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A Radiative Cooling System Using Water as a Heat Exchange Medium

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A passive cooling system, integrating radiative and convective cooling, was tested for a test cell in Sde-Boqer, Israel. The system was based on circulating water from a pond on the roof of the cell through a system of radiators, which removed energy from the system by nocturnal long wave radiation and convective losses. The water flowing through the system kept the radiators relatively warm, thus increasing radiative losses and eliminating convective gains. Wind screens were not necessary in this case. The radiators also served as a shading device over the roof during the day.

Introduction

Nocturnal radiative cooling of buildings has been studied extensively, particularly in the years following the energy crisis of the 1970's, when issues of energy conservation in buildings received considerable attention. The theoretical aspects of the subject were covered thoroughly by, among others, Clark and Berdahl (1980). Gordon & Zarmi (1981) described the transient behaviour of an unutilized radiator, expressing the relationship between the stagnation temperature, the relaxation time and the effective temperature of the surroundings. Givoni (1982) reviewed the basic physics describing the phenomenon and evaluated a number of strategies proposed to utilize its potential. In fact a number of workable systems were developed and implemented on experimental buildings. The greatest success in the field was claimed by Hay (1978, 1980), developer of the "Skytherm" system. A number of versions of this design were constructed, in Las Cruces (N.M.), Phoenix (Ariz.) and Atascadero (Ca.). These buildings were monitored and proved capable of maintaining the interiors comfortable even under extreme ambient conditions. However, no data is given on the contribution of radiative cooling alone to the total thermal performance of the houses.

Givoni (1982) concluded that a cooling system involving the circulation of air across an exposed metal deck cooled by nocturnal radiation was the most promising of the design solutions he investigated. The "Roof Radiation Trap" he developed (1977) was constructed along these lines. Ingersoll and Givoni described the operation of this system using a mathematical model they derived, and computed the cooling potential of such a system. They predicted an increase in the cooling rate of up to 46.9 watts per square meter of radiator compared with simply introducing the same volume of untreated ambient air, though this depended on the amount of air circulated through the input duct of the system.

The fairly modest cooling power achieved by what Givoni considered to be the type of system most suited to utilize nocturnal radiative cooling indicates that the potential of all such systems may in fact be quite limited. This is because nocturnal longwave radiation from materials commonly found on the earth's surface is rarely more than 100 watt*m^{-2}, even under ideal meteorological conditions. By comparison, noontime solar radiation levels in excess of 1000 watt*m^{-2} are common in many countries, and even solar heating systems installed in high-latitude countries can rely on solar radiation levels of several hundred watt*m^{-2} for at least part of the day.

Since the potential for radiative cooling of buildings is inherently limited, any system designed to make use of this phenomenon must be very efficient. Givoni (1982) identified two types of problems involved in the design of such systems, apart from the estimation of the meteorological parameters of the area under consideration:

a. Maximizing the *net* heat flux from the radiating surface, taking into account such problems as convective heat gain from the ambient air, and the effects of dust and dew on the radiator.

b. Utilization of the "cold" produced by the nocturnal radiation - the transfer of this cold to the building and the way in which it is utilized to provide comfort conditions.

Most of the work on radiative cooling has concentrated on studying the heat exchange occurring at the surface of the radiator and increasing its efficiency. Michell and Biggs (1979) compared the performance of a galvanized steel radiator painted with white titanium dioxide paint with that of a similar radiator covered with 12 µm thick sheets of "tedlar". Both were covered with polythene windscreens, which had a transmissivity in the infra-red region of about 85 percent. They concluded that there was no significant difference between the two cooling systems, which produced 29 watt*m^{-2} of cooling by circulating air against the lower surface of the radiator. Granqvist and Hjortsberg (1981) used selectively emitting coatings to achieve low temperatures in small test radiators with a three-layer polyethylene windscreen. A temperature depression of up to 14 °C below ambient air was achieved on a clear night. However, they also reported that for temperature depressions of up to 10 °C below ambient, ordinary paint with an emissivity of 0.9 (simulating a black body radiator) achieved a greater cooling rate under the same conditions. The highest cooling rate recorded for the selectively coated radiator was 61 watt*m^{-2}, with the radiator at ambient temperature. Lushiku and Granqvist (1984) describe the performance of a radiator consisting of a hollow section through which selectively infra-red emitting gases are circulated, radiating to the sky through a transparent, three-film polyethylene wind screen. Using C_2H_4 as the radiating fluid, temperature depressions of up to 10°C below ambient are reported when the circulation of the gas is stopped. A maximum cooling rate of 65 watt*m^{-2} was calculated for a radiator filled with this gas at ambient temperature.

The work described in the previous paragraph dealt with small scale test installations operating for short periods of time under controlled conditions. The type of system required for cooling a building would have to be effective even after prolonged exposure to ambient conditions. Two factors in particular reduce the efficiency of radiator systems incorporating transparent windscreens, selective coatings, or both. First, dust accumulation reduces the effect of both strategies of enhancing the performance of the radiator. Dust reduces the transmissivity of a so-called transparent windscreen considerably, and masks the selective radiation properties of special coatings. Secondly, unless the air is extremely dry, the radiator surface cools down to the dew point, whereupon condensation forms on it. At this point, the film of water collected on the radiator becomes the radiating surface, with an emissivity in the longwave spectrum similar to that of ordinary paint. The result is that in practice, both types of improved radiator systems, while being expensive and difficult to install and maintain, are not significant improvements over simple, painted metal surfaces.

Givoni (1982) concluded as much, and turned his efforts to the design of better heat transfer mechanisms with the fabric of the building. The basic issue involved is the following: since radiative cooling is effective only at night, a thermal storage mass must be incorporated in the building to carry over the benefits of nocturnal cooling to the warmer daytime hours when it is most needed. This in turn involves making a choice between two basic approaches:

a. The thermal storage mass of the building (in this case, generally a horizontal roof) is cooled directly, and sealed and insulated during the day to avoid unwanted heat gains. The "Skytherm" system mentioned briefly above operates on this principle, as does the "Living Systems" roof pond constructed by Hammond on a house in Davis, California.

b. The second option involves the use of a fluid, such as air or water, as a heat transfer medium between the thermal storage mass and a radiator constructed outside of the thermally insulated envelope of the building, generally on the roof. The "Roof Radiation Trap" designed by Givoni (1977) and the system proposed by Juchau (1981) operate on this principle.

