MODELING OF THE RADIATIVE, CONVECTIVE, AND EVAPORATIVE HEAT TRANSFER MECHANISM OF THE NEBRASKA MODIFIED ROOF POND FOR THE DETERMINATION OF COOLING PERFORMANCE CURVES

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ABSTRACT

A passive solar heating and cooling technique with a sizable potential impact but lacking widespread recognition is the roof pond. Much testing and evaluation of roof pond systems occurred during the 1970's and 1980's. In 1984 much of the work in roof ponds was summarized in a book by Rockwell International (1). For various reasons none of the roof pond systems which can survive severe climates requiring cooling and heating have not been widely accepted.

In 1982, a variant of traditional roof ponds was codeveloped by Richard Bourne of the Davis Energy Group and Bing Chen. The Nebraska Modified Roof Pond (NMRP) would retain the advantages of traditional roof ponds while obviating marry of the concerns associated with them. Construction of a test room began in the spring of 1982 and was completed during that summer. Since that time the NMRP has been undergoing a series of tests and evaluations

This paper presents the results from an analysis of the hourly cooling results and seeks to separate the radiative from the convective-evaporative component. The test room was set up as a calorimeter so that the total cooling could be readily ascertained while the water temperature of the pond is fixed. Under these test conditions the convection-evaporation component makes a significant cooling contribution.

1. THEORY OF OPERATION

Figures 1 and 2 show the Nebraska modified Roof Pond in both the heating and cooling modes of operation. In the heating mode no special roof apparatus is employed. Instead, the conventional application of the direct gain or thermosyohon passive solar heating method is employed. For summer cooling season, a pump turns on at night and distributes pond water atop the cement coated rigid insulation. The pond water loses heat via night sky radiation,
evaporation and convection. This cooled water then migrates back downwards to the pond via cracks in the floating insulation

Figure 3 shows the pond as it was configured for testing. The goal was to treat the pond -as a calorimeter (2). When the pump turns on at night the pond temperature would ordinarily drop as cooling commences. However, for these experiments the pond temperature was fixed by a thermostat which would burn immersed heaters oil The energy input by the heaters is a direct measure of the effective cooling for a fixed pond temperature. The results of this paper are from a two pump system with a 1375 liter 2-hr flow 'rate ,/m
over a pond area of 2.6 m2-. The pumps were turned on for an 8.5 hour period each night. The flow pattern is such that it covers the entire pond with an even distribution and -a pump discharge velocity of 27.36 km/hr (17 mph). The pond temperature was fixed at 21.101-. Pond, water surface, dewpoint and ambient temperatures were collected hourly. Night sky radiation was collected by a Fritschen 3040 pyrradiomter.

2. RESULTS

The presented results are for daily cooling capacity and are based on a range from measured performance results read from power meters to some combination of measured radiation with computed convection and evaporation values. The daily cooling capacity of the NMRP at a fixed 21.1 °c (70°F) pond temperature ranges from a low of 390 to a high of 3350 watt-hours per square meter. Table 1 summarizes the results.

TABLE 1

PART	TOTAL DAILY COOLING CAPACITY (W-hr/m^2)	DESCRIPTION
1	886	Taken from an equation derived from measured power meter data.
2	638	Uses measured radiation and computed averaged hourly convection and evaporation for still conditions
3	3350	Uses measured radiation and computed averaged hourly convection and evaporation values for forced conditions
4	390	-Taken from a regression of part 1 data
5	1735	Taken from a regression of part 2 data

3. EXPLANATION OF RESULTS

3.1 Part I (Table 1) 886 watt-hours/meter^2

This result was obtained from the totaled nightly power meter readings and reflects the actual measured nightly cooling capacity Elost in watt hours per square meter of the NMRP.

