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ANALYSIS OF HYBRID SOLAR SYSTEMS

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ANALYSIS OF HYBRID SOLAR SYSTEMS WITH ACTIVE COLLECTION AND PASSIVE DISTRIBUTION

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ABSTRACT

This study uses the TRNSYS simulation program to evaluate the performance of active charge/passive discharge solar systems with water as the working fluid. This design was introduced in the Village Homes development in Davis, Calif., and is currently being used by Trident Energy Systems in Davis (1,2).

TRNSYS simulations are used to evaluate the heating performance and cooling augmentation provided by systems in several climates. The results of the simulations are used to develop a simplified analysis tool similar to the F-chart and Phi-bar procedures used for active systems. This tool, currently in a preliminary stage, should provide the designer with quantitative performance estimates for comparison with other passive, active, and nonsolar heating and cooling designs.

1. INTRODUCTION

This paper discusses a hybrid solar design configuration combining active collector panels with a massive integral storage component that heats the building interior by radiation and free convection (active charge/passive discharge). Although systems of this type are now being installed, there has been little detailed analysis or simulation of their performance. Simplified tools for active or passive system analysis are not adequate because neither can include both the active collector component and the passive storage-to-room coupling. Two types of hybrid configurations are shown in Fig. 1 and are contrasted to active and isolated gain passive systems. In the internal water wall system, the solar collectors charge a radiant vertical wall, which passively heats the interior. In the solar-heated slab system, the floor slab is charged by pipes embedded in the concrete and must be insulated to prevent excessive losses via the earth. Neither system requires a fan coil unit to distribute the collected solar energy.

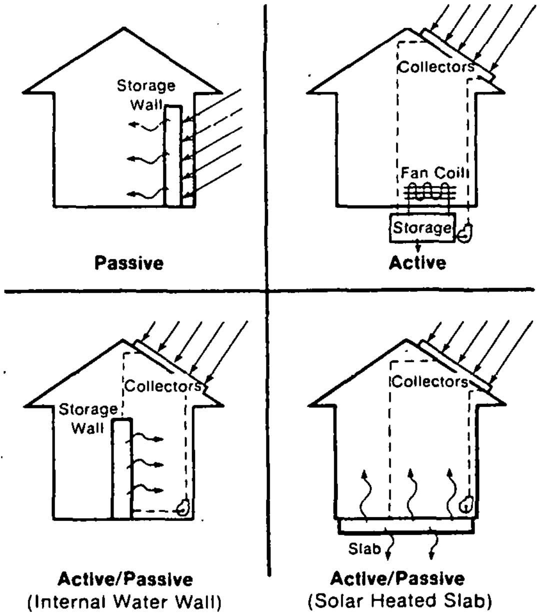

Figure 1. Comparison of hybrid solar configurations

2. THERMAL ANALYSIS METHOD

The thermal analysis is based on the TRNSYS simulation program (3). TRNSYS is used to evaluate system performance and to provide data for the development of a simplified design tool. The important design parameters that represent independent variables in the analysis are collector area and orientation, building heat loss, and collector and heat exchanger efficiencies.

The building is modeled as a one-node system with temperature set points of 20.5°C and 25.5°C and constant internal heat production. The standard liquid solar collector component is used with a water flow rate of $50\ \mathrm{kg\text{-}hr^{-1}\text{-}m^{-2}}$. The radiant storage wall or floor slab is assumed to be isothermal. Values for inside film conductances are from ASHRAE (4).

Simulation results for five U.S. locations are used to develop a simpler analysis tool based on the Phi-bar procedure developed by Klein (5, 6). Phi-bar gives the monthly fraction of usable absorbed solar energy in a system (Eq. 1) as a function of insolation level, ambient temperature, collector loss parameters, and the average collector inlet temperature:

$$Q_u = Q_A \bar{\phi} .^* \qquad [1]$$

The absorbed solar energy is given by Eq. 2, and $\bar{\phi}$ (Eqs. 3,4) is calculated according to Klein (5,6):

$$Q_A = A_c F_R' (\overline{\tau\alpha}) H_T . \qquad [2]$$

$$\bar{\phi} = f(\bar{K}_t, \bar{R}/R_n, H_n, I_c) \qquad [3]$$

where

$$I_c = U_L (T_i - T_a)/(\overline{\tau\alpha}) . \qquad [4]$$

The collector temperature is the only unspecified parameter because it is a function of absorbed solar energy, heating demand, storage capacity, and storage-to-room coupling. The results of hourly TRNSYS simulations are used to develop a correlation for the monthly average collector temperature in Phi-bar,

$$T_i = f(Q_A, Q_L, C_{st}, UA_{st}). \qquad [5]$$

The collector temperature function is estimated (Eqs. 6,7) for two classes of designs: an internal water wall with a conductance of 17 $W\text{-}°C^{-1}$ per cubic metre of water storage, and a 0.1-m deep concrete slab with 7 $W\text{-}°C^{-1}\text{-}m^{-2}$.