The choice between air and water as the heat exchange medium of a radiative cooling system where the thermal mass is cooled indirectly is central to the design of that system. Like most passive heating or cooling devices, it also has a great influence on the form of the building as a whole.

a. In the case of air, the contact between the radiator surface and the thermal storage mass is *indirect*. The air is cooled by the radiator, and in turn must be circulated through the house in order to cool its walls and floors, in the case of massive construction, or circulated through a special heat sink, such as a gravel bed, in the case of lightweight construction. The advantage of this type of system is that the temperature of the air can be reduced to a greater extent than that of water, since its specific heat capacity is much lower. (This does not mean, however, that the *rate of energy transfer* will be greater than in a water-based system!)

b. In the case of water, the contact between the radiator surface and the thermal storage mass can be *direct*. Due to the high specific heat of water, it can serve not only as the heat exchange medium but as part of the thermal storage mass, in the case of massive construction, or as the storage mass itself in the case of lightweight buildings. The water can be stored in a roof pond or in a reservoir underneath the floor, absorbing heat from the rest of the building during the day but exhibiting only a small rise in temperature.

Description of the System

Overview of System.

The system described in this paper is based on the circulation of water through a radiator with a hollow section. The water reservoir, in the form of a shallow roof pond, served as a heat sink which absorbed heat from the building (through a thin concrete roof). The circulation of water at a relatively high temperature prevented the radiator from being cooled to a low temperature, even though the cooling rate (and thus the amount of energy radiated from the system) remained high. Since the temperature of the radiator surface was greater than that of the ambient air throughout most of the night, convection assisted in the process of heat extraction from the radiator (and thus from the building as a whole) rather than impeded it.

A room-size chamber was designed to test methods of cooling on a larger structure, as a step towards establishing a cooling technology that could be used in a full-size building. The structure integrates a cooling mechanism with a storage mechanism, and a means of transferring energy between them.

Description of Test Chamber.

The test chamber (Fig. 1) consisted of a 2m x 2m x 2.5m high structure. The walls were made of 20cm hollow concrete blocks, insulated with a 5cm thick polystyrene board on the exterior surface. The polystyrene was protected by a white-painted 8mm thick acrylic plaster. The floor of the chamber was made of a concrete slab 10cm thick and insulated from the ground underneath by a board of 10cm polystyrene. The roof was made of a 10cm concrete slab. The structure was windowless and the door was made of a double layered panel, in which one layer included 4cm of polystyrene. Between the door and its frame a gasket was installed, and the door was tightened to the frame with screws, to ensure no air infiltration. An effort was made during the design and the construction of the unit to eliminate any heat bridges in the envelope of the building and any air infiltration into the structure.

The roof of the structure was designed to hold a water pond containing approximately 400 litres of water. Two Lordan LSC-F commercial solar water heater collectors were installed above the roof at 13 degrees tilt angle facing south. (This angle was chosen to enable comparison with another system investigated under the same research contract. Since Clark and Berdahl (1980) found that a surface inclined at 15 degrees to the horizontal radiates only 7% less than an otherwise similar horizontal radiator, this was deemed to have little effect on the overall results.) The glass of the collectors was removed and their exposed surface painted white, to prevent overheating during the day. Each collector measured 2.18 x 1.27 meters, and consisted of 12 copper water pipes of ⅞" diameter, each installed at the centre of a copper strip 10 cm wide running along the long axis of the radiator. Two distributing copper pipes of ½" diameter ran along the short axis of the radiator, on both sides. Water from the roof pond was circulated at night by a small water pump through the collectors and back to the pond. The water was covered with a 10cm floating polystyrene board and the air space between the collectors and the roof pond was enclosed, insulated and sealed against air infiltration to prevent the water from being heated by convection. Temperature was monitored at various points of the circuit, and the amount of water circulated was recorded. Wall, ceiling and air temperatures were recorded at several points in the interior of the test cell (Fig. 1).

Operation of the System.

The water that circulated through the collectors was cooled by both *radiation* and *convection* (for most of the night). This in turn gradually reduced the temperature of the water in the pond. The concrete roof of the structure was then cooled by the water, thus lowering the air temperature inside the structure. The mass of the structure and its insulation helped maintain the low interior temperature throughout the daily cycle. During daytime, the white collector functioned as a roof shading device, allowing only 14 litres of water (the collectors' capacity) to be heated. It is important to emphasize that unlike most evaporative cooling systems, the cooling process described here did not affect the water vapour content of the air inside the structure. Thus the improvement in thermal comfort due to the reduction in the temperature of the air was not offset by a rise in the humidity.

The operation of the water pump was controlled by means of a timing device. Water circulation started at 19:30, when the temperature of the radiator dropped below that of the water in the roof pond (This was found by observation after several days of operation). The pump was turned off at 05:00, shortly after sunrise. The rate of flow was controlled by means of a valve mounted at the outlet of the pump.

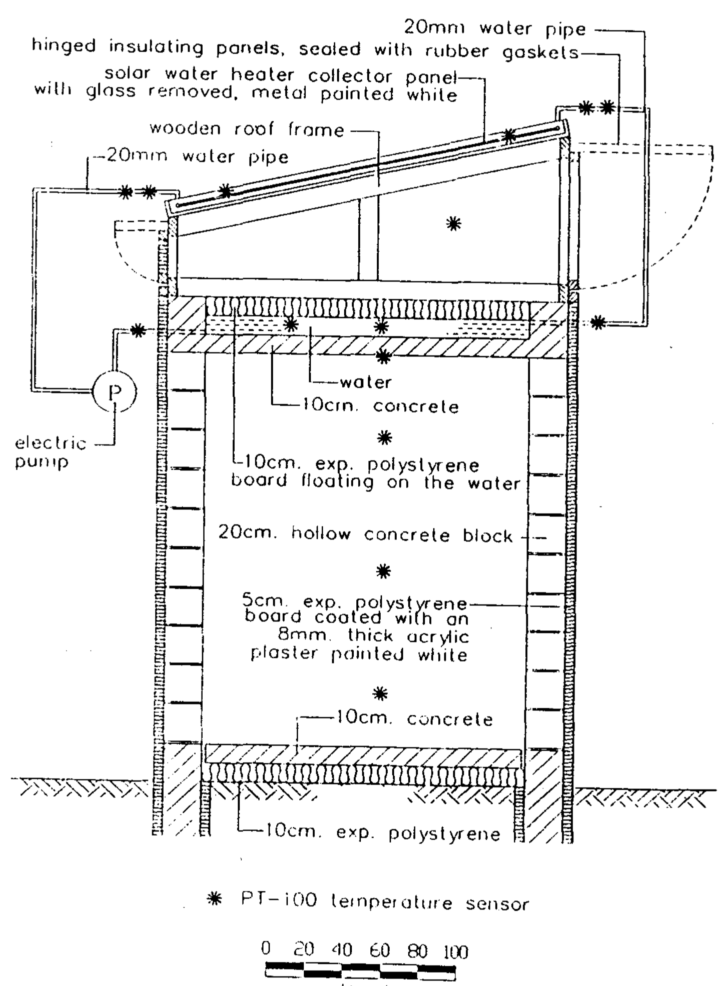

Figure 1. Section through test cell

Installation and Operating Costs

The system installed was constructed of commercially available components, bought "off the shelf". Principal among these were the solar collector panels, each costing approximately $150, an electric water pump, which cost about $200, and various polyethylene pipes and fixtures which cost another $150. It should be noted that conventional buildings in Israel are of massive construction with flat concrete roofs, so that the test cell required no structural modifications. The concrete was water-proofed with an acrylic sealing compound, but for long-term use traditional techniques such as use of EPDM are probably indicated.