(1) Elost= Erad + Econv + Eevap - Ewater

Elost = total NMRP heat transfer
Erad =radiative heat transfer
Econv =convective heat transfer
Ewater =change in potential water energy

(2) Ewater = (C/A) (Twi - *Twf)*

Twi =initial water temperature (◦C)
Twf =final water temperature (◦C)
c =heat capacity of the water (1009.5 w-hr/C)
A =roof pond surface area (2.6 m^2)

There was some concern that Ewater could be affected by rainfall. It was calculated empirically and found to be less than 3% of the total Elost and was disregarded. There are 36 data points used in a regression analysis to develop the cooling equation (2).

(3) Elost = 7786 - 345 **x** Tambient w-hr/m2
Tambient = ambient temperature (◦C)

For an ambient temperature of 20◦C (68◦F) the nightly cooling value can be computed from equation 3 to be 886 w-hr/m^2.

3.2 Part 2 (Table 1) 638 watt- hours/meter^2

This result is derived from summing the measured hourly radiation values and Computed convection and evaporation under still conditions. As such it represents a lower boundary for expected cooling since the water is being pumped and sprayed onto the roof.

The convection loss from the pond in w/m^2 is given by equation 4.

(4) Oconv = hc (Tambient - Twater surface)
hc = heat transfer coefficient (w/m^2-◦C)

Clark and Berdahl (3) *and* Niles (4) predict values of hc equal to 0.8 w/m^2-◦C ,when Tambient > Tws and 3.5 w/m^2-◦C when Tambient < Tws. Both values are for still conditions.

The evaporative component of cooling in Btu/hr-ft is given by equation (5).

(5) Qevap = (Hfg hc (W-Wws)) / (0.897 Cp)
Hfg = latent heat vaporization (Btu/lb)
CP =heat capacity of moist air
(0.24 Btu/lb-◦F)
w =humidity ratio (lbs water/lbs dry air)
Wws =humidity ratio (lbs water/lbs dry air) under saturated conditions (at Tws)

A psychometric chart is used to find the humidity ratios, W *a@ W..* The latent heat of vaporization Hfg is -find by equation (6).

(6) Hfg **=** 970.4 + 0.999 x (212-Tws)

The average of the hourly radiation, and the computed evaporation and convection components for still conditions gave 75 watts/meter^2. This value is multiplied by the pump time period of 8.5 hours per day to yield the averaged nigh cooling capacity of 638 watt-hours/meter^2. For the duration it is of interest to note that the minimum computed cooling capacity varies from a low 8.5 to a high of 1488 watt-hours/meter^2.

<u>3.3 Part 3 (Table 1) 3350 watt-hours/meter^2</u>

This value of cooling capacity is similar to part 2, namely that hourly measured radiation is used and computed convection and evaporation calculations added. However, the value for the heat transfer coefficient is based on forced conditions when the pumps are on Given that the pump hose was spraying water out with a velocity of 27.36 km/hr (11 mph) it <u>is</u> reasonable to consider values of higher hc.

For non still or forced conditions, the heat transfer coefficient is given by one of three approximations which differ. Proposed by Jurges and discussed by McAdams (5) is equation 7.

(7) hc = 1 + 0.3 v Btu/hr-ft^2
v = velocity of water in mph

At 11 mph hc is 6.1 Btu/h r-ft^2 (34.9 w/m^2-◦C).

The second equation for heat transfer is proposed by Clark and Blanpied for windspeeds of between 3 to 10 mph

(8) hc = 0.5 + 0.3 v

For an 11 mph wind speed (or water speed for NMRP), hc is 5.4 Btu/hr-ft^2-◦C (30.9 w/m^2-◦C).

Another equation developed by the Clark team at Trinity University for forced hc is given in equation 9.

(9) $hc = 0.49 + 0.24\ v$

For an 11 mph (27.36 km/hr) velocity, hc is 4.57 Btu/hr-ft^2-◦F (26.1 w/m^2-◦C).

