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Analysis of an Active Charge/ Passive Discharge Solar Space Conditioning System

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ANALYSIS OF AN ACTIVE CHARGE/PASSIVE DISCHARGE SOLAR SPACE CONDITIONING SYSTEM

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ABSTRACT

Recently builders have shown considerable interest in combining the features of active and passive solar space heating systems into a hybrid system employing active collection and some form of passive discharge/storage device. We examined the performance and economics of a hybrid, air-based, residential system using 18.5 m^2 of roof-mounted air collectors and a hollow-core slab that discharges directly to the space by radiation and convection. In addition to space heating, the system provides domestic hot water heating and summer cooling by night venting of the slab. The system is assumed to be installed in a fairly "tight" new house with a floor area of 140 m^2 and 7 m^2 of south-facing glazing.

Preliminary slab design parameter sensitivities were examined by simulating the slab under steady-state conditions using a three-dimensional multi-node model. These preliminary findings were employed in developing an annual simulation of the entire system and house using the TRNSYS computer code. A limited number of sensitivity analyses were conducted with TRNSYS. These included sensitivities to climate, collector parameters, slab design, heat transfer parameters, heating loads, and controls, as well as an economic and performance comparison with an air-based active solar system using rockbed storage. The hybrid system heating performance and economics under the base case conditions were comparable to those of the active/rockbed system. The hybrid system collector outlet temperatures were lower than those of the active system, yet the inlet temperatures were higher, yielding comparable collector efficiency.

1. INTRODUCTION

Traditionally, there have been two approaches to the application of solar energy to building space heat: active systems which use an array of solar collectors (usually mounted on the roof) and passive systems which capture solar energy by means of building design. Active systems generally offer the advantage of better control while passive systems are less expensive. Recently, builders have shown considerable interest in combining these two approaches in so-called hybrid systems. The most popular concept is to use an active solar collector array to heat a passive storage device which transfers heat directly to the space by radiation and convection.

The passive storage device is typically a slab floor, wall, or ceiling and does not take up the extra space associated with active storage. It also operates at a lower temperature (due to the large surface area for heat transfer) and thus does not require the higher collector outlet temperatures of normal active systems. Unlike many passive systems, discharge of heat is not limited to only the south side of the building.

The hybrid approach has been used with both liquid and air collectors. Swisher(1) investigated a liquid system employing a concrete slab floor containing plastic water tubes. This study(2) complements Swisher's work by focusing on air systems, and additionally includes summer cooling, domestic hot water, and the effects of some direct gain.

Previous work in hybrid air systems was done by Evans and Klein(3) at the University of Wisconsin. They developed F-Chart modifications to model a system in which air from the collectors was discharged directly into the space with the building structural mass being used as storage. Neeper and McFarland(4) of Los Alamos Scientific Laboratory simulated similar systems. Barnaby et al.(5) investigated the use of hollow core concrete slabs in commercial buildings. Johnston(6) performed daily simulations of hybrid systems using pre-cast concrete panels. Finally, Nicklas(7) presented design guidelines for residential passive discharge systems which were based on monitored systems.

This paper presents the results of detailed annual simulations of a residential air-based active charge passive discharge system. The thermal analysis program, MITAS, was used to investigate the performance and optimum design of the hollow core concrete block floor, and an analysis of sensitivities to a wide range of parameters was performed using the TRNSYS program. Design guidelines are given, and the delivered energy cost of the hybrid system is compared to that of a typical active system employing rock bed storage.

2. DISCUSSION

A schematic of the active charge/passive discharge system modelled is shown in Figure 1. Domestic hot water is preheated by collector outlet air via an air-to water heat exchanger. During the heating season, this air is directed to the floor slab. In the summer, the collector outlet air bypasses the floor slab, and the slab is cooled at night by flushing with outside air.