Operating costs were negligible - the electric pump used had a power consumption of 60 watts, and was capable of circulating water through a much larger system of collectors.

Data collection

The data acquisition system was based on a Data Trapper model 1806 manufactured by Z.L. & Co. Electronic Industries Ltd., Israel. Temperature measurements were made with PT-100 sensors. Relative humidity was measured using a Rotronic Hygromer model L-200. Wind velocity was monitored with a Lambrecht Transmitter for Wind Velocity model 1469, which was installed near the test room at a height of 3.5 meters above the ground (the height of the radiator surface). All data were recorded at 3 minute intervals, from which 15 minute averages were calculated. The volume of water that was circulated each night was read manually the next morning on Arad magnetic multi-jet water meters with a resolution of 1 litre.

Analytical Methods

Determining the Cooling Power of the Radiator

Determination of the total cooling power of the radiator was done by measuring the water temperature difference between the entrance and the exit of the radiator:

$$Q_t = (T_{in} - T_{out}) \cdot c \cdot \frac{dV}{dt}$$

where

Q_t - the momentary cooling power [watts]

$T_{in} - T_{out}$ - temperature difference [^oC]

c - the specific heat of water $\left[watts*hrs*m^{-3}*^oC^{-1}\right]$

$\frac{dV}{dt}$ - the rate of flow of water [m^3*hr^{-1}]

Heat Exchange Processes at the Radiator Surface

Heat exchange between the radiator and the ambient involves two mechanisms - convection and radiation. The two mechanisms may be either complementary, or they may act in a way that counteracts each other, depending on the temperature of the radiator and on the ambient meteorological conditions.

Convective heat exchange

The general expression for the convective heat exchange at the surface of the radiator (Q_c) is:

$$Q_c = h_c \cdot (T_{rad} - T_{air})$$

Q_c - convective heat exchange ($watt*m^{-2}$)

h_c - convective coefficient ($watt*m^{-2}*^oC^{-1}$)

T_{rad}, T_{air} - the radiator and air temperature (°C)

The convective heat exchange depends on the temperature of the air and its velocity, which is expressed in the convection coefficient. Clark and Berdahl (1980) developed a series of expressions for evaluating the convective coefficient of the boundary layer under various conditions. They present the following simplified form of the general equation describing forced convective heat exchange under conditions of turbulent flow, which is accurate for wind speeds of about 1.5 - 5 $m*sec^{-1}$ (The equation is converted to metric units)

$$h_c = 0.76V + 2.8$$

where

h_c - convective coefficient [$watts*m^{-2}*^oC^{-1}$]

V - wind speed [$m*sec^{-1}$]

This expression was used to calculate the convective heat exchange that occurred in practice, even though the wind speeds that were recorded were in fact lower than 1 $m*sec^{-1}$ for at least part of the night. This may result in a small overestimation of the effects of convection, but the absolute error involved is quite small, considering the low temperature difference between the radiator and the ambient air. (For wind speeds of less than about 0.5 $m*sec^{-1}$, Clark and Berdahl suggest that the surface coefficient h_c is equal to 3.5, if the radiator is horizontal and is warmer than the ambient air, so that free convection takes place.)

Radiative heat exchange.

The procedure that was used to determine the net radiative cooling followed the one published by Givoni (1982). According to this procedure, the net radiative cooling is expressed by

$$R_{net} = \sigma \cdot \varepsilon_{rad}\left(T^4_{rad} - \varepsilon_{sky} \cdot T^4_{air}\right)$$

where

R_{net} - the net radiative cooling [$Watt/m^2$]

σ - the Stephen-Boltzman constant, $\left(5.67*10^{-8}Watt/m^2/^oK^4\right)$

ε_{rad} - the emissivity of the radiator

T_{rad} - the absolute temperature of the radiator [°K]

ε_{sky} - the sky emissivity

T_{air} - the absolute temperature of the ambient air [°K]

Sky emissivity was calculated using the expression developed by Clark and Berdahl (1980)

$$\varepsilon_{sky} = 0.006T_{dp} + 0.74$$

where

T_{dp} - dew point temperature

The dew point temperature(°C) was computed as a function of the ambient air temperature (T_{air}) and the relative humidity (RH), using the expression by Murray (1967) (Citing Tetens):

$$T_{dp} = 237.3 \cdot \frac{\ln RH + a \cdot b}{(a - \ln RH) + a \cdot b}$$

where

$$0 \leq RH \leq 1$$
$$a = 17.2693882$$

and

$$b = \frac{T_{air}}{T_{air} + 237.3}$$

Determining Convective Cooling as a Proportion of the Total Cooling

As has already been mentioned, the radiators were cooled by both radiation and convection, since their surface temperature was generally greater than that of the ambient air. The proportion of cooling due to each mode of heat transfer was determined by placing a plywood sheet parallel to the radiator, about 20 cms above it, thus in effect blocking out the sky as a heat sink. The radiator was therefore cooled by convection and by radiative heat exchange with the plywood sheet.

Unlike radiation to the sky, which is affected by meteorological conditions and cloud cover, and is therefore difficult to measure accurately, the radiative heat exchange with the plywood sheet is fairly simple to assess. This was done using the expression proposed by Givoni (1976):

$$q_r = 5.6987\, E \cdot \left[\left(\frac{T_2}{100}\right)^4 - \left(\frac{T_1}{100}\right)^4 \right]$$

where

q_r - the net radiative head exchange per unit area [watts*m²]
E - the effective emissivity of the two surfaces
T_1, T_2 - the absolute temperatures of the radiating surfaces [°K]

The value for E is given by the following relationship:

$$E = 1/(1/\varepsilon_1 + 1/\varepsilon_2 - 1)$$

where ε_1 and ε_2 are the emissivities of the two parallel radiators.

The total cooling power calculated for the covered radiator using the above procedure shows good agreement with the cooling power calculated using the temperature difference between the entry and exit from the radiator. Figure 2 displays the calculated and measured cooling rates for a typical night. It was therefore concluded that the expression used to calculate the convective heat exchange at the surface of the radiator did in fact give a fairly accurate estimate of this component of the total heat exchange between the radiator and the surroundings.

