Roof Cooling Techniques

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ABSTRACT: Roof cooling techniques can help exploit ambient heat sinks selectively so as to contribute further, or more directly, to the cooling of buildings. Two recent European projects have investigated a series of possible applications suited to Mediterranean climates and building typologies, and the results form the basis of a handbook on Roof Cooling Techniques. Following experimental measurements on test cells in Spain, Greece and Israel a dynamic model was developed and applied to parametric studies investigating a range of roof cooling techniques combining radiative and evaporative cooling processes: variants of roof ponds, water-based and air-based radiators. The parametric studies were extended to produce comparative applicability maps and guidelines. These give a measure of likely cooling energy savings compared to air conditioning and likely thermal comfort improvements for free-running residential buildings. The paper will present the main findings and design guidelines produced by the parametric studies.

Keywords: evaporative cooling, radiative cooling, computer modelling, maps of applicability

1. INTRODUCTION

Roofs offer protection from the elements, but can also help exploit ambient energy sources and sinks, thus making a positive contribution to the heating, cooling, ventilation and daylighting of building spaces. The mainstream approach to roof design has emphasized the roof's protective function. This includes protection from sun, ambient air temperature, wind, rain and snow. Most European countries enforce a prescriptive application of thermal insulation as means of reducing space heating loads.

Though almost always necessary, protective mechanisms are not sufficient in themselves to make a building independent from conventional heating and cooling systems. To become independent of conventional air-conditioning systems whilst achieving thermal comfort conditions for its occupants, a building requires suitable energy sinks for the dissipation of excess heat at times and renewable heat sources for space heating at other times. Readily available renewable heat sources are provided by incident solar radiation and by a building's heat gains from occupancy. Permanent heat sinks are the ambient air, the ground, water masses and the sky - when their temperatures are suitably lower than those of the spaces we aim to cool in buildings. A temporary heat sink is provided by the thermal capacity of the building structure that can allow heat to be stored until a permanent heat sink becomes available.

The main processes of heat dissipation to permanent heat sinks are:

- *convection* and *evaporation*, where the heat sink is the air, described by its dry bulb temperature (Tdb) and its wet bulb temperature (Twb).
- *long-wave radiation*, where the heat sink is the sky, described by the effective sky temperature (Tsky).

This paper reviews the *selective* coupling of two of these heat sinks, the ambient air and the sky, with roof elements aiming to provide heat dissipation and cooling for the thermal comfort of building occupants. The balance between protecting a roof from these parameters and allowing selective exposure for cooling is a function of time, as well as of location and of building function.

In Southern European locations such as Athens and Seville, as well as in other parts of the world with hot summers, the ambient dry bulb temperature will be above 25°C for much of the daytime period throughout the cooling season. In such locations air will be a source of heat gain at these times, but may act as a heat sink providing a cooling potential at night-time when its temperature normally drops below 25°C. In some other regions, on the other hand, the ambient dry-bulb temperature may act as a heat sink even during daytime. The number of degree-days in which the ambient dry bulb temperature is *lower* than 25°C in the cooling season gives us a measure of the cooling potential by convection, typically night-time ventilation. As might be expected, this potential is much higher in the north than in the southern regions of the continent. It is in fact so substantial in Northern Europe that it should be capable of disposing of any cooling loads in most well-insulated buildings with good solar protection. When the ambient dry-bulb temperature is not low enough to provide effective cooling, the building may nevertheless be cooled by evaporation or long wave radiation. The cooling potential of these mechanisms may be evaluated by means of the *wet bulb temperature depression* and the *sky temperature depression*, respectively.

The theoretical basis for passive cooling of buildings is well-established. Recent years have seen the publication of several books on the subject [1-3]. However, there has been relatively little experience in setting up and running passive cooling systems, other than nocturnal ventilation. An architect seeking to incorporate a passive cooling technique in a specific building project finds he has no means of answering several questions:

1. What is the most appropriate passive cooling technique for the particular location?
2. What is the optimal configuration of the system?
3. What are the anticipated energy savings resulting from its application, if it is installed as a replacement to a conventional cooling system or in addition to one?
4. What are conditions in the building likely to be in the absence of a conventional cooling system?

A design handbook for roof cooling techniques [4] attempts to fill this gap. It includes a computer tool, RSPT (RoofSol and PDEC Tool), which has been developed to assist the architect in answering these questions, so as to benefit from the potential for natural cooling. This paper describes RSPT and demonstrates its application, and gives detailed recommendations concerning the design and application of several natural cooling techniques.