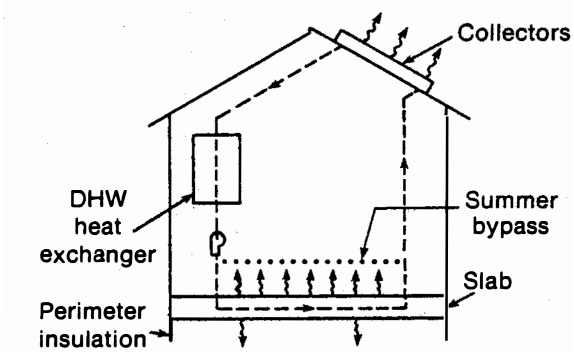


Fig. 1. Hybrid space heating system.

The computer code, TRNSYS, was selected to model this system. TRNSYS is the most widely used program available for modeling active solar energy systems and is well known by SERI researchers. Although no subroutine was available for a hollow core slab floor, an appropriate model was developed by modifying an existing Trombe wall subroutine. In order to avoid excessively long run times, a simple one-dimensional finite difference network was used to model vertical heat transfer in the slab. The three nodes used are shown in Figure 2. In order to validate the accuracy of the TRNSYS slab model, a separate three dimensional model was analyzed using the MITAS (Martin Marietta Interactive Thermal Analysis System) program. This steady-state slab model also provided information on temperature gradients along the slab.

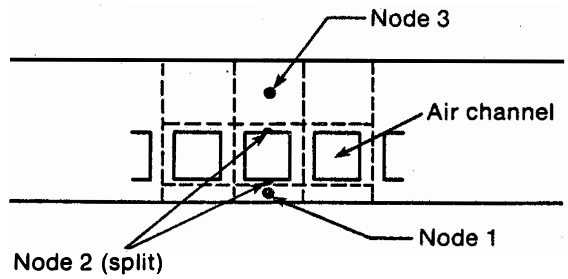


Fig. 2. Cross sectional end view of nodal representation of slab in TRNSYS.

Performance sensitivities to a variety of parameters were determined by changing the inputs to a base case model. Washington, D.C. was chosen as the base case location because its climate is in the middle of the range experienced in the U.S. and it has a sizable population. A TMY data tape provided hourly ambient temperatures, insolation values, and humidity values. Base case building parameters are shown in Table 1. Note that this building is representative of new construction in that it is fairly "tight" and that direct solar gains through south facing glass and internal gains are included.

TABLE 1. BASE CASE BUILDING PARAMETERS

Location: Washington, D.C.
Weather Data: TMY
Size = 10m x 14m = 140 m^2
UA = 475 kJ/hr°C
Capacitance (excluding slab) = 8000 kJ/°C
Windows on south side = 7 m^2
Internal gains = 1950 kJ/hour
Auxiliary heating capacity = 35,000 kJ/hour
Auxiliary heating system air flow rate = 1500 kg/hour
Heating setpoint = 20°C
Night setback = 5°C
Cooling setpoint = 25.5°C
Collector space heating Δt_{on} = 10°C
Collector water heating Δt_{on} = 5°C
Collector space heating Δt_{off} = 2°C
Ventilating Δt_{on} = 5°C
Ventilating Δt_{off} = 2°C
Heating season = October 1 through April 30

Control parameters are also shown in Table 1. The heating season is comprised of those months with an average number of degree-days greater than 300. The collector blower operates whenever the collector outlet temperature exceeds the preheat water tank temperature by 5°C or is 10°C higher than the slab tempera-ture (with a room temperature less than 24.5°C). The auxiliary system maintains room temperature whenever heat from the slab is not adequate. The slab can be bypassed to supply DHW-only heating when there is no space heating load. Nighttime ventilation of the slab with outside air occurs in the cooling season whenever the outside air temperature is more than 5°C below the slab temperature. Cooling loads are otherwise met by direct ventilation of the space with outside air or, when the outside temperature is greater than room temperature, by air conditioning.

Base case collector parameters are shown in Table 2. The collector area of 18.5 m^2 (200 ft^2) is consistent with the low space heating requirement of the building. This area also represents the maximum area which still supplies a marginal DHW contribution as shown by the results of TRNSYS sensitivity runs given in Figure 3. A standard air collector flow rate was assumed, and the collector tilt represents latitude + 10°.