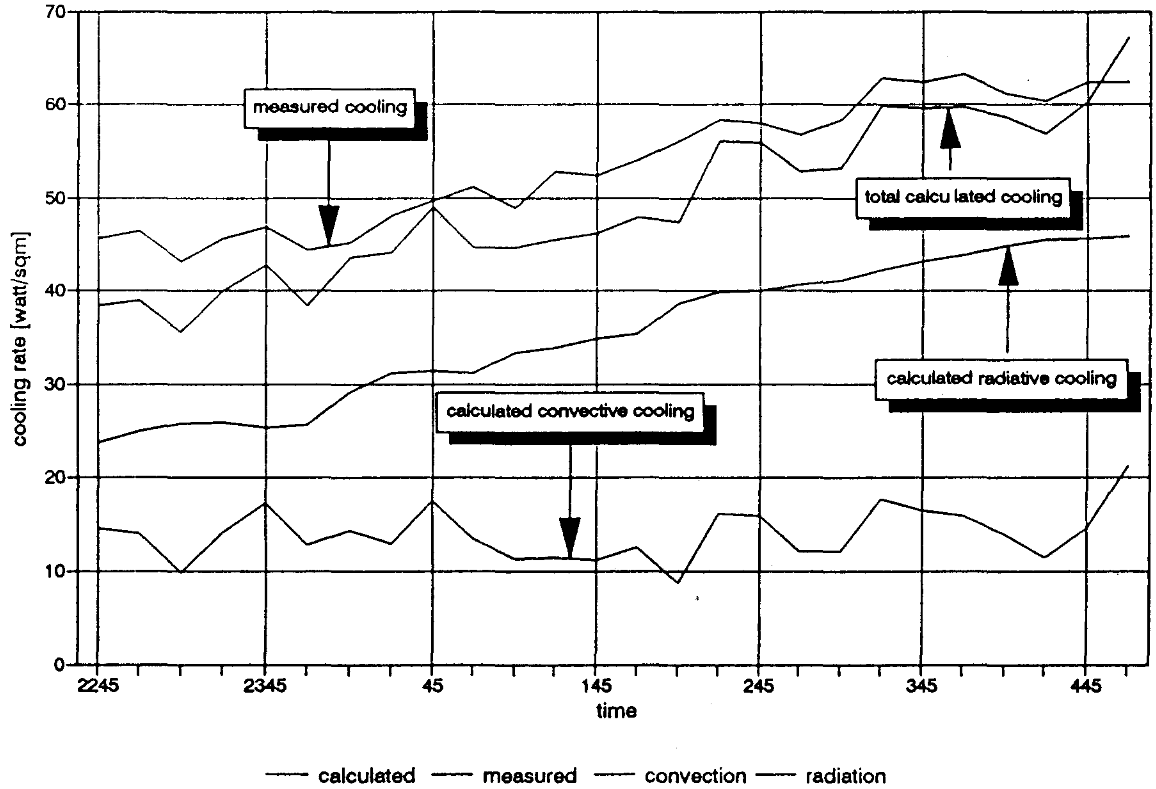

Figure 2. Calculated versus measured cooling rate for covered radiator, 24 August, 1990.

Results

Effect of the System on Test Chamber Internal Air Temperatures

For the test chamber air to be cooled, two conditions had to be met:

a. The water on the roof pond had to be cooled sufficiently.

b. The thermal coupling between the roof pond and the rest of the test chamber had to be effective.

The concrete slab roof did in fact prove to be a satisfactory means of transferring energy from the interior of the test cell to the roof pond. Figure 3 displays the temperatures of the roof pond, concrete ceiling and interior air of the test cell on a typical two-day period in the August 1988. Due to its high thermal conductivity, the temperature of the roof's lower surface (the ceiling of the test chamber) was always within 1°C of the temperature of the water in the roof pond. The average air temperature inside the test cell also reflected the moderating influence of the water, confirming its role as an efficient heat sink for energy absorbed inside the test cell by conduction through its walls. Three sensors located at different heights in the chamber measured temperatures identical to within 0.1°C, indicating that there was no air stratification, possibly due to the fact that the cold surface was at the *top* of the space.

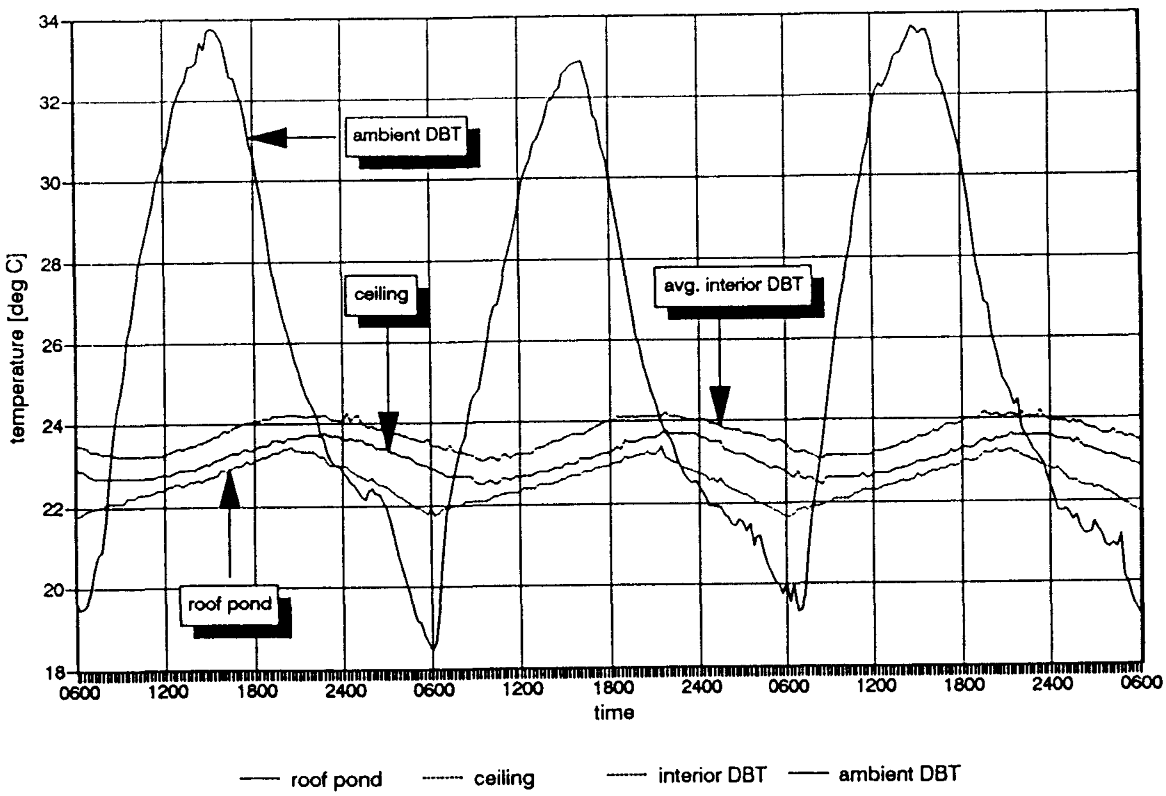

Figure 3. Test cell interior, roof pond and ceiling temperatures, 14th - 16th August, 1988.