Internal water wall:

$$T_i = 20 + 0.160\, Q_A/(C_{st}\Delta T) + 7.3\, Q_A/Q_L \text{ (°C)} \qquad [6]$$

Solar heated slab:

$$T_i = 20 + 0.035\, Q_A/(C_{st}\Delta T) + 3.4\, Q_A/Q_L \text{ (°C)}. \qquad [7]$$

These temperature functions will require further work with TRNSYS for expansion into a more precise and general correlation that will provide the collector temperature for any storage configuration and inside conductance. The primary restriction in generalizing this technique is that the storage capacity is large enough to prevent frequent overheating of the room air requiring the venting of excess energy. The minimum capacity appears to be about 800 $kJ\text{-}°C^{-1}$ per square metre of collector area. Capacities below this value result in rapid deterioration of system performance and should not be considered for a passive discharge application. System performance continues to improve as storage capacity increases, as illustrated in Fig. 2.

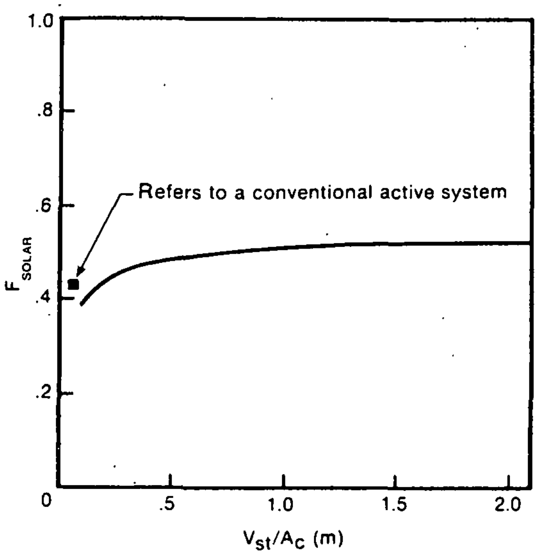

Figure 2. System performance vs. storage capacity for internal water wall (Washington, D.C. A_C = 24 m²)

In the case of the solar-heated slab, the thermal losses via the earth depend on the collector temperature. The equations for collector temperature, solar gain, and ground loss therefore must be solved simultaneously. Slab-to-earth losses are assumed to follow the ASHRAE relation

$$Q_g = fp\,(T_{slab} - T_{ambient}) \qquad [8]$$

where p is the exposed perimeter and f depends on the perimeter insulation (for insulation 0.5-m deep and 0.05-m thick, f = 0.5 $W\text{-}m^{-1}\text{-}°C^{-1}$) (4). On a monthly basis, T_{slab} and $T_{ambient}$ are replaced by T_i and T_a.

The collector system must be deactivated in the summer to prevent overheating of the building interior. Timing the fall and spring change overs is difficult because the storage component can take a

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*For nomenclature, see Sec. 6

week or more to charge or discharge if sized to provide a large solar fraction. Simulations show that the change overs should be made when the mean ambient temperature is about 19°C or 20°C, but in reality, the decision must be left to the resident's judgement.

3. SYSTEM PERFORMANCE FEATURES

Several features of the active charge/passive discharge configuration can provide economic advantages over other types of systems. Because the solar storage component is integral with the building interior in this configuration, as in a purely passive system, the ratio of storage capacity to collector area must be large to allow uniform and relatively low storage temperatures. The collectors, therefore, operate at temperatures lower than those necessary in conventional active systems. This decreases the impact of collector losses and suggests the application of less efficient and less costly collectors, which could result in significant savings in system costs.

Fig. 3 compares the solar fractions delivered, as a function of collector area, for active, passive, and two types of hybrid designs (the SLR method was used to estimate passive performance) (8). The collectors for the active and hybrid systems are single-glazed, with relatively high loss coefficients. Note that at high solar fractions, when the active storage temperature and collector losses increase, the performance suffers compared to the hybrid designs. This advantage would be negated by more expensive double-glazed collectors, but cheaper collectors can be effectively used in the active charge/passive discharge design.

If the storage component also serves as a necessary structural member, such as the floor slab, the only incremental cost for the solar storage is for embedding a heat exchanger coil. If the storage component is merely an energy accessory, however, the cost will be unjustified, unless the component contributes substantially to reducing cooling loads as discussed below.

If used to supplement the solar slab heating rather than to directly heat the room air, the backup heating system can be combined with the solar system for high solar fraction designs. This would eliminate the necessity of a forced-air auxiliary system, resulting in a substantial cost saving. Thus, it is possible to combine structural and storage components, integrate backup heating and solar control systems, avoid a forced-air heater, and use relatively inexpensive collectors to contribute to the cost competitiveness of the hybrid solar heating systems.

