FULL YEAR PERFORMANCE SIMULATION OF A DIRECT-COOLED THERMAL STORAGE ROOF (DCTSR) IN THE MIDWEST

Richard C. Bourne
Davis Energy Group, Inc.
123 C Street
Davis, CA 95616
and
Dr. Bing Chen
Passive Solar Research Group
University of Nebraska at Lincoln
University of Nebraska at Omaha
Omaha, NE 68182

ABSTRACT

Previous papers by the authors describe the direct-cooled thermal storage roof (DCTSR) concept and prior small-scale developmental and monitoring work. DCTSR water containment is provided by a single-ply roof membrane in thermal contact with occupied space below. Hard-topped rigid insulation panels float on the 311 to 411 water storage layer. During summer nights, storage water is distributed above the insulation panels where it is cooled by evaporation and night sky radiation before draining back into the water layer through panel joints. The cooled water provides a thermal flywheel effect to reduce subsequent cooling loads. In winter, storage water may be warmed from below by internal gains or direct solar gains reflected or reradiated from other room surfaces; water remains below the insulation layer during heating load conditions.

A 1024 ft2 research building has recently been constructed with a DCTSR covering the entire roof surface, on the University of Nebraska Allwine Prairie Preserve near Omaha. This paper reports use of a modified version of the MICROPAS full year hourly simulation program to estimate performance of the new DCTSR project. Roof zone evaporative cooling algorithms were added to MICROPAS, and the simulation was calibrated to a prior 256 ft2 DCTSR test installation. The new test building was modeled with and without the DCTSR in conjunction with an Omaha weather tape.

1. INTRODUCTION

The direct-cooled thermal storage roof (DCTSR) concept was conceived by Richard Bourne in 1979 and has undergone small-scale testing since 1982 by both Davis Energy Group and the University of Nebraska's Passive Solar Research Group (PSRG). The primary goal of prior DEG work has been DCTSR development for application as an improved commercial building roof system which extends roof life and reduces cooling loads. PSRG work has concentrated on evaluating potential heating and cooling energy savings in the Midwest.

The essential DCTSR feature (see Fig. 1) is a layer of water (typically 311 to 411 deep) covering the entire roof membrane, with the water layer in turn covered by a floating layer of UV-protected, moisture-proof insulating panels. Extended DCTSR roof life is projected because the roof membrane is protected from the sun, wind, temperature extremes, falling objects, and drain-clogging debris. Storage water is pumped atop the insulating panels at night, and is cooled by evaporation and night sky radiation before draining back through panel joints. The cool water remains below the panels in the day time to provide full or partial building cooling.

In the most economical DCTSR configuration (called "Type 111) the roof membrane is not insulated from occupied space below, permitting direct building cooling through the roof deck. The Type 1 DCTSR cannot be used to dehumidify because dripping water could cause interior damage if the ceiling surface were allowed to be colder than the indoor dew point temperature. Other potential DCTSR configurations insulate storage water from occupied space, allowing lower (mechanically chilled) summer water temperatures. Current simulation work evaluates only the Type 1 DCTSR.