2. THE RSPT SIMULATION TOOL

Given appropriate inputs for the building and a roof cooling technique selected by the user from a program menu, RSPT performs hourly thermal simulations for the selected configuration, as well as for a reference building that is generated automatically for comparison. The output produced is in the form of predicted energy savings compared to a fully air-conditioned reference building, or as a measure of reduced hours of overheating for free-running buildings. The software can perform these simulations for any individual location for which the weather data required are available or included in the database provided. Alternatively, the output can be provided in the form of coloured maps that provide comparative information on the relative performance of roof cooling techniques over a wide geographic area. At present the maps are drawn mainly for parts of Europe, but they could be extended to other regions.

2.1 Building modelling

The main characteristics of the building modelling methodology used by the RSPT software are:

- Heat transfer through opaque elements is calculated by means of response factors, which are in turn calculated by a detailed finite difference model for transient heat transfer. Heat transfer is considered as one-dimensional in walls and slabs, and two-dimensional in elements below ground.
- Heat transfer through transparent and semi-transparent elements, which occurs mainly by direct radiant transmission and where the effects of thermal inertia are small, is calculated in steady state, using the solar and thermal transmittance values given by product manufacturers.
- Solar gains are modelled with respect to both direct and diffuse radiation, taking account of shadows cast by external obstructions as well as by the building's own surfaces.

The program's energy balance equations calculate indoor surface and air temperatures as a function of hourly meteorological parameters and inputs by the user. The calculation of the indoor air temperature takes account of internal heat gains, energy exchanges by ventilation and air infiltration, and the output of HVAC systems (for space heating or cooling). RSPT solves the balance equations iteratively at each time step in the following sequence:

1. The effects of an HVAC system are simulated under idealised conditions or as described by a proportional control law with inputs of surface and air temperatures as calculated in a previous time step;
2. Surface temperatures are calculated successively for the following time step with all other parameters known;
3. The indoor air temperature is calculated with all other parameters known as above.

In this approach, two to four iterations are required at each time step. Because of the nature of the calculation techniques used, time steps need to be short in order to obtain accurate results. Typically, they are set at 10-minute intervals whilst meteorological magnitudes, which are read from the meteorological file for the location, are assumed constant over hourly intervals.

2.2 Component modelling

The natural cooling techniques (NCT) that have been modelled and implemented in RSPT are water ponds, cooling panels, air or water radiators and passive downdraft evaporative cooling (PDEC) towers. These cooling techniques may be modelled individually or coupled together in a number of different combinations. For example, buildings with more than one storey may employ cooling panels in the intermediate floors, which are coupled with a roof pond that releases heat to the environment. The roof pond may be cooled directly by evaporation and radiation, and it may also be coupled with water-based radiators to increase the effective cooling area beyond the surface of the pond.

The present paper discusses only roof ponds and cooling radiators. A complete description of all models can be found in Yannas et al. [4].

2.2.1 Roof ponds:

This technique consists of a shallow pond of water on the roof, which absorbs heat from the building interior and dissipates it to the environment. A dynamic model was developed which is based on the pond's global thermal balance, integrating all mechanisms of heat transfer occurring in the system: absorption of solar radiation in the water and at the bottom; convective and radiative exchanges; and evaporation at the surface. Solution of the equations provides the water mass evaporated for the given calculation period and the water temperature in the pond, assuming it is well-mixed and neglecting any vertical gradients that may exist in the pond. The roof pond may be exposed to the environment or fitted with a cover.

2.2.2 Water and air based radiators:

The modelling of water and air based radiators applied for cooling purposes does not differ much from that of water-based solar collectors. A typical plate and tube geometry with back insulation and no cover has been assumed. The plate can be provided with a selective coating, and the user may specify three emissivities corresponding to the emission bands of the so-called atmospheric window.

2.3 Displaying the results

The RSPT tool can be used in two ways:

a) To investigate possible energy and comfort improvements from different roof cooling techniques for given building and location parameters. This is done by running the simulation repeatedly, making modifications to the cooling system until an optimal solution is obtained.

b) To provide comparative applicability indicators by generating performance maps for different techniques over a wide geographical area.

Given the description of a user-defined building and site data including a weather file, the RSPT tool produces an estimate of energy savings from roof cooling techniques by performing two sequential simulations comprising a single run. First, it simulates the user-defined building with the roof cooling application selected plus an HVAC system. Next, it simulates the same building description with the same HVAC system but without the roof cooling application. The results of this simulation mode include

- *Energy demand* for space cooling in kWh, based on a set point temperature of 25°C. Residential buildings are assumed to be occupied and to require cooling continuously. Commercial buildings are assumed to be occupied during standard office hours on weekdays only, and cooling is therefore provided intermittently. Summer conditions apply during the period June to September, inclusive (a total of 122 days).
- *Energy savings* on air-conditioning as the difference in energy demand between the reference case and a building with roof cooling.

