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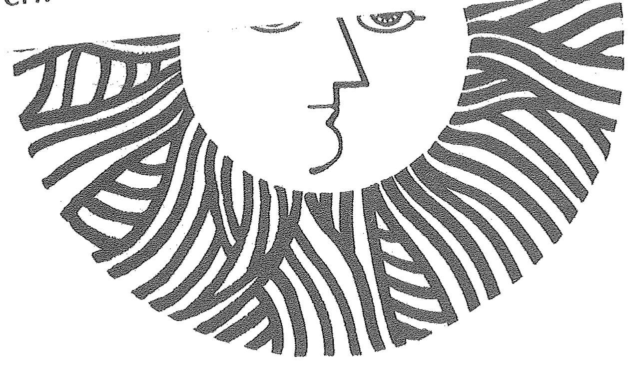

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A SIMULATION MODEL FOR THE PERFORMANCE ANALYSIS OF ROOF POND SYSTEMS FOR HEATING AND COOLING†

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ABSTRACT

A detailed computer model has been developed for simulating the dynamic thermal behavior of roof pond systems. The model is composed of outer movable insulation, an optional evaporative water layer over water bags on steel decking, and an inner movable insulation. A control strategy for the movable insulations which provides near optimum thermal performance is included in the model. An hourly thermal balance analysis of the system is performed using theoretical and/or empirical expressions to determine the heat transfer coefficients for each of the surfaces in the model. The model has been used to study the effect on system thermal performance of [1] the R-value of both the top and bottom movable insulations; [2] the depth of the pond water, and [3] the depth of the evaporative layer. The heating and cooling potentials of the roof pond have also been investigated in four climates. The model was developed for incorporation into the public domain building energy analysis computer program BLAST.*

INTRODUCTION

The concept of using water on roofs as a thermal moderator of the indoor climate has long been recognized and practiced. Recently investigators have begun to quantify its energy saving potential [1-7]. The roof pond system was tested on a small-scale prototype in Phoenix, Arizona [1,2] and on a full-scale prototype in Atascadero, California [4]; the system proved to be effective in both locations. A roof pond solar house located at New Mexico State University in Las Cruces has also performed satisfactorily [6]. In addition, Clark et al. [7] have developed a computer model which predicts that an evaporatively aided roof pond would substantially reduce the sensible cooling load even in the more humid regions of the United States. The purpose of the present work is to develop a public domain simulation model of sufficient detail and flexibility to permit rapid evaluation of heating and cooling potentials of roof pond systems, and to investigate the selection of optimal design parameters.

MODEL

The physical elements represented in the model are (1) movable top insulation, (2) air gap, (3) optional evaporative layer of water, (4) plastic membrane encasing the water (5) pond water, (6) steel support deck, (7) air gap, and (8) a movable bottom insulation leading to the conditioned space (Fig. 1). During the heating season, the top insulation panels are opened during the day so that solar energy may be absorbed and stored in the water and transferred into the room. Night losses are reduced by closing the upper insulation, permitting heat to continue to flow into the room from the water. In more severe conditions the lower insulation can be utilized to further reduce the heat losses to the outside air. In addition, the lower

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*BLAST (Building Loads Analysis and System Thermodynamics) is copyrighted by the Construction Engineering Research Laboratory, U.S. Department of the Army, Champaign, Illinois.

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insulation may provide improved comfort control for the occupied space. Cooling is enhanced by flooding the encased pond with water, which is covered during the day but uncovered during the night to permit evaporative, radiative, and convective heat losses. A detailed description of the model and the calculation procedure and assumptions is given in Ref. [8]. This report focuses mainly on simulation results.

CALCULATION PROCEDURE AND ASSUMPTIONS

All heat flows in the system are assumed to be one-dimensional. The dynamic behavior of the system is simulated by performing steady-state thermal balance calculations at each time step, writing heat balance equations for each element of the system considering radiation, conduction, convection, and evaporation, as appropriate. The thermal capacities of the insulation layers, plastic, and steel are assumed to be zero. The temperatures and heat flux components of each element of the system are computed; the temperatures serve as initial conditions for the thermal balance calculation during the subsequent time step.