The effect of the cooling system was ultimately reflected in its capacity to maintain the interior of the chamber cooler than the ambient temperature. The *mean daily internal air temperature* of the test cell was on the average 2.2 oC lower than the *mean daily ambient* dry bulb temperature, throughout the 6-week measurement period. When water circulation was stopped to monitor the thermal behaviour of the chamber without the intervention of the cooling mechanism, within two days the mean daily internal air temperature stabilized at an average deviation of 0.25 oC from the mean daily ambient temperature.

Figure 4 displays the daily maximum and minimum internal air temperature and ambient air temperature for a period of three weeks in the summer of 1988.

Calculated Cooling Rates

The system described here consistently produced cooling rates of approximately 80 watts*m^{-2}. Each 2.78 m^{-2} radiator therefore provided approximately 1.5 kWh of cooling per night. The cooling rate was nearly constant throughout the night, so that the average nightly cooling rate reported here is comparable to *peak* cooling rates reported elsewhere. The following figures, describing the results for a three-week measurement period in 1990, give the net cooling rate of the *radiator*, calculated as described above, averaged over 7 hours of operation each night, from 22:00 hrs to 05:00 hrs:

Highest average nightly cooling rate	104 watt*m^{-2}
Lowest average nightly cooling rate	59 watt*m^{-2}
Mean value for a three-week period	81 watt*m^{-2}

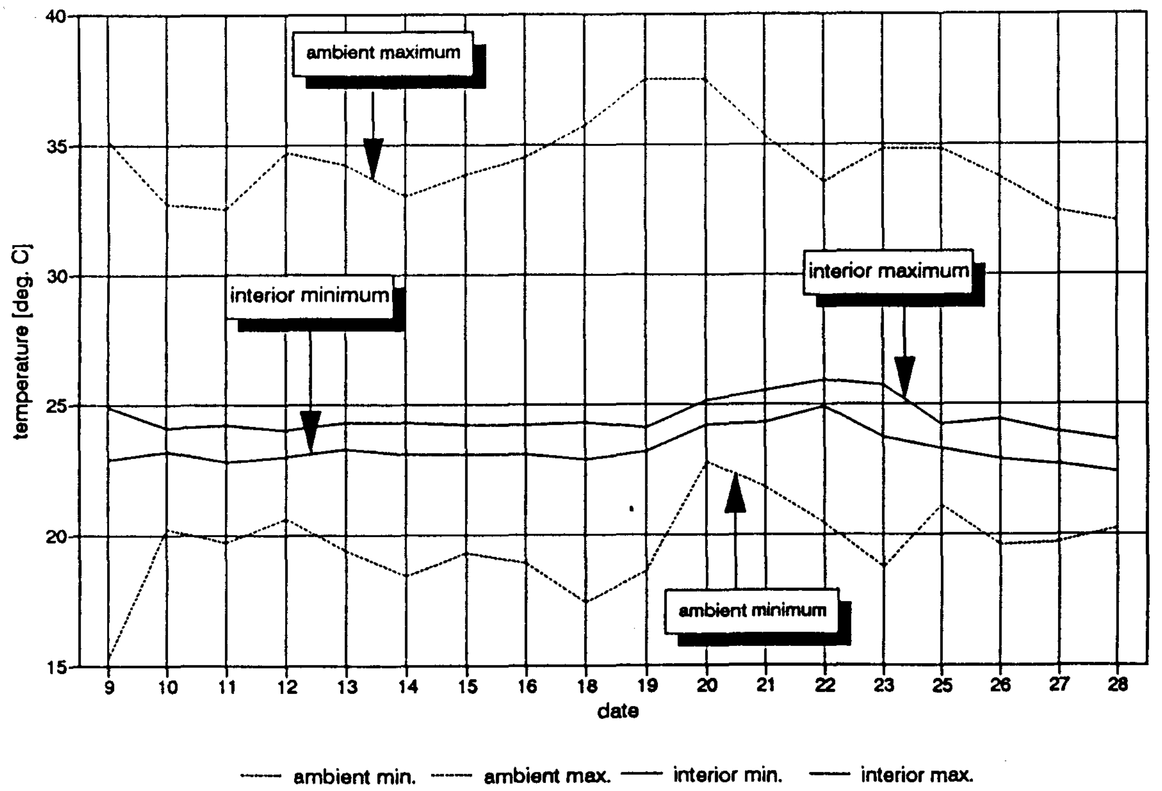

Figure 4. Test chamber interior and ambient dry bulb temperature (DBT), 9th- 28th August, 1988.