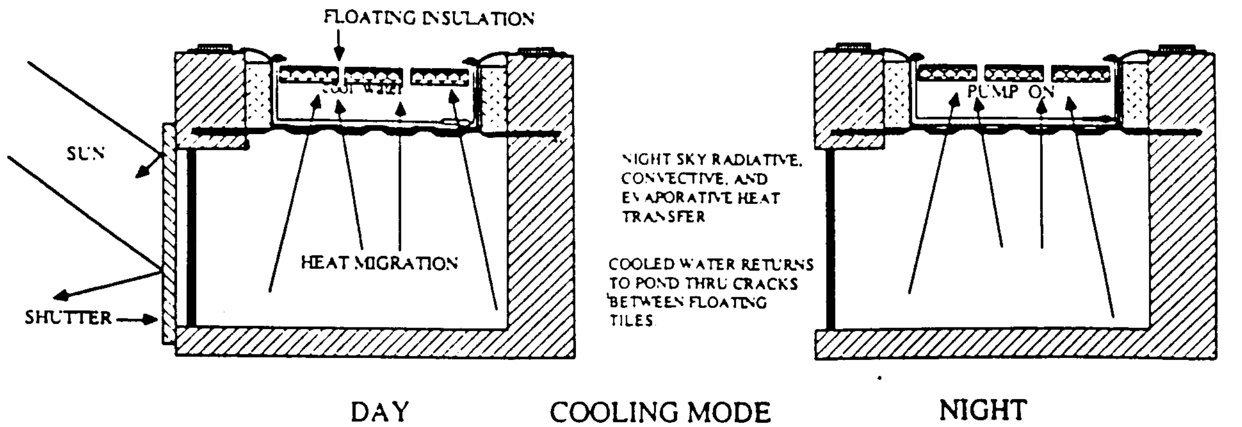

Fig. 1. Schematic DCTSR Section View

In winter, the DCTSR water offers opportunities for reducing heating energy costs by storing excess solar and internal gains to maintain an average indoor temperature nearer the indoor set point than can be maintained in a building with lower mass; particular benefits should accrue in buildings with passive solar glazing features. Active solar collectors can potentially be coupled to the DCTSR, whose large mass and direct contact with space below will contribute to increased solar collection efficiencies. Active solar coupling to the DCTSR has not been modeled.

Prior development work includes construction and testing of two prototypes (a 256 ft2 DCTSR over a garage in Davis, CA and a 20 ft2 "Nebraska Modified Roof Pond" test cell in Omaha, NE). The Davis prototype has only been tested in cooling mode, and results have only been reported in funding proposals. Three prior ASES papers (1.2,3) and a University of Nebraska master's thesis (4) describe results from the Omaha test project.

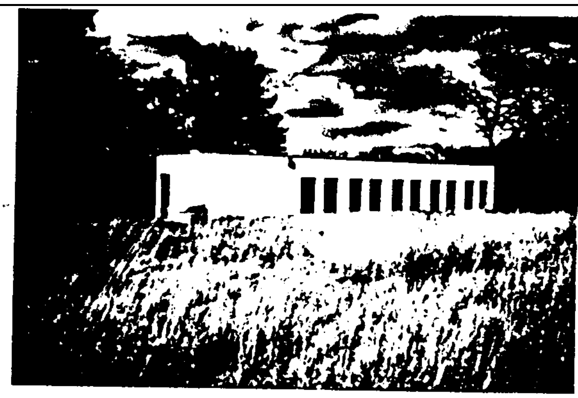

Fig. 2. Building from Southwest

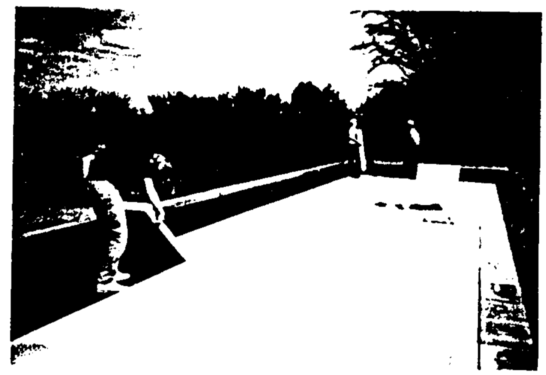

Fig. 3. DCTSR Panel Placement

The first "full building" DCTSR has been installed on the recently-completed University of Nebraska Energy Research Center (located on the Allwine Prairie Preserve west of Omaha). Fig. 2 provides a view of the 1024 ft2 (161 x 641) slab-upgrade building from the southwest, Fig. 3 shows -.he DCTSR during placement of the 3-1/211 thick cement topped (extruded polystyrene) insulation panels, and Fig. 4 shows the completed DCTSR with water distribution tubing in place, prior to filling with water. Roof drains allow a 6" maximum water depth, which may be reduced for experimental purposes. A filtration system removes residue during summer night water circulation hours. A wide variety of water distribution patterns, rates, and schedules may be used during cooling season operation.