Multiple reflections within the plastic layer were accounted for and an overall extinction coefficient was assumed for this layer. Since water selectively absorbs solar radiation [9], five different wave length segments were used to estimate the intensity of radiation at any depth of water and hence the energy absorbed by the water. This calculation utilized a slightly modified expression from Ref. [10]. Infrared radiative heat exchange between the roof and the sky was estimated by assuming the sky to be black with a radiative temperature related to the ambient air temperature using an effective sky emissivity. The clear sky emissivity was calculated by the method of Brunt [11]. A linear cloud cover dependence was included by assuming an effective sky emissivity of unity for a completely cloudy sky.

The convective heat transfer coefficient between the plastic or the exposed surface of the outer movable insulation panel and the ambient air was calculated using a relation [12] which includes a linear wind speed dependence. Convective and evaporative transfers between the evaporative layer and the ambient air were calculated using the relations recommended by Ref. [13]. At present the model assumes zero infiltration between the outer insulation panels and the water pond. It is, however, recognized that these infiltration losses may have a significant effect on the system performance and the model will be modified to include such effects.

The radiative exchange between the ceiling and the room surfaces was estimated by assuming all surfaces to be black bodies. The radiative temperature of the walls and floor surfaces were assumed to be the same as the mean room air temperature. The convective heat transfer coefficient between the system and the inside air was calculated using standard equations which relate the Nusselt number to Rayleigh number.

Heat flow through the top and bottom insulations is assumed to be by conduction only. Heat flow across the air gaps is composed of radiation and convection-conduction. The convective-conductive heat transfer coefficients across the air gaps and those between the plastic or the steel deck and the water included a Rayleigh number dependence with appropriate lower bounds. The physical properties of water were taken to be functions of temperature; all physical properties of air, with the exception of volumetric coefficient of expansion, were assumed constant.

In the simulations reported here, monthly average environmental data were used to construct average days representing each month for the four climates considered: Atlanta, Ga., Phoenix, Az., Sacramento, Ca., and Washington, D.C. Hourly horizontal insolation values were generated from monthly average daily total solar radiation on a horizontal surface following the procedure of Liu and Jordan [14]. The code is easily amended to accommodate hourly meteorological data.

An insulation control strategy which maximizes heat gain during the heating season and heat loss during the cooling season was developed. For each hour, simulations were performed with the top insulation in the open position, and separately, in the closed position; the bottom insulation panels were closed for both of these initial analyses. The insulation position which resulted in higher net heat gain by the system from the environment during the heating mode of operation, or the lower heat gain during the cooling mode, was chosen for the top panels. Once the optimal top insulation position was determined, the position for the bottom panel resulting in higher heat gain by the room during the heating mode, or higher heat loss from the room during the cooling mode, was chosen. Table 1 shows the insulation positions determined by this strategy for a room temperature of 22°C.

SIMULATION AND DISCUSSION OF RESULTS

The performance of the roof pond system is expressed in terms of the heat flow rate per unit area of the deck separating the pond from the occupied space. A standard set of system parameters was used for comparative analysis for both heating and cooling modes of operation. This baseline case consisted of 3 cm thick polyurethane top and bottom insulating panels (conductivity = 0.09 $kJ\text{-}m^{-1}hr^{-1}\text{-}^{o}C^{-1}$) and 20 cm of pond water with a 3 cm evaporative layer for the cooling mode. The pond was assumed to be flooded for all of the cooling season simulations and the room temperature was taken to be constant for each simulation.