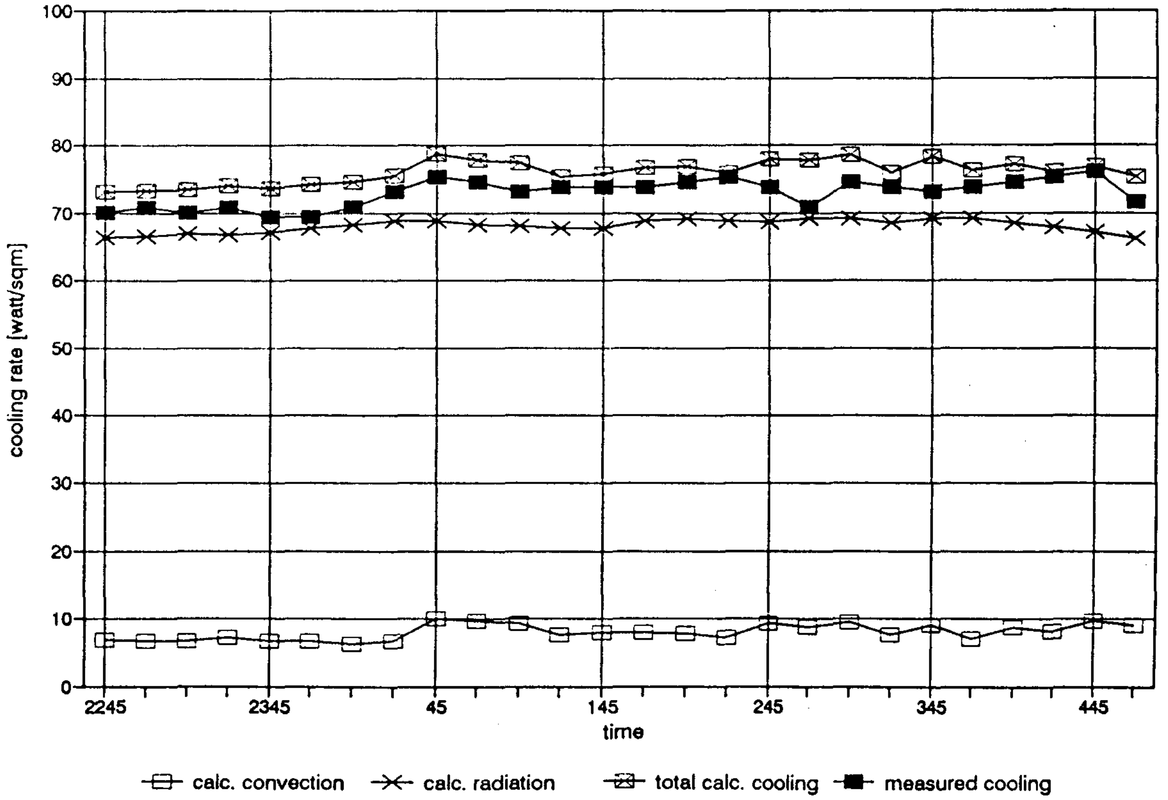

Figure 5. Net cooling rate on a typical night, 8th August 1990.

Figure 5 shows the net cooling rate for one radiator on a typical night, calculated for fifteen minute intervals according to the procedure described above (Section 3).

The Effect of Altering the Water Flow Rate on the Temperature Difference between Radiator Inlet and Outlet (ΔT)

Altering the water flow rate had a marked effect on ΔT, the difference in water temperature between the radiator inlet and outlet. At high water flow rates, ΔT was as low as 0.1 °C, whereas at low flow rates ΔT] was as much as 1 °C or more. The following mathematical expression describing the relation between the two quantities was found by regression analysis, using average nightly values of ΔT as the dependent variable, and the water flow rate *(dV / dt)* as the independent variable:

$$\Delta T = 0.045 + \frac{0.175}{dV / dt}$$

Figure 6 displays the relationship described by this expression, which was found to have a coefficient of correlation $r^2 = 0.96$.

this hypothesis for the range of flow rates actually monitored. For flow rates of about 0.1 $m^3 * hr^{-1}$ to 0.9 $m3 * hr^{-1}$, equivalent to circulating the whole volume of the roof pond 3.5-30 times per night, the average nightly cooling rate was more or less constant (Fig. 7). The differences between the values recorded for the various nights is partly accounted for by the meteorological conditions prevailing during the nights when measurements were taken. The correlation between the cooling rate and the water flow rate was insignificant ($r^2 = 0.08$).

The difference between roof pond temperature and ambient DBT

The difference between the temperature of the water in the roof pond, which is in effect the inlet temperature of the radiator, and the ambient dry bulb temperature, reflects the relation between the meteorological conditions and the thermal inertia of the system. Water stored in the roof pond functions as a heat sink, soaking up excess heat transmitted from the building by means of the thin concrete roof. If the system is incapable of radiating all of the excess energy at night, the temperature of the water in the roof pond rises. Thus, for example, the difference between the roof pond temperature and ambient dry bulb temperature is at a maximum on a cool night following a heat wave lasting several days. It was found that this factor had a significant effect on the cooling power of the system.

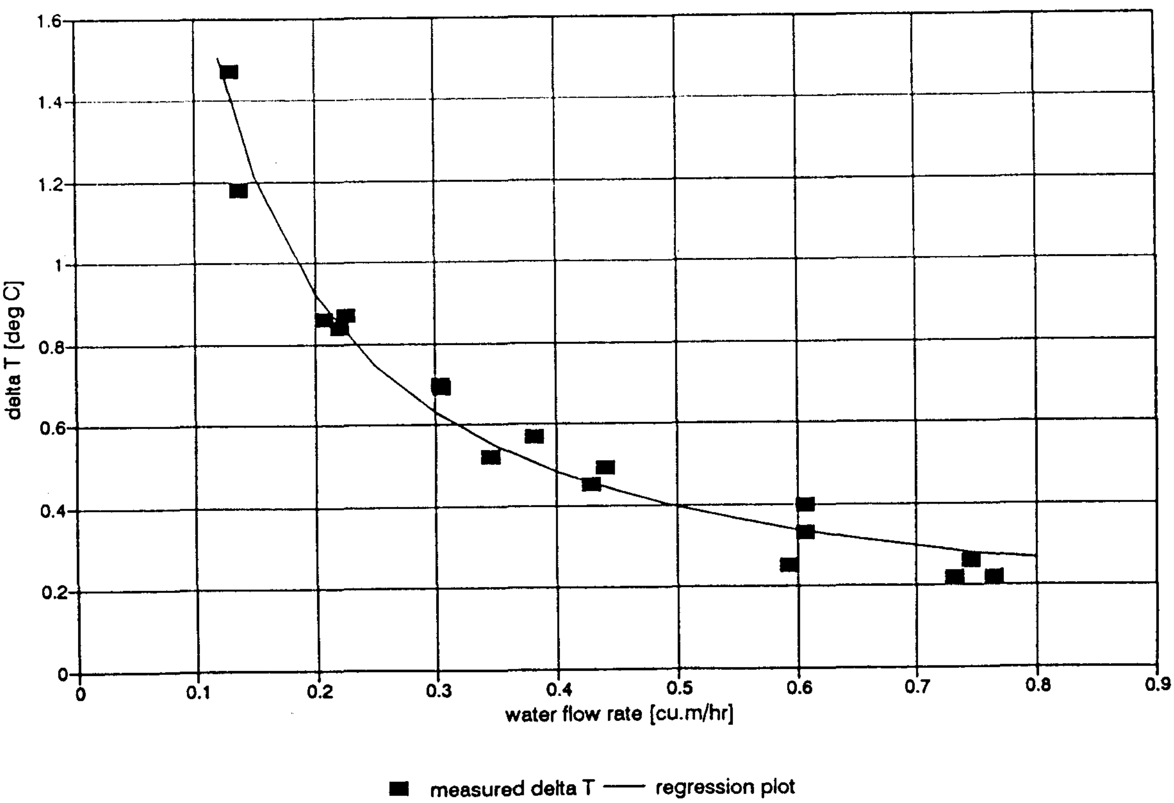

Figure 6. Difference between radiator entry and exit versus water flow rate.

Factors influencing the cooling rate

Water flow rate

It was initially assumed that increasing the water flow rate would increase the cooling rate, since this would limit the reduction in the radiator surface temperature, thus increasing both radiative and convective heat exchange. While this may be true at very low water flow rates, the data does not support this hypothesis for the range of flow rates actually monitored.