Likewise, the thermal comfort improvement that may result from the implementation of a roof cooling application without an HVAC system is determined by two consecutive simulations. First, the indoor air temperature in the building is calculated with the roof cooling application in place. The calculation is then repeated for an otherwise identical building with a user-defined reference roof that represents the conventional roof that would have been specified in the absence of the roof cooling application. In both cases, the indoor air temperature is free-floating, and the comfort improvement, if any, is measured as a reduction in the number of hours the simulated indoor air temperature exceeds one of three predetermined set temperatures representing the upper limit of thermal comfort: 25ºC, 27ºC or 29ºC. The software also outputs the difference in the peak and mean indoor air temperatures between the reference building and the building with roof cooling elements.

Comparison of the suitability of different locations for application of a particular cooling technique can be done by means of maps of applicability. These maps have been generated by performing paired simulations (of buildings with and without a roof cooling application) using hourly data describing a typical meteorological year at 100 locations representing a range of different climatic conditions all over Europe. The simulation results for the base locations were then correlated with their monthly mean climatic data. The correlations thus obtained were used to interpolate performance parameters for additional locations in Europe using mean climatic data as the correlation parameter.

Figure 1 shows a map of Europe displaying the percentage of energy savings gained by installing an optimal roof pond on a single-storey, air-conditioned residential building. Figure 2 displays the number of

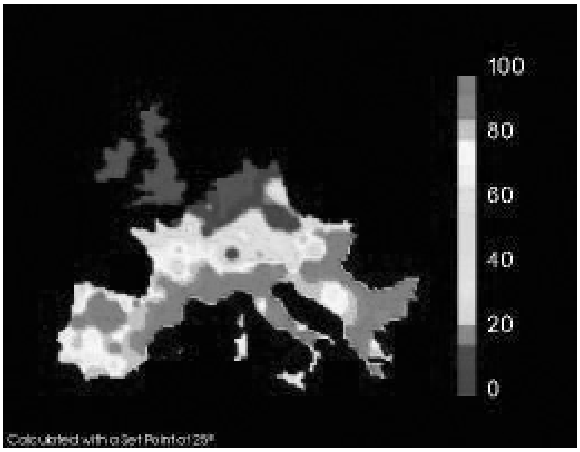

Figure 1: Map of Europe showing % energy savings in a single-storey residential building cooled by an optimal roof pond (Depth – 30cm, spray height - 1.3m, droplet radius - 1mm, 1 water change per hour, cover – daytime only, spraying – continuous.)

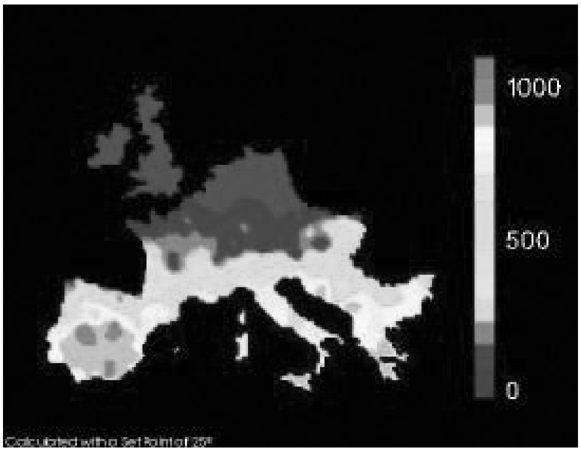

Figure 2: Map of Europe showing number of hours with indoor temperature greater than 25°C in a single-storey residential building cooled by an optimal roof pond (as above).

hours temperature in the same building is predicted to be over 25°C if there is no air-conditioning and cooling is provided only by the roof pond.

3. CASE STUDY: SEVILLE, SPAIN

RSPT was used to evaluate the contribution of passive cooling to provision of thermal comfort in a single-storey residential building in the city of Seville in southern Spain (latitude 37.24N).

Seville has more than 11 hours of sunshine daily in summer, average ambient air temperatures are about 28°C and the mean maxima are above 36°C in July and August. Table 1 summarizes the cooling potential in Seville employing different techniques:

Table 1: Temperature of heat sinks for cooling by convection (Tdb), evaporation (Twb) and radiation (Tsky) at Seville, Spain. Data are for 122 days of summer, June-September.