Figures 2 and 3 show the importance of the top and the bottom insulations to the roof pond performance in Phoenix for the heating and cooling modes, respectively. It is apparent that the top insulation is critical to the roof pond performance. The bottom insulation serves no purpose in Phoenix; however, it could be beneficial for other more severe climates or for prolonged sunless periods during the heating season or cloudy nights during the cooling season. The effects of varying the thickness of the top insulation are shown in Figs. 4 and 5; it can be seen that increasing the insulation level improves the performance of the roof pond for both heating and cooling purposes. Note that in Phoenix there is little benefit to insulation thicknesses greater than 3 cm.

The effect of varying the depth of the water in the roof pond is shown in Figs. 6 and 7. The daily net heat gains (area under the curves in Fig. 6) increase by about 15 percent as the pond depth is increased from 5 to 15 cm. Further increases of pond depth have no significant effect on daily heat gains in the heating mode. In the cooling mode, increasing the pond depth improves the overall daily cooling performance only slightly. Figures 6 and 7, however, reveal that as the pond depth is increased the daily range of variation of heat flux into or out of the room is decreased. Therefore, although nearly equal areas under the curves in Fig. 7 suggest comparable overall daily cooling performance for different pond depths, a deeper pond may provide more stable comfort conditions. Any conclusion on comfort conditions should, however, consider the thermal mass of the entire building. The effect of the evaporative layer on the cooling potentials of the roof pond was studied by performing simulations with and without an evaporative layer for Phoenix in August. The results shown in Fig. 8 demonstrate that 1000 $kJ\text{-}day^{-1}m^{-2}$ of cooling can be achieved with an evaporatively aided roof pond while without evaporation the room actually gains 100 $kJ\text{-}day^{-1}m^{-2}$. Figure 8 also shows the evaporative, radiative, and convective components of the heat flux from the roof to the outside for those hours that the top insulation is open. The different behavior of convective losses for the two cases (with and without an evaporative layer) results from using the different expressions to estimate the convective heat transfer coefficient between the ambient air and the flood surface, or the dry plastic surface. Further research is needed to develop more reliable relationships for convective and evaporative heat transfer. Simulations for the more humid climate of Atlanta show that an evaporative layer would improve the cooling performance of the roof pond by 100 percent. Variation of the thickness of the evaporative layer proved to have no significant effect on the cooling potential of the roof pond.

The model was also used to simulate the heating/cooling performance of the roof pond for constant interior temperatures ranging from 16 to 28°C in all four of the climates considered in this study. The results for the months of January and July are presented in Figs. 9 and 10, respectively. It is readily seen that a significant advantage may be realized in both the sensible heating and cooling potentials if slight accommodations are permitted in the room thermostat setting. A thorough assessment of roof pond potentials is best carried out after the model is incorporated into a building energy analysis program. However, in order to present an order of magnitude of the extreme heating and cooling loads for a typical building (excluding the roof), these loads are also shown in Figs. 9 and 10. These loads are simply calculated using an effective overall constant U value of 200 $kJ\text{-}m^{-2}{}^{o}C^{-1}day^{-1}$. This value agrees well with that estimated for the Atascadero experimental residence (4). Figure 9 suggests that the heating needs of a typical residential building in Phoenix can be easily met by a roof pond. For the other three cities, the heating performance of the system does not appear as attractive. It should be stressed that the heating performance of the roof pond can be improved by including inflatable air cells over the water bags. Examination of Fig. 10 shows that adequate cooling in all four cities could be achieved by an evaporatively aided roof pond. Present construction codes reduce the heating/cooling loads by a factor of 2 to 4. This enhances the attractiveness of a roof pond as an important passive solar design option.

CONCLUSIONS

A detailed thermal model for roof pond systems has been developed for integration into the building energy analysis computer program BLAST. In BLAST it will permit rapid trade off analysis of roof ponds in comparison to other passive and conventional building systems. The model has been used to investigate the system performance sensitivity to the major roof pond design parameters. The major results of these studies are:

- While the overall daily performance of the roof pond is relatively insensitive to the pond depth, the hourly results vary substantially; this implies that use of models which predict daily average performance may be misleading.
- The dynamic behavior of the roof pond is sensitive to the level of the top insulation. In Phoenix, however, there is little benefit to polyurethane insulation thicknesses over 3 cm. For further improvement of the system performance, efforts should be concentrated on reducing infiltration losses from the panels rather than increasing the insulation level.
- The use of movable insulation between the roof pond and the occupied space would be of questionable thermal merit.
- An evaporative layer improves the cooling performance of the roof pond, but its thickness has negligible effect.

