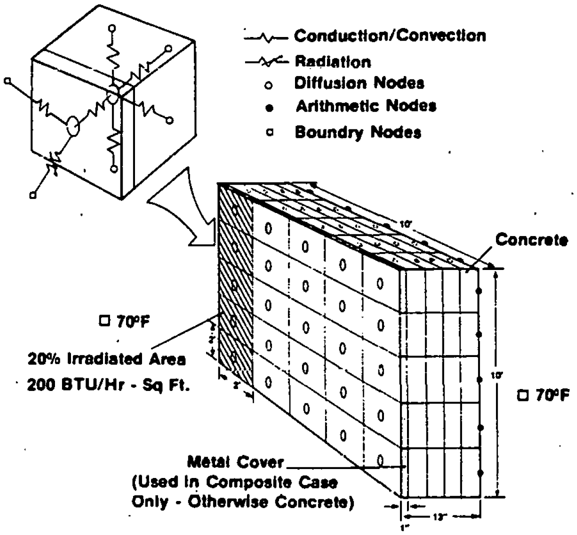

Fig. 1. Mass Wall Thermal Network Schematic. The 152-node thermal network model used in this study to investigate the performance of thermal storage walls is shown (a) along with a resistance/capacitance schematic of a surface node on the left edge of the wall.

which the radiation conductors are handled add to the stability and convergence of the solutions obtained. An integral energy balance is computed every time step by summing the wall heat losses and net energy storage and subtracting the total heat sources applied to the wall. This system energy imbalance is less than one percent of the heat sources applied to the wall.

The resistance elements shown in the schematic represent conduction, convection, and radiation couplings in the network. A constant absorbed heat flux of 200 Btu h^{-1} ft^{-2} is applied to various areas of the front surface (20%, 60%, 100%) for the first six-hours of the simulation. After this six hour charging period, no heat flux is applied and the wall is allowed to discharge for the next 18 hours. The convection conductors were evaluated every time step using the average natural convection constant temperature correlations [2]:

$$\overline{Nu} = 0.59 \ (Gr_L \ Pr)^{0.25},$$

$$10^4 \leq Gr_L \ \ Pr \leq 10^9 \quad \text{(laminar)},$$

$$\overline{Nu} = 0.13 \ (Gr_L \ Pr)^{0.333},$$

$$10^9 < Gr_L \ \ Pr \leq 10^{12} \quad \text{(turbulent)},$$

where Gr_L is the Grashof number based on the total height of the wall and an average surface temperature of the five surface nodes along the height of each of the five vertical strips. The Prandtl number, Pr, of air is assumed constant at 0.72, and $\overline{Nu}$ is the average Nusselt number. The convection coefficient is calculated from the average $\overline{Nu}$ and applied to each of the five individual nodes along the strip.

The radiation coupling coefficients are calculated from $\epsilon A \sigma$, where ϵ is the surface emissivity, A is the nodal area, and σ is the Stefan-Boltzmann constant (1.713 x 10^{-9} Btu h^{-1} ft^{-2} $°R^{-4}$). This assumes the gray-body approximation for radiation to a black-body environment with a view factor of 1. The conduction couplings are calculated from KA/L, were K is the material thermal conductivity, A is the cross-sectional area for heat transfer, and L is the path length separating node centers. The same network is used both for concrete and metal front surfaces. The only change is the conductivity of the front surface node couplings between the two cases. An identical thermal capacitance for these nodes (one-inch concrete) is used in all cases. This is done because the objective of this analysis is to compare the thermal storage enhancement due to a highly conductive front surface material and not an increased capacitance effect. Table 1 lists the thermophysical properties used in the simulation.

Both front and back face boundary temperatures are held constant at 70°F. The back face is allowed to radiate and convect to the boundary node using a constant emissivity of 0.8 and a constant convection coefficient of 0.4 Btu h^{-1} ft^{-2} $°F^{-1}$. Detailed temperature-varying calculations of the convective heat transfer coefficients on the back

Table 1. THERMOPHYSICAL PROPERTIES USED IN MODEL

Component	Material	Emissivity	Density (LBM ft^{-3})	Thermal Conductivity (Btu h^{-1} ft^{-1} $°F^{-1}$)	Specific Heat (Btu LBM^{-1} $°F^{-1}$)
Wall	Concrete	0.8	131.8	0.76	0.21
Cover	Aluminum	0.8^a	131.8^b	110.0	0.21

[a] 0.2 used in selective surface studies.
[b] Same as concrete (see text).

surface have very little influence on the comparative results and thus are not warranted. An energy balance summary as well as nodal temperatures are printed out at hourly intervals for each case simulated.