The following expression found by regression analysis, with the average nightly cooling rate (Q) as the dependent factor, and the temperature difference between the roof pond and the

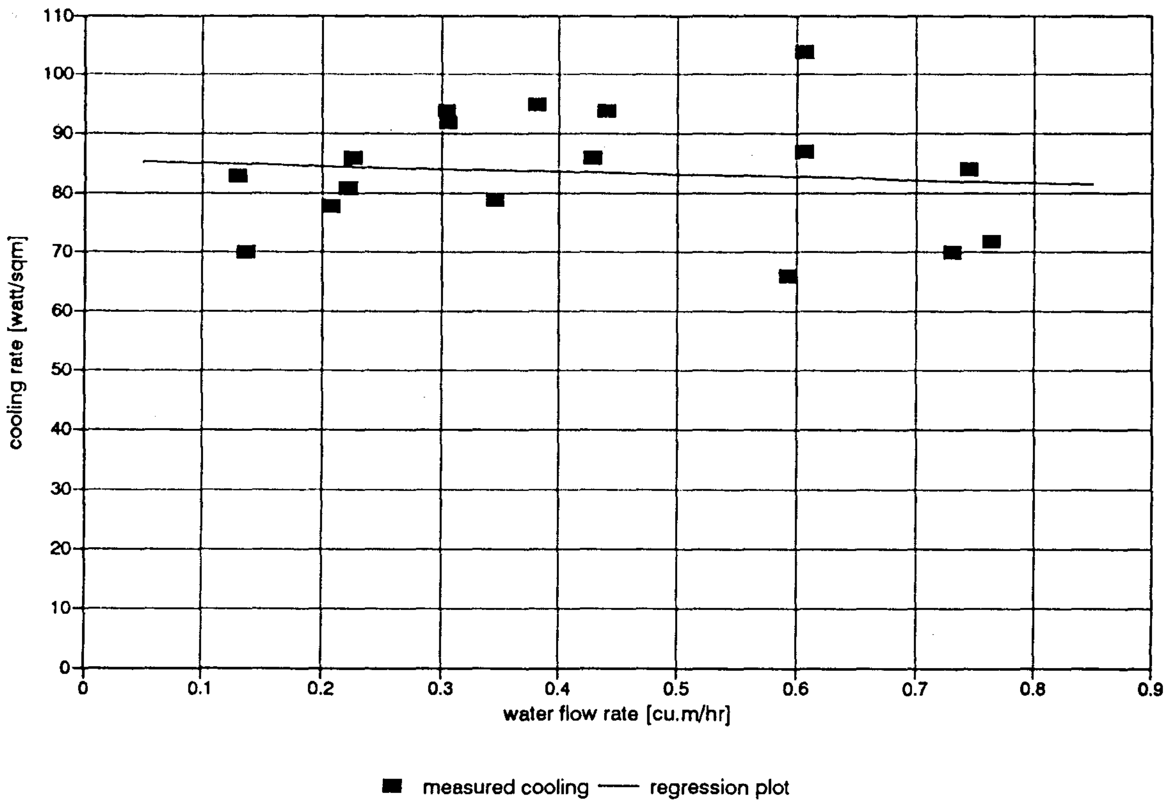

Figure 7. Average nightly cooling rate versus water flow rate.

ambient dry bulb temperature ($\Delta T_{p\text{-}a}$) as the independent factor, yielded a coefficient of correlation $r^2 = 0.76$:

$$\overline{Q} = 12.02 \cdot \Delta T_{p\text{-}a} + 52.84$$

Figure 8 displays the relationship between the average nightly cooling rate ($\overline{Q}$) and the temperature difference between the roof pond and the ambient dry bulb temperature ($\Delta T_{p\text{-}a}$)

Other meteorological factors

The other meteorological factors monitored, including ambient dry bulb temperature *(DBT)*, relative humidity *(RH)* and wind speed at the height of the radiator surface *(WIND)*, were found to have very little effect on the average nightly cooling rate of the radiator. It should be noted, however, that since the meteorological conditions in Sde-Boqer are fairly constant throughout the summer, this finding should be viewed as valid only under similar, fairly constant, conditions. Also, while the correlation between each of the meteorological factors and the average nightly cooling rate was not very high, it was still possible to infer the **qualitative** effect of these factors on the operation of the system.

Thus, since the temperature of the roof pond was nearly constant throughout the experiment, lower night-time dry bulb temperatures generally resulted in a higher value for $\Delta T_{p\text{-}a}$, and thus in higher cooling rates.

The relative humidity was generally high throughout the night-time measuring periods, typically reaching values of 85-90% in the early morning hours. High atmospheric moisture content reduces the effective sky temperature and thus the radiative component of the total cooling effect, and this is born out by the results of the correlation study carried out.

The effect of wind was to increase the cooling rate, since the temperature of the radiator was generally higher than that of the ambient air for most of the night.

As has already been indicated, effective sky temperatures were not measured directly, but were calculated indirectly using temperature and humidity data. This method does not take into account cloud cover, particularly if the sky is cloudy for only part of the night, so that meteorological conditions on the ground are not affected. Thus while longwave radiative cooling is reduced immediately by passing clouds, the cooling rate calculations based on meteorological conditions do not take this into account. While the sky conditions were generally clear throughout the measurement period, regular observations of the sky were not in fact carried out. At least some of the variations recorded in the average nightly cooling rates may be attributed to this factor.

Discussion of results

Analysis of the results shows that the most significant factor affecting the cooling power of the system was the difference in temperature between the water in the roof pond and the night-time ambient air. This finding has two consequences:

a. The system is *self-regulating* in the sense that greater daytime heat loads also result in higher night-time cooling rates.