The relatively poor heating season performance of the system in the other cities is not surprising; the addition to the model of an upper glazing would be desirable.

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TABLE 1. Insulation Control Strategy

LOCATION	JANUARY			AUGUST				
					WITH EVAPORATIVE LAYER		WITHOUT EVAPORATIVE LAYER	
	SUNRISE/ SUNSET	TOP INSULATION Open/Closed	BOTTOM INSULATION Open/Closed	SUNRISE/ SUNSET	TOP INSULATION Open/Closed	BOTTOM INSULATION Open/Closed	TOP INSULATION Open/Closed	BOTTOM INSULATION Open/Closed
ATLANTA	8am/6pm	12 noon/4pm	Always Closed	6am/8pm	9pm/7am	Always Open	12 mid/7am	Always Open
PHOENIX	8am/6pm	10am/4pm	Always Open	6am/8pm	8pm/7am	Always Open	2am/7am	Always Closed
SACRAMENTO	8am/6pm	12 noon/4pm	Always Closed	6am/8pm	7pm/7am	Always Open		
WASHINGTON	8am/6pm	12 noon/4pm	Always Closed	6am/8pm	8pm/7am	Always Open		

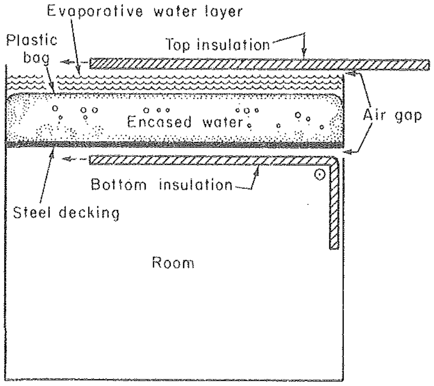

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Fig. 1. Schematic of Roof Pond Model Components

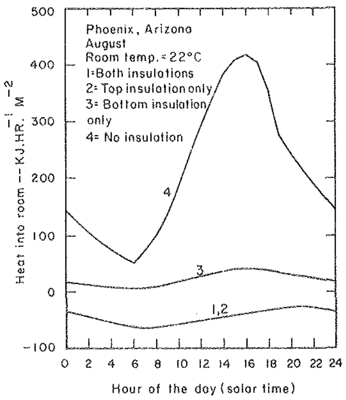

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Fig. 3. Effect of Top and Bottom Insulation on Cooling Performance of Roof Pond

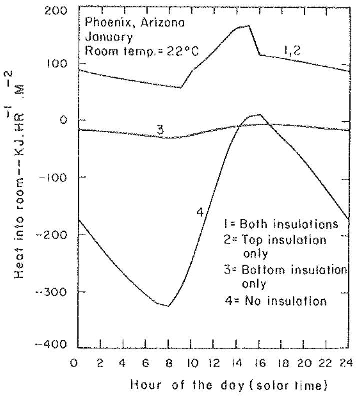

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Fig. 2. Effect of Top and Bottom Insulation on Heating Performance of Roof Pond

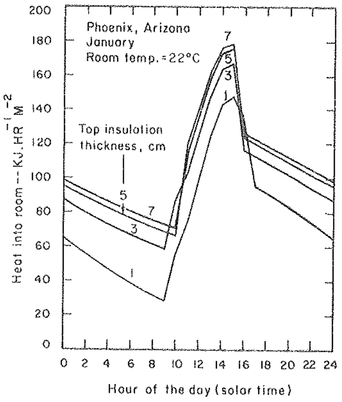

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Fig. 4. Effect of Top Insulation Thickness on Heating Performance of Roof Pond