3. RESULTS

3.1 Uniform Irradiation Assumption

The first simulations investigate the uniform irradiation assumption on the homogeneous concrete storage walls. The model is run for 20% and 60% of the wall irradiated discretely, starting from the left edge of the wall and moving to the right. The model is then run using the identical total heat input as in the 20% and 60% cases, but uniformly applying the heat to all the front surface nodes. The results of this case are shown in Figs. 2a and 2b, where the integrated net energy stored in the wall, normalized to the incident radiation, is plotted versus charging time. Figure 2c shows the integrated six-hour normalized storage value versus percent area irradiated. The discrepancy in the uniform irradiation assumption is greatest for the 20% irradiation case, where approximately 7% less storage is noted at six hours for the discretely irradiated case. This effect is almost entirely due to convection loss. In the case of uniform irradiation, the entire surface area is at a modest uniform temperature of 83°F at six hours. The $Gr_L Pr$ for this case is in the lower range of the turbulent regime, slightly over 10^{10}, with a resulting film coefficient of 0.53 Btu h^{-1} ft^{-2} $°F^{-1}$. In the discretely irradiated case, the irradiated strip is at 129°F and the remaining area of the front surface is still near the initial 70°F at six hours. The first strip has a $Gr_L Pr$ number of 10^{11}, resulting in a film coefficient of 0.84 Btu h^{-1} ft^{-2} $°F^{-1}$. The total convection loss rate for the discretely irradiated case is 30% higher, for the whole surface, than the uniform irradiation case at six hours.

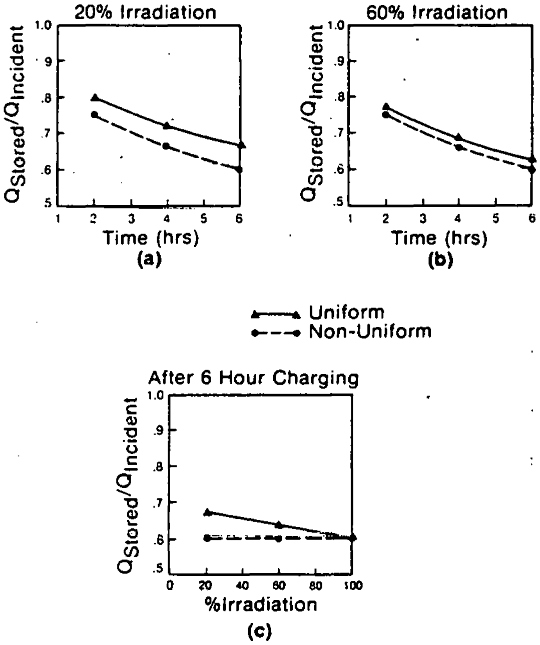

Fig. 2. Effect of Nonuniform Irradiation. Most passive models assume that when solar radiation is applied to a storage wall, the energy is distributed uniformly on the surface. The effect of this assumption is shown for cases where (a) 20% and (b) 60% of the wall surface is irradiated discretely with 200 Btu h^{-1} ft^{-2}. In the uniform cases depicted above, an equivalent heat flux of 40 Btu h^{-1} ft^{-2} and 120 Btu h^{-1} ft^{-2}, is distributed uniformly over the entire wall surface for the 20% and 60% cases, respectively. Each value represents the integrated energy stored normalized to the incident energy. Figure 2(c) shows the stored energy as a function of percent irradiation integrated over a six-hour charging period.

The difference in energy stored is more predominant in the 20% irradiated case because the assumption between discrete and uniform irradiation has its largest disparity in this case. As irradiation time increases and surface temperatures continue to rise, the effect becomes more apparent. This is shown in Fig. 2a, where the discrepancy in integrated energy stored at two hours (4%) is less than the difference at six hours (7%). The radiation loss in the discrete case is also increased above the uniform case (3% at six hours) because of the elevated temperatures, but not nearly as significantly as the increased convection loss.

Normalized energy stored during the discharge cycle is shown in Figs. 3a and 3b. Discharge is unaffected by the irradiation assumption during charging, with the exception that there is slightly more energy available in the wall if the uniform assumption is used.

3.2 Composite Walls

A highly conductive (one-inch thick aluminum) metal surface is simulated as the front cover of the mass storage wall in an attempt to reduce surface temperatures by spreading the absorbed energy over more of the storage wall surface during periods of partial irradiation. It is hypothesized that reduced surface temperatures will lead to a reduction in front surface heat loss and a corresponding increase in wall energy storage. The results of this study are shown in Figs. 4a and 4b for 20% and 60% irradiated area, respectively. The normalized energy storage is plotted against charging time for the case with and without the metal cover. Figure 4c shows the integrated six-hour normalized storage value versus percent area irradiated.

The use of the aluminum cover adds very little (less than 3%) to the storage capacity of the wall. This behavior is due to compensating effects. As expected, the magnitude of the front surface temperature is reduced, and the lower

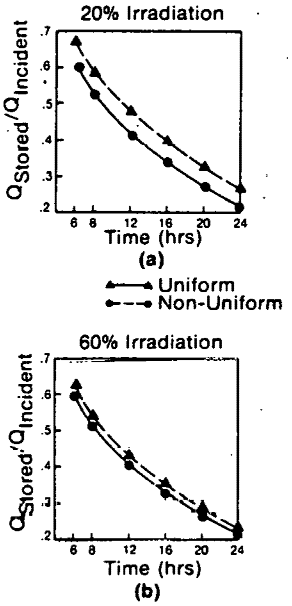

Fig. 3. Nonuniform Irradiation: Discharging. The effect of the uniform irradiation assumption on the normalized energy in storage during the discharge period for (a) 20% and (b) 60% of the wall surface is shown.