An additional benefit for this system is realized in the cooling mode for cases where integrating the solar storage within the building increases the internal thermal mass of the structure. During much of the cooling season in many climates, the internal heat gains and average ambient temperatures are such that the average building temperature can be kept within the comfort zone. However, the daily ambient temperature peaks, which are approximately coincident with maximum solar gains, drive the room temperature above the comfort level. A substantial increase in internal heat capacity can damp out these temperature peaks and thus reduce the air-conditioning demand. This additional energy stored during the day can be expelled if night-time ventilation is available. TRNSYS simulations show up to 60% reductions in sensible cooling loads for internal water wall systems compared to conventional systems with similar building construction.

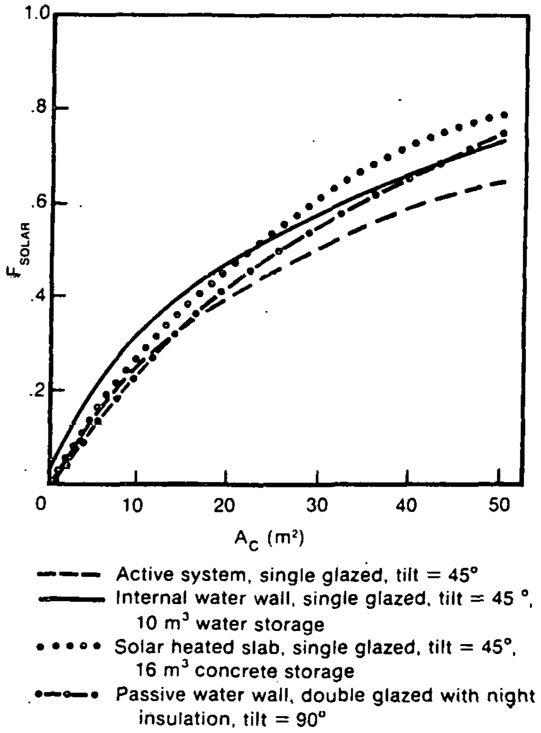

Figure 3. Performance comparison of four solar systems (Washington, D.C.)

The collector system can be operated at night for radiant cooling augmentation in arid climates. This requires collectors without glazing or with removable glazing for sufficient radiative transfer. Use of the collectors in the cooling mode is not considered in the simulations.

The hybrid configuration also has some advantages over passive systems. The collector system provides better control of losses and thus more efficient collection. Because only the collectors require southern exposure, there are less architectural restrictions than in most south wall passive systems. Concentration of heating on the southern exposure is a problem in many passive designs, but the active charge/passive discharge design facilitates more balanced heat distribution and better use of the radiant transmission from the storage component (the solar-heated slab suffers in this regard when applied to multistory frame buildings). As in passive systems, comfort in a hybrid building depends on large storage capacity and adequate ventilation to avoid overheating. The hybrid systems' economic attractiveness depends on whether the above benefits, together with the multiple functions provided by the components, compensate for the expense of extra hardware such as collectors, plumbing, and controls.

4. CONCLUSION

The analysis technique described here performs the thermal analysis for two classes of active charge/passive discharge solar heating systems using familiar, well-used relationships. This technique can also be applied more generally and perhaps integrated into analysis tools that consider other active and passive configurations. Weaknesses of the method should be noted, however. First, the convective and radiative coupling between the storage element and the interior is not easily defined, and ASHRAE film conductances are used. ASHRAE approximations are also used for the slab losses via the earth. These equations can, however, be directly replaced by improved relationships, and solved in the same manner. The literature regarding this problem is unfortunately very sketchy. Although the isothermal storage assumption is a gross approximation, the potential error introduced is insignificant compared to the uncertainty of the above heat transfer mechanisms.

The systems considered in this analysis are patterned after those introduced in the Village Homes development in Davis, Calif. (1). Larger developments are now under way in Davis using the solar-heated slab design (2). This analysis indicates that active charge/passive discharge system performance is comparable to other solar designs and discusses some of the necessary design trade-offs for these systems. There are also several features that can make the hybrid configuration an economically attractive solar application in many climates.

5. NOMENCLATURE

Q_u - usable solar energy

Q_A - absorbed solar energy

$\bar{\phi}$ - monthly ratio of usable to absorbed solar energy

A_c - collector area

F_R' - collector removal factor with heat exchanger correction (see Ref. 7)

$(\overline{\tau\alpha})$ - average transmittance absorptance product

U_L - collector loss coefficent

H_T - total monthly radiation on collector surface

H_n - average radiation on collector surface at noon

$\bar{R}$ - ratio of average daily radiation on collector surface to average daily radiation on a horizontal surface

R_n - ratio of radiation on collector surface to average daily radiation on a horizontal surface at noon

$\bar{K}_t$ - ratio of average total to extra terrestrial radiation on a horizontal surface

I_c - critical radiation level (see Ref. 5)

T_i - average collector inlet temperature

C_{st} - total heat capacity of the storage component

Q_L - monthly building heating load (includes slab losses)

Q_g - slab loss

UA_{st} - overall thermal conductance between the storage component and building interior

T_a - average ambient temperature

ΔT - allowable room temperature swing

p - exposed slab perimeter

f - slab loss factor

F_{solar} - annual solar fraction

6. ACKNOWLEDGMENT

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