TABLE 2. BASE CASE COLLECTOR PARAMETERS

Collector area = 18.5 m^2
Air flow rate = 50 kg/hr-m_c^2
Tilt = 48°
$\tau\alpha$ = .81
U_L = 25 kJ/hr-m^2-°C
F' = .9

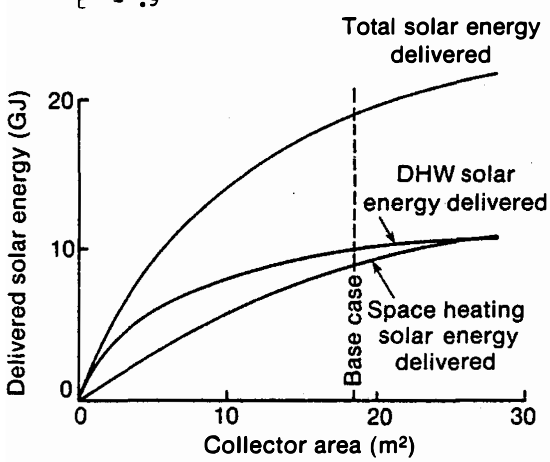


Fig. 3. Sensitivity of solar energy delivered to collector area.

DHW system data is given in Table 3. The daily loads follow the pattern developed by Rand Corp. with a daily consumption of 225 kg. supplied at 55°C(8). Preheat storage tank losses are assumed to reduce the space heating load.

TABLE 3. BASE CASE HOT WATER DATA

Daily Load = 225 kg
Minimum required hot water temperature = 55°C
Preheat storage tank volume = .35 m^3
Storage tank conductance(U) = 1.7 kJ/hr-m^2-°C
Ratio of storage tank height to diameter = 2
Flow rate between air-to-water heat exchanger and storage tank = 700 kg/hr
Air-to-water heat exchanger effectiveness =.5
Main inlet water temperature = 15°C

In determining optimum slab geometry, we investigated the number of transfer units (NTU's) for various cases, where

$$NTU = h_{as}(4dL)/(mC_{pa})$$

and L = channel length
d = channel width
m = air mass flow rate through the channel
C_{pa} = specific heat of air
h_{as} = air-to-channel heat transfer coefficient

An energy balance on the channel yields:

$$mC_{pa}\frac{dT_a}{dx} = h_{as} \cdot 4d \cdot (T_{slab}-T_{air})$$

The solution is:

$$T_{air\ out} - T_{air\ in} = (1-e^{-NTU})(T_{slab}-T_{air\ in})$$

Figure 4 shows TRNSYS results for the base case as a function of NTU's. It can be seen from this that the energy delivery increases little at an NTU above 1.0. We found that by using standard concrete blocks (see Figure 5) and assuming a slab size equal to the house floor area (10m x 14m), an NTU of 1.1 is attained. Thus this configuration provides sufficient heat transfer while limiting materials and installation costs.

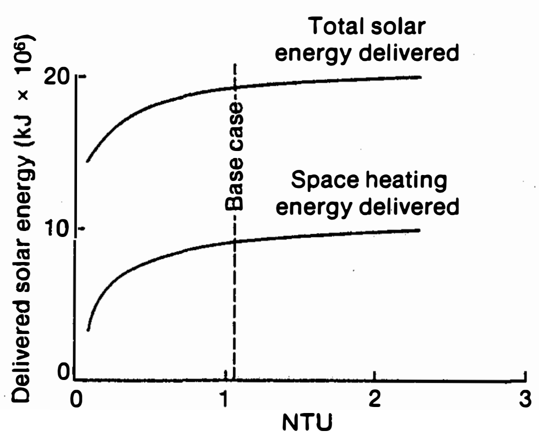


Fig. 4. Sensitivity of delivered energy to NTU.