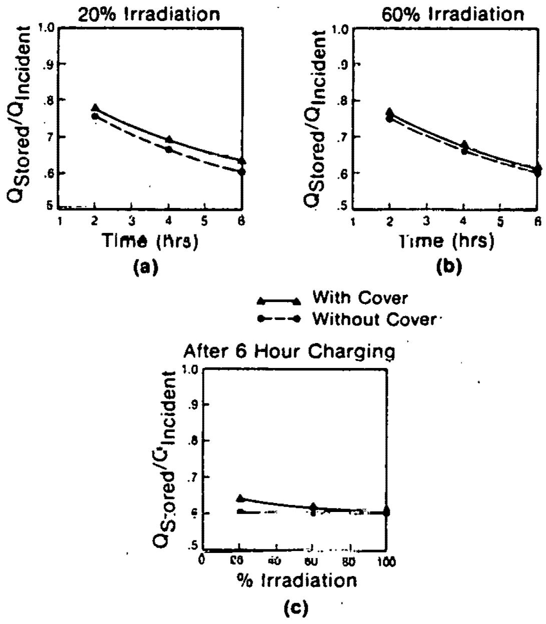

Fig. 4. Highly Conductive Metal Front Cover: Charging. The effect of a one-inch aluminum cover on the front surface of the storage wall is depicted for cases where (a) 20% and (b) 60% of the wall surface is irradiated discretely. Each value represents the integrated energy stored normalized to the incident energy. Also shown is the normalized energy stored versus percent irradiation integrated over the six-hour charging period (c).

front surface temperatures result in decreased heat loss. However, this effect is offset by increased heat loss associated with having the non-irradiated surface area at a higher temperature. The net effect is essentially no change in energy storage capacity of the wall. The storage capacity is ultimately limited by the relatively low thermal conductivity of the concrete storage material. This can be improved by increasing conductance into and through the wall [3].

The small increase in storage that the metal cover does accomplish is from a reduction in convection loss because of lower temperature. This is very similar to the phenomenon encountered in the uniform versus descrete irradiation study. However, the reduced convection loss in this case is not as pronounced as in the uniform irradiation case. The metal cover, even though highly conductive, does exhibit some temperature gradients, which lead to increased convection losses.

3.3 Selective Surface

The application of a selective radiation coating enhances the thermal storage characteristics of the wall by as much as 13%, as shown in Figs. 5a and 5b. This is consistent with the finding in Ref. 3. The front surface emissivity was changed from 0.8 to 0.2 to simulate the selective coating. Using

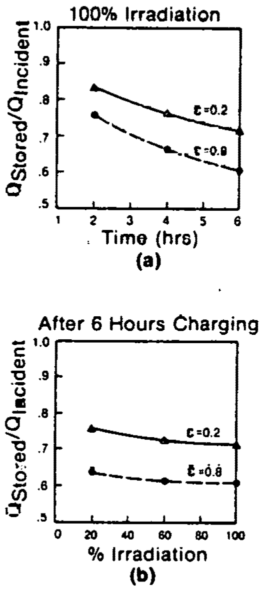

Fig. 5. Highly Conductive Metal Front Cover with a Selective Surface: Charging. The effect of a one-inch aluminum cover, with selective surface (emissivity $\epsilon = 0.2$), is depicted for the case where 100% of the surface is irradiated (a). Each value shown is the integrated energy stored normalized to the incident energy. Also shown is the energy stored after the six-hour charging period, versus percent irradiation (b).

the 0.8 emissivity and the metal cover, the distribution of front losses are 55% radiation and 45% convection during charging. Using the selective surface, the losses are 24% radiation and 76% convection. Even though the distribution between radiation and convection losses has changed significantly, the total losses are reduced only 9-13%. This is because using a selective radiation coating increases surface temperatures and the resulting temperature-dependent convective film coefficients. Figure 6 depicts the effect of the selective surface on the discharge cycle. The normalized energy in storage during discharging is plotted versus time. The additional energy stored (in the selective surface case) during charging is available for release during discharging.

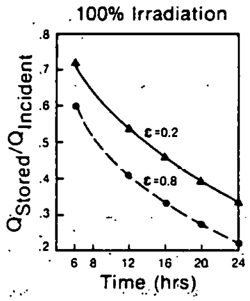

Fig. 6. Composite Wall with Selective Surface: Discharging. The effect of the selective surface during the discharge period is shown. The normalized energy in storage during the discharge period is plotted against time.

4. CONCLUSIONS

The major conclusions reached in this study are as follows:

(1) The assumption of uniform irradiation, one-dimensional heat transfer, used to analyze thermal storage walls, is adequate to predict the overall energy storage of the wall, but will not predict realistic temperatures when the wall is shadowed or nonuniformly irradiated.

(2) Using a metal front cover to enhance the storage characteristics of the wall during periods of partial irradiation improves the performance by less than 5% and is unwarranted.

(3) Using a selective radiation coating on the front surface of a storage wall can improve the performance by 13%.

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