The goal of preliminary simulation work presented in this paper is to benchmark expected DCTSR performance on the new building, and to project the impact of several building features and control strategies on DCTSR energy savings. The analyses specifically project impacts of glazing areas, floor coverings, internal gains, roof absorptivity, and set back/setup thermostat control.

2. ANALYTICAL METHODS

Thermal performance of the new building with and without the DCTSR was modeled using a modified, multizone full-year hourly version of MICROPAS, California's most widely used building thermal energy simulation program. The DCTSR was modeled as a discrete zone in thermal contact with occupied zone below. The standard MICROPAS "isothermal" mass option, with appropriate variable parameter values, was used to simulate the storage water.

Evaporative cooling algorithms were added to the DCTSR zone to simulate DCTSR heat rejection performance, with time-clock and low limit temperature controls. Program controls start the evaporative cooler (simulating the water distribution-heat rejection cycle) at a preset time each night; the cycle continues on a full hour basis until either time expires or the lower limit water temperature is reached.

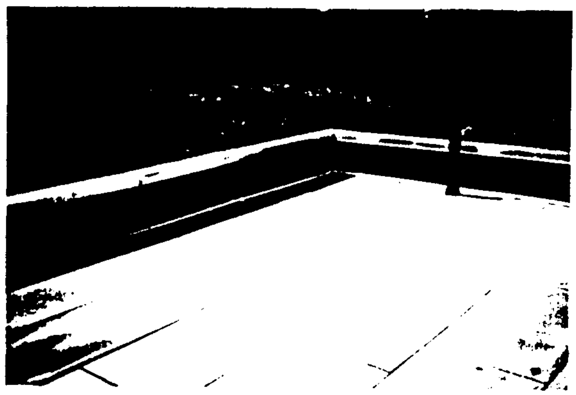

Fig. 4. DCTSR Distribution Piping

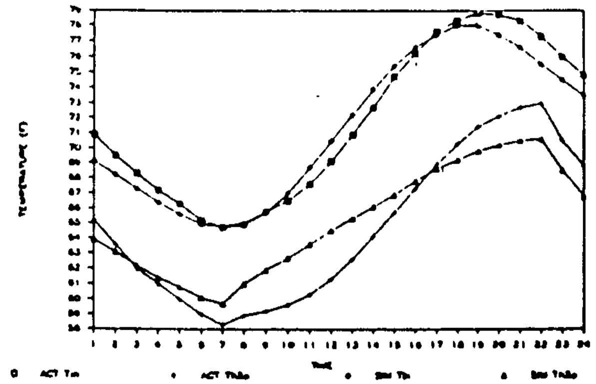

Fig. 5. Davis Calibration Results

The model is currently limited by its inability to separately compute evaporative and radiant losses to the night environment. Heat rejection is modeled to be entirely dependent on storage water-ambient wet bulb temperature difference. However, the algorithm, when calibrated with test data, should yield reasonable results because higher humidity outdoor conditions which reduce potential evaporative cooling also reduce radiant heat loss to the night sky.

The evaporative cooling flow rate parameters were adjusted to calibrate the model vs. test data from the 256 ft2 Davis, CA prototype. Fig 5 shows calibration results, which minimize the root-mean square "actual minus simulated" temperature difference totals for storage water and "below ceiling" air temperature. Actual outdoor temperatures were used for the calibration, which tracks actual indoor and storage water temperatures within about two and three degrees (F), respectively. More detailed simulation and calibration work will be completed from on-site monitoring in the next year.

Both DCTSR and conventional (R-19 insulated) roofs were modeled. With the exception of roof-related and other specifically-varied building parameters identified in Table 1 below, identical inputs were used for all runs. The building was modeled as constructed, with 641 width oriented east-west, and all 193 ft2 of fixed, double-glazed windows facing south. All solar gains were directed to indoor air-coupled mass rather than to the floor or walls. Walls are of 2 x 6 construction with R-19 insulation. An infiltration rate of d.4 air changes per hour was assumed. Summer water distribution operation for the DCTSR was simulated from 11 PM until 7 AM, or until water temperature was lowered to 60 F. Comfort setpoints were 65 F heating and 80 F cooling, respectively. Winter setback temperature was 55 F from 5 PM to 8 AM (simulating office building occupancy) ; summer setup temperature was 85 F on the same schedule.