The cooling capacity of 394 w/m^2 is computed by adding the measured radiation and the calculated forced convection and evaporation using the intermediate hc value of 30.9 w/m^2-◦C and finding the average. The maximum cooling capacity from the hourly data set using equation (7) is 976 w/m^2 . Integrating this over an 8.5 hour period yields a peak cooling under ideal conditions of 8296 watt-hours per square meter. The minimum cooling capacity for forced conditions using equation 9 is 39 w/m^2 and when integrated over 8.5 hours 331.5 watt-hours per square meter.

3.4 Part 4 (Table 1) 390 watt-hours/meter-2

For parts 4 and 5. a predictor equation was developed using regression analysis an the data generated in parts 2 and 3. The data consisted of the hourly radiative and computed convection and evaporation components. For still conditions with a pond temperature of 21.1◦C (70◦C), the nightly cooling capacity is given by equation (10).

(10) Elost = 1210_- 41 Tambient w-hr/m^2

For an ambient temperature of 20◦C (68◦F) the nightly cooling capacity is 390 w-hr/m^2. The correlation coefficient r2 was 0 .4 9 for the data set.

3.5 Part 5 (Table 1) 1735 watt-hours/meter^2

The process for part 4 is repeated here in part 5 for forced conditions. The nightly cooling capacity is given by equation (11).

(11) Elost = 7955 - 311 Tambient w-hr/m2

For an ambient temperature of 200C the nightly cooling capacity is 17 35 w-hr /m2. The correlation coefficient, r2 was 0.86 for the data set.

4. COMPARISON TO TRINITY UNIVERSITY RESULTS

Table 2 is taken from graphs developed at Trinity University from their wet roof pond (6). The cooling capacity for two roof pond temperatures is shown for a number of U.S. cities.

Contrast the first column of Table 2 to the range of the measured and computed Omaha values of 390 - 1735 W-hr/m^2 which are also for a fixed pond temperature of 21.1°C, The NMRP performs favorably.

TABLE 2
DAILY COOLING CAPACITY FOR SEVERAL U.S. CITIES

City, State	Cooling Capcmity (w-hrAn2)	
	Water Temperature	
	21.1°C (7O°F)	25.6°C (78°F)
Atlanta, GA.	210	740
Baltimore, MD.	470	1170
Housbon, TX.	40	540
Miami, FL	30	450
Phoenix, AZ.	280	840
San Antonio, TX.	110	700

5. CONCLUSIONS

A number of observations and conclusions can be considered at this stage of research.

(1) On first observation the NMRP oerformance compares favorably with standard roof ponds. This is in addition to certain operating advantages that the NMRP already enjoys.

2) Our results are for a test pond which is being operated as a calorimeter. One must keep in mind that for the Trinity University wet roof ponds, the pond load is driven by the building itself.

(3) Cooling capacity decreases with increasing ambient temperature and decreases with decreasing water flow rate.

6. NOMENCLATURE

°C = Celsius degrees
°*F* = Fahrenheit degrees
M^2 = area in square meters
w = @r in watts
hr = time in hours
NMRP = Nebraska Modified Roof Pond
PSRG = Passive Solar Research group

7. REFERENCES

(1) Maratt W., Murray K. and S Squier, Roof Pond Systems, Energy Technology Energy Center, Rockwell International ETEC-83-6, (April 1984).

(2) Chen et al, Cooling Performance Curve For The Nebraska Modified Roof Pond, proceedings of ASES conference, Portland, Or. (June 1987).

(3) Clark G. and P. Berdahl, Radiative Cooling: Resources and Applications., proceedings 5th Passive conference, Amherst, Ma. (Oct 1980), 36 pp.

(4) Niles P. et al. Cooling Rate Equations, draft version under contract EG-77-C-03-1600, DOE (1978).