For the base case, the Reynolds number for flow in the channels is about 1900 indicating that the flow is near the upper limit of the laminar regime. Data from Kreith(9) was used to determine the appropriate Nusselt number (Nu = 4.1) and corresponding heat transfer coefficient (h_{as} = 2.38 kJ/hr-m^2°C). For heat transfer from the slab surface to the room, a combined linearized radiation and convection heat transfer coefficient was used. The convection coefficient was obtained from recent experimental results at SERI for an enclosed space over a heated floor (10):

$$h_C = Nu \times k_a \ / \ \text{floor-to-ceiling height}$$

The resultant combined heat transfer coefficient, h_{sr}, is 27.9 kJ/hr-m^2-°C.

Ground losses from the slab floor were considered to be perimeter losses to ambient air. A 1.2 m deep perimeter insulation with a resistance of .5 hr-m^2°C/kJ was assumed. Investigations at Lawrence Berkeley Laboratory have shown perimeter losses with such insulation to be about 1.12 kJ/hr°C. This was converted to an area-based conductance as:

$$U = 1.12\ P/A$$

where A is the slab area and P is the perimeter. Allowing for the thermal resistance of the slab itself yielded an overall loss coefficient of .39 kJ/hr°Cm^2. The effects of ground heat capacity were investigated by adding a fourth node to the TRNSYS slab model. Since this changed the solar space heating contribution by less than 4 percent, the ground capacitance was neglected in the sensitivity runs.

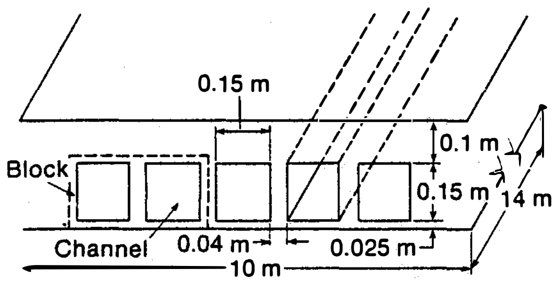


Fig. 5. Slab dimensions.

3. RESULTS

As shown in Figure 3, the total useful energy contributed by the solar system in the base case is 19.2 GJ. Of this amount, 10.1 GJ is delivered in the form of hot water for domestic use, or 74% of the domestic hot water load of 13.7 GJ. The other 9.1 GJ contributes 44% of the winter space heating load of 20.7 GJ (this load has been adjusted for internal gains and direct solar gains through south-facing windows). Finally, night flushing of the slab in the summer reduces the total sensible cooling load from 11.1 GJ to 5.8 GJ. In the base case there are some overheating problems. The maximum room temperature reaches 30°C in October and April due primarily to direct solar gains through south-facing windows. Additional overheating was prevented by shutting off the collector fan whenever the room temperature exceeded 24.5°C. The temperature difference along the slab under steady state conditions is less than 2°C yielding uniform heating throughout the house. The average air temperatures for collector inlet and outlet during the heating season are 27.9°C and 51.4°C, respectively. The fan power required to force the air through the 50 channels in the slabs is negligible due primarily to the relatively large cross sectional area of each channel.

We examined the sensitivity of the hybrid system performance to a number of parameters including climate, building loads, slab configuration, heat transfer coefficients, and slab conductivity. Of the three additional cities examined (Madison, Albuquerque, and Fort Worth--see Figure 6), the hybrid system space heating performance is most markedly different in Albuquerque due to the combination of a high UA for the house, high insolation levels, and cool nights. The space heating loads in each city are not in proportion to the severity of the winter climates because the overall building loss coefficient has been adjusted in each climate to reflect optimum insulation levels as suggested by Balcomb(11,12). There is little variation in the hybrid system contribution to the domestic hot water loads which are the same in all cities. Finally, the largest cooling load contributions occur in Madison and Albuquerque due to the cool summer nights there.