Run	Roof Type	Roof Abs. (1)	Setback (2)	Int. Gain (3)	Glazing (4)	Carpet (5)
1	R19 Conv	0.3/0.3	yes	10,000	actual	light
2	DCTSR	0.3/0.3	"	"	"	"
2a	"	0.3/0.0	"	"	"	"
3	R19 Conv	0.3/0.3	yes	10,000	actual	none
4	DCTSR	0.3/0.0	"	"	"	"
5	R19 Conv	0.3/0.3	no	10,000	actual	light
6	DCTSR	0.3/0.0	"	"	"	"
7	R19 Conv	0.3/0.3	yes	30,000	actual	light
8	DCTSR	0.3/0.0	"	"	"	"
9	R19 Conv	0.3/0.3	yes	10,000	103	light
10	DCTSR	0.3/0.0	"	"	"	"
11	R19 Conv	0.3/0.3	yes	10,000	actual	heavy
12	DCTSR	0.3/0.0	"	"	"	"

TABLE 1: SIMULATION INPUT VARIATIONS

Notes:
1. Roof Absorptivity: heating/cooling
2. Setback: includes heating setback & cooling setup
3. Int. Gain: daily internal gains in BTU's
4. Glazing: runs 9,10 have 41 ft2 S & N, 10.5 ft2 E & W
5. Carpet: light= R1.0, heavy= R3.5

The goal of Runs #1 and #2 was to provide a basic comparison of anticipated thermal performance for the DCTSR and conventional roof. Run 2a assumed DCTSR intermittent daytime summer water distribution to maintain insulation panel top temperatures at or near ambient, and became the standard for subsequent runs. Runs 3 and 4 assumed an exposed slab floor, whose thermal mass was expected to slightly reduce the value of ceiling water mass; runs 11 and 12 assumed thick carpet and pad rather than the standard commercial. carpet without pad. Runs 5 and 6 assumed no setback; setback was expected to adversely affect the DCTSR heating season savings potential. Runs 7 and 8 increased internal gains, which was expected to increase the projected DCTSR heating savings percentage. Runs 9 and 10 substituted a more typical glazing configuration for the actual passive solar configuration; this change was expected to reduce the DCTSR heating season savings percentage.

3.0 RESULTS

Table 2 provides projected annual heating and cooling loads for the 12 runs listed in Table 1.

For the base case (light colored roofs, setback and setup, low internal gains, actual glazing, light carpet), Runs #1 and #2 project DCTSR savings at 44% in cooling season and 2% in heating season. The limited projected heating season savings are attributable in part to lower-than R19 DCTSR roof thermal resistance; the thickest commercially-available topping panels are of 311 thick (RI5) extruded polystyrene. Run #2a shows that a zero absorptivity DCTSR surface in summer (as may be achieved by intermittent daytime roof cooling) should generate an additional 9.5% DCTSR cooling load reduction.

Runs #3 and #4 show the adverse effect of carpet on both heating and cooling loads, even with setback and setup thermostat control. Removing the light commercial carpet reduces projected "conventional roof" heating and cooling loads by 9.3% and 17.1%, respectively (Run #3). Without carpet, DCTSR heating loads are almost 4% higher than conventional (Run #4), probably because the slab becomes more effective as a thermal mass, reducing the potential water mass benefit. Projected I%" cooling savings are little affected by removing the carpet. As expected, Runs #11 and #12 show further erosion of projected energy savings as carpet thermal resistance is increased.