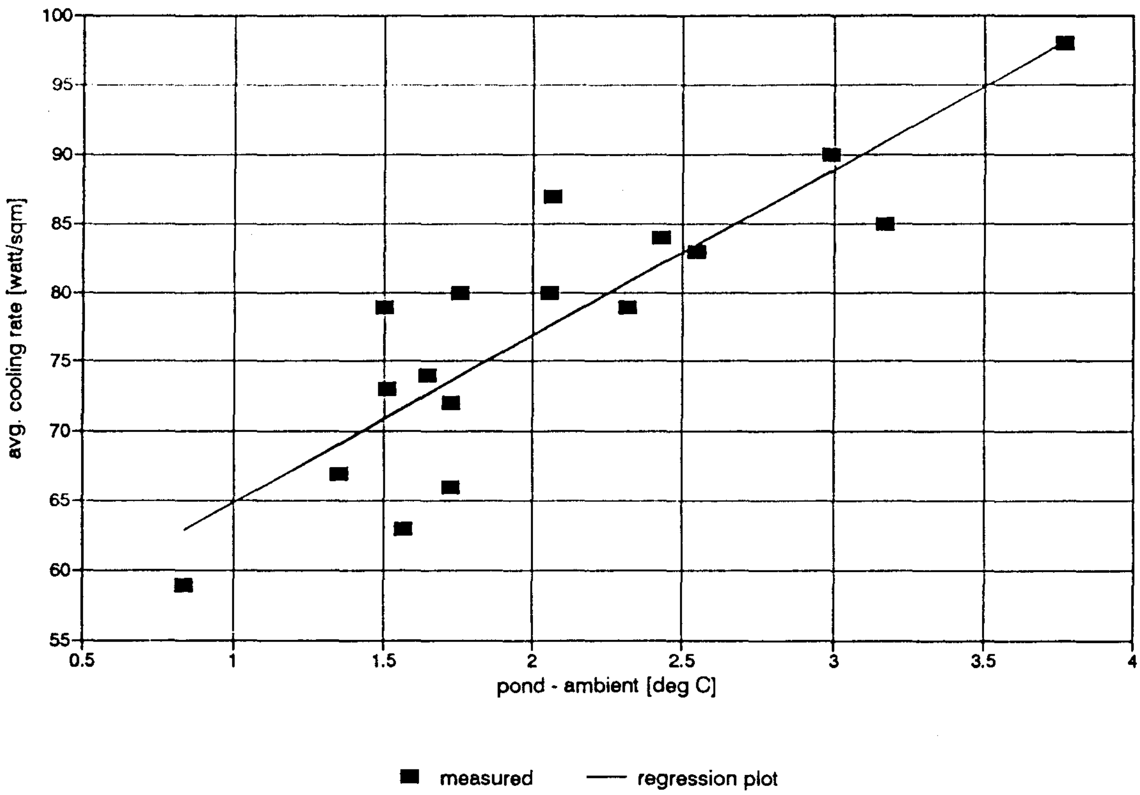

Figure 8. Cooling rate versus the difference between pond temperature and ambient DBT.

b. Since the temperature of the roof pond is related to the *amount* of water in it, the volume of water on the roof becomes an important design consideration. There are two conflicting processes involved:

* The cooling effect of the roof pond on the building at any given moment is directly related to the temperature of the water. The roof pond should therefore be as cold as possible.
* The rate at which heat is removed from the system is *inversely* related to the temperature of the radiator. The roof pond, and thus the radiator, should therefore be as warm as possible - while still being colder than the building itself.

The amount of water in the roof pond is therefore seen as a means of fine-tuning the cooling system, adapting it to the local climatic conditions. The effect of factors such as the daily amplitude of the ambient air temperature could be modified by altering the amount of water in the roof pond, thus changing its temperature pattern. This process of optimization is one of the current topics under research.

Perhaps the greatest advantage of the proposed system is the close coupling between the radiator and the thermal storage mass of the building. As a result of this coupling, the temperature of the radiating surface was maintained fairly high - generally higher than that of the ambient air throughout most of the night. This has two advantages:

a. When the radiator temperature is *higher* than the ambient air temperature, convective heat exchange increases the rate at which energy is removed from the system, rather than impede it. This feature of the system obviates the need for wind screens (Givoni 1982), which previous research has shown are essential for achieving low radiator temperatures.

b. Since the radiator temperature is not only fairly high but is also nearly constant - the temperature of the roof pond is only reduced by about 3-4 °C on a typical night - the cooling rate is nearly uniform, at a level similar to *peak* cooling rates reported by other researchers.

It has already been mentioned that the proposed cooling system does not increase the moisture content of the air in the room, but cools it indirectly through contact with the cold surface of the ceiling. The cold, exposed surface of the ceiling also has a beneficial side-effect. Since it is unobstructed by furniture etc., it reduces the mean radiant temperature (MRT) of the room considerably. The thermal comfort of a person in the room would thus be improved considerably, beyond the effect of the reduction in dry bulb temperature, through radiative heat loss to the cool ceiling.

The radiators had the added benefit of functioning as the outer layer of a double shell roof, shading the roof pond from the sun during the day. This reduced the heat load on the building significantly, and highlights the attractions the proposed system holds as an integrated cooling technology.

Conclusion

A system consisting of a roof pond in which the water is circulated through a radiating roof, is able to maintain the radiator at a relatively warm temperature, thus increasing the potential cooling power. The system described here is feasible and fairly simple to implement, and has a number of beneficial side effects. However, the potential cooling power of any system based mostly on long wave radiative cooling is inherently limited. Its application for cooling a building should be considered in conjunction with other passive cooling and heating techniques, and will require extremely careful design of the building and its details.

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References

1. Clark, E., Berdahl, P. (1980) "Radiative cooling: Resource and Applications" In: Miller, H. (Ed.) *Proceedings of the Passive Cooling Workshop*, Amherst, Mass. Oct. 20, 1980. Centre for Energy Efficient Design, Berkeley, Ca. pp. 177-212.
2. Givoni, B. (1976) "Man, Climate and Architecture," 2nd. Edition, Applied Science Publishers Ltd., London.
3. Givoni, B. (1977) "Solar Heating and Night Radiation Cooling by a Roof Radiation Trap", *Energy and Buildings*, Vol.1, pp. 141-145.
4. Givoni, B. (1982) "Cooling Buildings by Longwave Radiation - Review and Evaluation", *Research Report to the Israeli Ministry of Energy and The US Dept of Energy*. J. Blaustein Institute for Desert Research, Ben-Gurion University of the Negev, Sede-Boqer Campus, Israel. 62 pp.
5. Gordon, J. M., Zarmi Y. (1981) "Transient Behaviour in Radiative Cooling", *Solar Energy*, Vol. 27, pp. 77-79.
6. Granqvist, C. G., Hjortsberg, A. (1981) "Radiative cooling to low temperatures: General considerations and application to selectively emitting SiO films", *Journal of Applied. Physics*, Vol 52, No.6, pp. 4205-4220.
7. Hay, H. (1978) "Skytherm Design Evaluation; Skytherm Production Research", *Proc. 3rd. Annual Solar Heating and Cooling R&D Branch Contractors' Meeting.*
8. Hay, H. (1980) "Skytherm Natural Thermal Control - Design, Production and Commercialization", *Proc. U. S. Department of Energy Passive and Hybrid Solar Energy Program Update Meeting*, Washington, D. C., Sept. 21-24, 1980, pp. 3-80 - 3-83.
9. Ingersoll, J., Givoni, B. *Modelling the Performance of Radiant Cooling*, unpublished report.
10. Juchau, B. (1981) "Nocturnal and Conventional Space Heating Via Radiant Floors", *Proc. 1st. International Passive and Hybrid Cooling Conference*, Miami, Fl.
11. Lushiku, E. M., Granqvist, C. G. (1984) "Radiative cooling with selectively infrared-emitting gases", *Applied Optics*, Vol. 23, No. 11, pp. 1835-1843.
12. Michell, D., Biggs, K. L. (1979) "Radiation Cooling of Buildings at Night", *Applied Energy*, Vol. 5, No. 4, pp. 263-275.
13. Murray, F. W. (1967) "On The Computation of Saturation Vapour Pressure", *Journal of Applied Meteorology*, Vol.6. pp. 203-204, 1967.