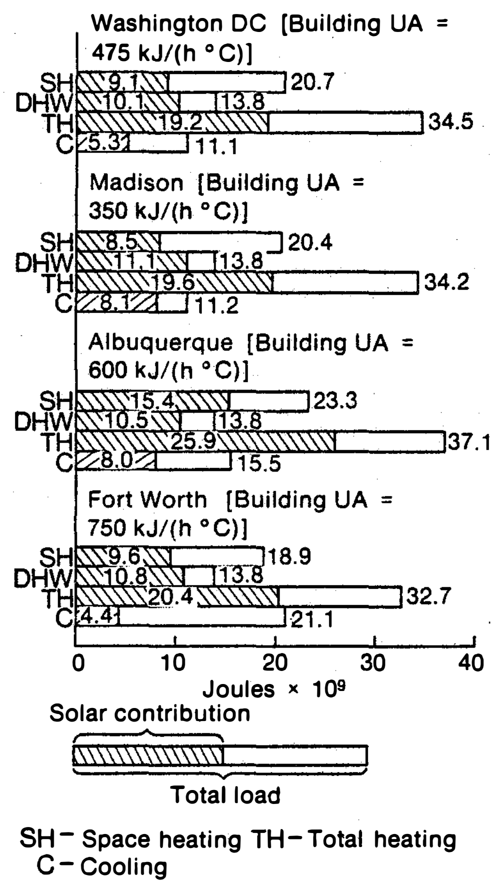
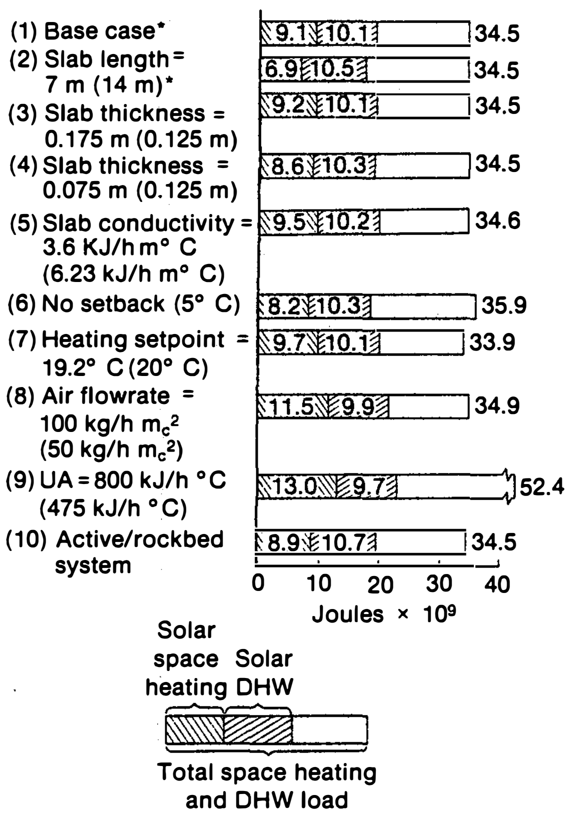


Fig. 6. Hybrid system energy contribution by climate.

Sensitivity analyses to the system design parameters indicate that the system performance is most sensitive to decreases in NTU, increases in the air mass-flow rate through the system, and the building UA. The sensitivity of system performance to NTU as shown in Figure 4 dictates the performance sensitivity to the size and number of slab air channels, and the air-to-slab heat transfer coefficient since these parameters do not appear elsewhere in the simulation. Although the slab length is also a parameter in the formula for NTU, a change in the slab length will also alter the area available for heat transfer to the room and the ground. Thus, as shown in case 2 of Figure 7, a decrease in slab length results in an even larger decrease in the space heating contribution than would be indicated by the formula for NTU and Figure 4. Figures 7 and 8 show little sensitivity of the results to other slab parameters such as thickness (cases 3 and 4), conductivity (case 5), and the heat transfer coefficient from the slab to the room.

Figure 7 also presents the performance sensitivity to the heating setpoint (case 7) and night setback (case 6). Since the heated slab increases the mean radiant temperature of the room, the same comfort level can be achieved at a room air temperature of 19.2°C as is realized at 20°C with a conventional floor slab(1). At this heating setpoint the



* Base case values are shown in parenthesis for the parameter examined. All other base case values are held constant.

Fig. 7. Performance sensitivities.