(5) McAdams, W. H., Heat Transmission, Graw Hill (1954)

(6) Clark, G. et al Validated Simulations of Roof Pond Cooled Residences in U. S. Climates, prepared under DOE contract DEAC03-79CS30201, (Aug. 1983)

Figure 1
Operation Of The Nebraska Modified Roof Pond System During The Heating Mode

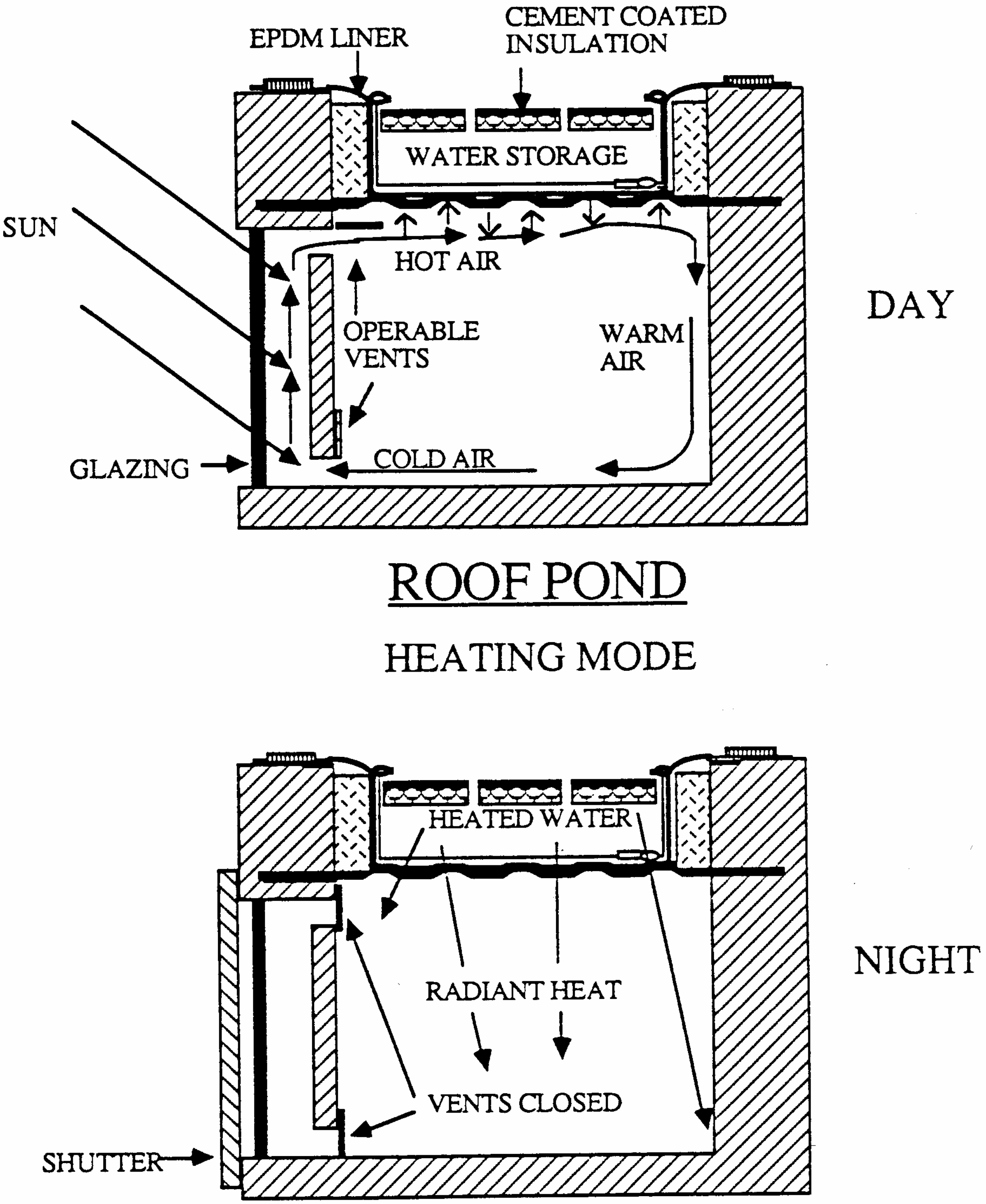

Figure 2
Operation Of The Nebraska Modified Roof Pond System During The Cooling Mode