TABLE 2: SIMULATION RESULTS

Run	Description	KBTU Loads Heat	KBTU Loads Cool	% Savings (1)(2) Heat	% Savings (1)(2) Cool
1	Conv. Base	25.9	16.1	-	-
2	DCTSR (2)	25.4	8.99	2.0	44.1
2a	DCTSR Base	25.4	7.46	2.0	53.6
3	Conv. w/o carpet	23.5	13.3	9.3	17.1
4	DCTSR " "	24.4	6.20	-3.8	53.4
5	Conv. w/o setback	35.5	17.5	-37.1	-9.0
6	DCTSR " "	33.7	8.43	5.1	51.8
7	Conv., high int. gain	23.6	19.3	8.9	-20.2
8	DCTSR, " " "	22.9	9.75	2.8	49.5
9	Conv., min. glazing	30.4	6.46	-17.4	59.9
10	DCTSR, " "	31.7	1.75	-4.2	73.0
11	Conv. w/heavy carpet	26.5	16.5	-2.3	-2.9
12	DCTSR " "	25.6	7.56	3.1	54.2

Notes: 1. % savings are vs. Run #1 for Runs #2, 3, 5, 7, 9, 11
2. " " vs. run above for Runs #4, 6, 8, 10, 12

Runs #5 and #6 show the higher heating and cooling loads which result when winter night setback and summer night setup (as for a typical office building occupancy) are removed. For the conventional roof (Run #5)i constant thermostat settings at the 65 (F) heating setpoint and 80 (F) cooling setpoint increases heating and cooling loads by 37.1% and 9.0%, respectively. DCTSR heating savings (Run #6) increase to 5.1% without setback, confirming that setback reduces DCTSR savings because the water mass inhibits rapid indoor temperature change. Cooling load savings in KBTU's/yr. also increase without cooling setup.

Runs #7 and #8 show the projected impact of higher internal gains, which reduce heating loads and increase cooling loads. Run #8 results suggest that total and percentage heating savings increase with internal gains, as expected; the water mass absorbs a portion of the internal gains and thereby limits indoor temperature rise in moderate winter weather. The DCTSR is also projected to save more cooling load KBTU's as internal gains increase, suggesting that DCTSR pay backs might improve noticeably under high building occupancy conditions.

Runs #9 and #10 project the impact of glazing area on building energy performance with and without the DCTSR. Reduced glazing area and more uniform glazing distribution increases projected heating loads by 4.5 million BTU's/yr. but reduces projected cooling loads by more than twice that amount (compared to Run #1). These results suggest that the building's "passive solar" heating features may not produce a net energy savings when increased cooling loads are considered, depending on heating and tooling system efficiencies. (Summer shading of glazing, not modeled here, would reduce negative summer impact of the large actual glazing area.) Run #10 results suggest that the DCTSR can nearly eliminate cooling loads in a building with low internal gains and a more normal glazing area. However, a DCTSR heating penalty vs. the conventional roof is projected in Run #10, probably due to the reduced likelihood of overheating (which the DCTSR counters) in the normal glazing case.

Run #2 "Peak cooling sequence" hourly DCTSR temperature profiles were also evaluated to assess the potential for condensation on the ceiling. Fig. 6 plots projected hourly outdoor drybulb, outdoor dewpoint, indoor drybulb, and DCTSR water temperatures. Assuming that the air conditioning system removes sufficient moisture to prevent indoor dew point temperature from exceeding outdoor dewpoint temperature, no ceiling condensation should occur because DCTSR temperature would never drop below out door dewpoint temperature.

4. CONCLUSIONS

Based on detailed (but apprximative) hourly computer simulations for a newly completed research building, the DCTSR is projected to reduce commercial building cooling loads in the Omaha climate by 44 to 73%. Among the variables studied, projected cooling savings are most significantly affected by glazing configuration and internal gains. Computer studies indicate that moisture will not condense on ceiling surfaces unless significant internal moisture sources are present.

Projected heating loads with the DCTSR range from 4% above to 5% below loads for the conventional comparison cases. Reduced glazing, an exposed floor slab, and night setback all tend to reduce DCTSR heating season savings vs. conventional roof construction. Coupling of low cost active solar collectors to the low temperature DCTSR water layer should be studied as a potentially cost-effective heating season energy conservation strategy,

5. REFERENCES

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