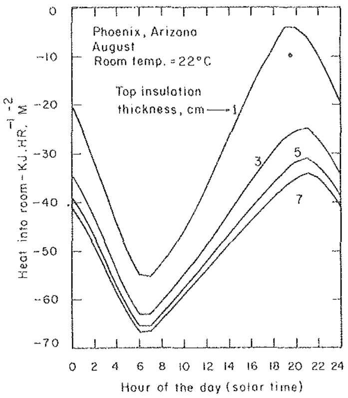

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Fig. 5. Effect of Top Insulation Thickness on Cooling Performance of Roof Pond

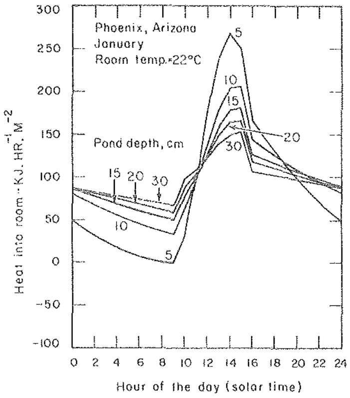

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Fig. 6. Effect of Pond Depth on Heating Performance of the Roof Pond

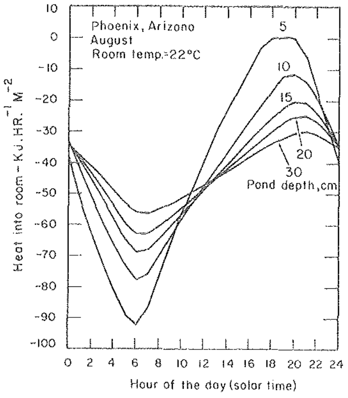

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Fig. 7. Effect of Pond Depth on Cooling Performance of the Roof Pond

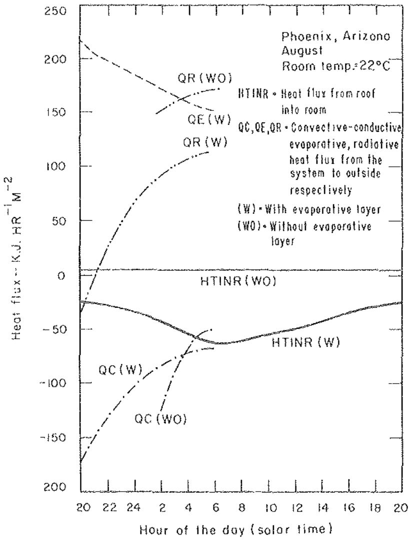

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Fig. 8. Effect of Evaporative Layer on Cooling Performance of the Roof Pond

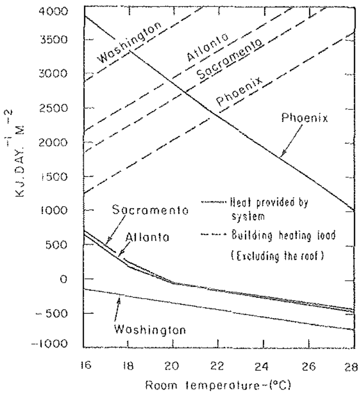

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Fig. 9. Heat Provided by Roof Pond and Typical Building Cooling Loads for July

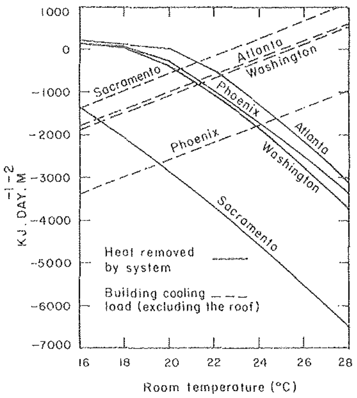

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Fig. 10. Heat Removed by Roof Pond and Typical Building Cooling Loads for July

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