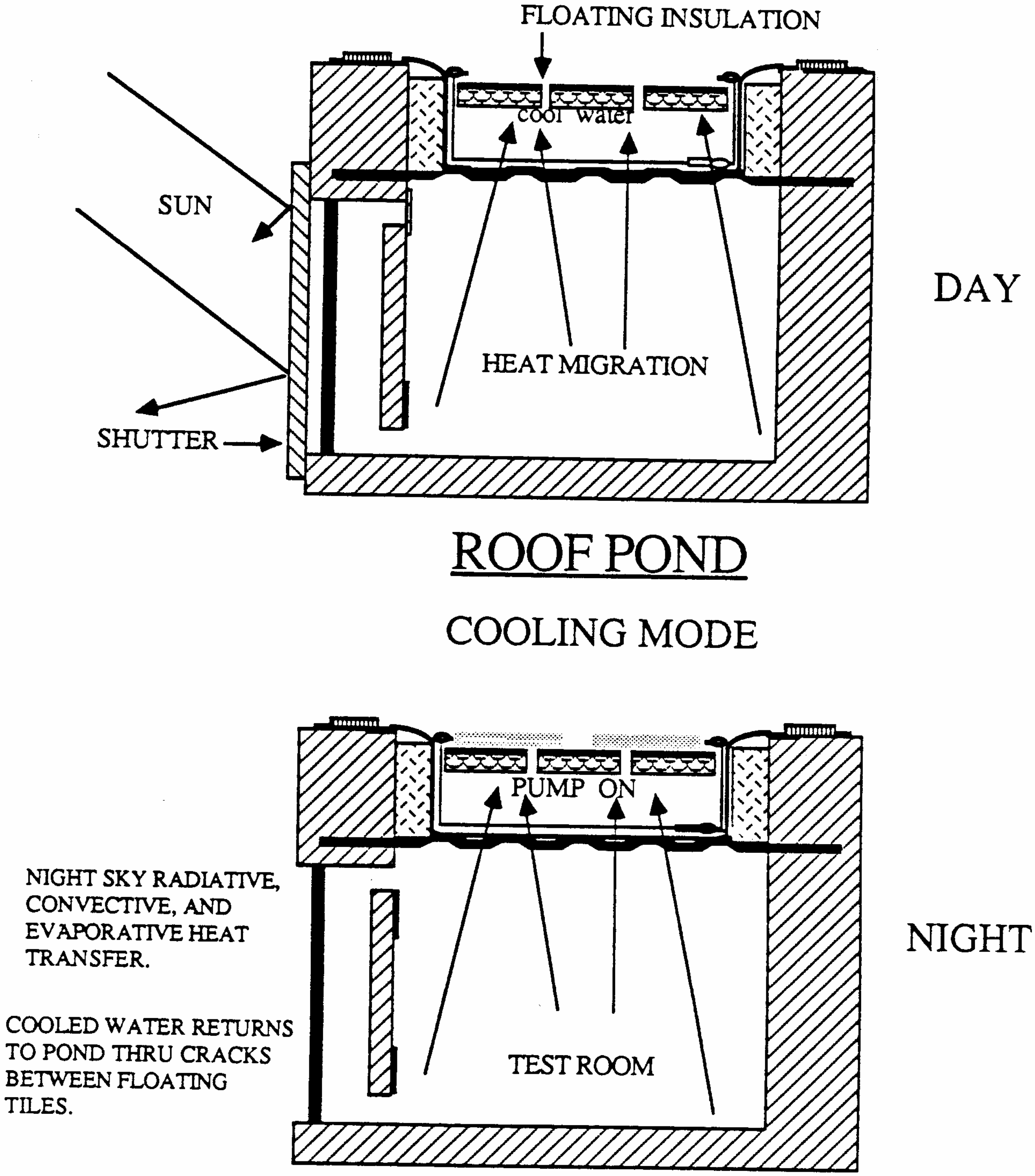

Figure 3
Instrumentation And Sensor Layout During The Summer 1986 Experiments