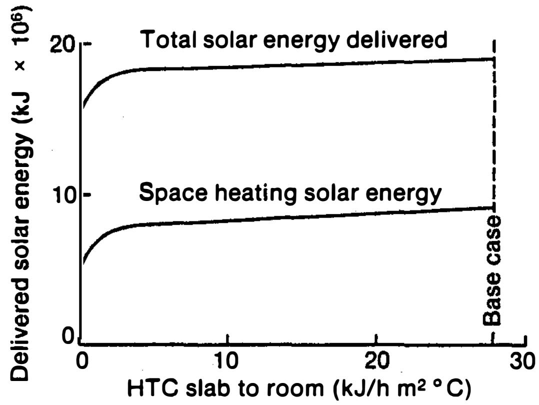


Fig. 8. Sensitivity of delivered energy to the HTC from slab to room.

hybrid system space heating contribution increases by 0.6 GJ due to the higher temperature differences between the slab and the room air. Similarly, the elimination of the night setback of 5°C reduces the hybrid system space heating contribution by 0.9 GJ due to the lower temperature differences between the slab and the room air at night.

The significant increase in the hybrid system space heating contribution when the air mass flow rate is doubled as shown in Figure 7 (case 8) is principally a result of the lower collector air temperatures that result. The hybrid system contribution to space heating is also significantly increased if the house UA is increased to 800 KJ/hr°C as shown in Figure 7 (case 9). Although not apparent in Figure 7, this increase in the heating load also results in fewer overheating problems and more efficient use of direct gains through south-facing windows.

Finally, Figure 7 presents the space and water heating contributions that might be expected from an active system with rockbed storage (case 10) in the same house as the base case. The combined space and water heating contribution from the active system slightly exceeds that of the hybrid system. However, the cooling contribution from the hybrid system gives it an overall performance edge. No cooling is assumed from the active/rockbed system due to potential condensation problems in the rockbed and the large flow rates that would be required. On an economic basis, the hybrid system also enjoys a slight edge only if its cooling contribution is included. As shown in Table 4, the incremental system costs are similar for all components except storage. The hybrid system slab incremental cost is based on estimates by Mitchell(13) in which the cost per square foot is slightly larger than twice that of a conventional slab. The hybrid system becomes relatively more attractive with larger collector areas, as the slab costs remain constant while the rockbed storage costs will increase with an increase in rockbed and collector size.

TABLE 4. INSTALLED COST COMPARISON OF TWO 200 ft^2 AIR COLLECTOR SOLAR ENERGY SYSTEMS

Rock Bed vs. Slab Discharge

	Rock Bed System	Slab System
Collector costs	$4000	$4000
Storage cost	1850	2662
Air handlers (and DHW heat exchanger) cost	1800	1500
Controls cost	1125	1125
System Cost	$8775	$9287
Heating energy delivered (GJ/yr)	19.5	19.2
Annual heating capacity cost $/(GJ/yr)	450	484
Heating and cooling energy delivered (GJ/yr)	19.5	24.5
Annual energy capacity cost $/(GJ/yr)	450	379

4. CONCLUSIONS

The heating performance of the hybrid system is not very sensitive to many of the slab design parameters such as its thickness, its conductivity, and the heat transfer coefficient from the slab to the room. Changes in other slab parameters such as the slab length, the heat transfer coefficient from the channel air to the slab, the channel cross sectional area, and the number of channels, can degrade heating performance below that of the base case, but show little potential for improving it. The heating performance is more uniformly sensitive to the building, control, and collector parameters. Of these, the heating performance is most sensitive to the collector area, air mass flow rate, and the building UA. The summer cooling performance is largest in climates with cool nighttime temperatures such as those found in Madison and Albuquerque. For the base case, the hybrid system performance and economics are comparable to those of an active system with rockbed storage. Although the hybrid system collector outlet temperature is lower than that commonly found in an active/rockbed system, the return air temperature to the collector is higher than the outlet of a highly stratified rockbed preventing significant gains in efficiency. Thus the collector efficiency improvement one might expect for a liquid collector array with slab discharge is not realized in the case of an air system.

5. ACKNOWLEDGEMENT

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