	Tdb	Twb	Tsky
mean max	41.1	22.3	26.1
mean	25.5	17.8	11.5
mean min	13.9	12.3	0.5

The base case residential building was a single-storey detached dwelling of 100m^2 occupied floor area. External walls of 90m^2 exposed surface area were of cavity construction with hollow and solid brick leafs insulated with 40mm mineral wool in the cavity, giving an overall thermal transmittance (U-value) of 0.66 W/m^{2}K. The building was assumed to have windows of a total area of 10m^2 fitted with double glazing and distributed evenly in the north, east and south elevations.

Three different roof constructions were associated with this base case model: Two of these, labelled “Ll” and “Ll+”, were of lightweight construction consisting of a structural steel deck with a layer of mineral wool insulation of 40mm and 62mm thickness respectively, giving U-values of 0.79 and 0.54 W/m^{2}K. An additional roof variant, labelled “Hl” consisted of 20cm ceramic tiles (thermal capacity 220kJ/m^{2}K) and 5cm concrete topping (thermal capacity 105 kJ/m^{2}K) over a plastered ceiling, with 4cm thick polystyrene insulation above. The thermal transmittance of this roof variant was 0.58 W/m^{2}K.

One further roof configuration was modelled: a steel deck with no thermal insulation, having a calculated U-value of 5.88 W/m^{2}K. This variant, labelled “L”, does not meet building regulations, and therefore was not evaluated as a reference variant. However, as will be seen, it represents an important variant with respect to roof ponds.

The dwelling was assumed to have four occupants with metabolic gains of 45.4 W per person latent heat and 71.8 W per person sensible heat. Internal gains from lights were taken as 4.4 W/m^2 and for equipment 4.4 W/m^2. In the air-conditioned variant the cooling system was assumed to operate continuously to maintain indoor temperature to a thermostat setting of 25°C.

The calculated cooling energy required to maintain an indoor temperature below 25°C at all times was 1718-2394 kWh (Table 2). Without air conditioning, the predicted indoor temperature in the reference buildings would rise above 25°C for 1706-1765 hours (some 60% of the occupancy period), reaching peak temperatures of 32.2-36.8°C.

Of the three reference dwellings, the one with the heavyweight roof performs best, because it provides additional heat storage in the roof structure compared to the two lightweight variants. Ll+ has a lower cooling load than Ll since it is better-insulated.

The reference building was then equipped with a roof pond to provide passive cooling. The base case pond (labelled ‘exposed’) was 30cm deep and had no cover. It employed sprayers circulating the equivalent of 1 pond volume per hour, spraying water drops 1mm in diameter to a height of 1.3m above the water surface. Sprayers were assumed to operate continuously. The same pond was then simulated with a cover insulating the pond during the daytime, and sprayers operating at night (labelled ‘covered’).

According to the simulations, addition of a pond with sprayers to the three reference roofs resulted in energy savings of 44-56%, by reducing the load and operating period of the conventional HVAC system.

However, the simulations also showed that a roof pond installed over a steel deck with no insulation (variant “L”) would require no backup cooling system at all, if it included an insulating cover during the daytime: peak air temperature in the building was predicted to be only 25.3°C, with the temperature exceeding 25°C for only 7 hours throughout the entire

Table 2: Summary performance data for two roof pond variants (‘exposed’ and ‘covered’) installed on a single-storey detached dwelling in Seville, for a summer period lasting 122 days. (% values are relative to the ‘ref’ case.)

ROOF CONSTRUCTION		COOLING ENERGY DEMAND					THERMAL COMFORT					
		ref	exposed		covered		ref		exposed		covered	
		kWh	kWh	%	kWh	%	hours >25°C	peak °C	hours >25°C	peak °C	hours >25°C	peak °C
L	steel deck, no fixed insulation		440		72				250	28.0	7	25.3
Ll	steel deck, 40mm mineral wool	2394	1064	44	905	38	1723	36.8	820	30.7	702	30.0
Ll+	steel deck, 62mm mineral wool	2084	1158	56	1025	49	1706	36.1	902	31.1	819	30.6
Hl	25cm masonry, 4cm polystyrene	1718	896	52	802	47	1765	32.2	660	28.5	570	28.3

summer. In the other variants the thermal coupling between the roof pond and the occupied spaces was inhibited by the mediation of the thermal insulation layers required to satisfy building regulations.

4. DESIGN GUIDELINES

The following design guidelines have been drawn up on the basis of parametric studies carried out using the RSPT software [4]. They are backed up by experimental results obtained during the ROOFSOL project.

4.1 Roof ponds cooled by evaporation

Roof ponds cooled by evaporation may have insulating covers to reduce daytime solar gains, and water sprays to enhance the cooling rate. Recommendations for each of the possible combinations of these features are given below.

4.1.1 Uncovered, no sprays:

The water pond is permanently exposed to ambient air without a cover. There is no spraying system. This is the simplest roof pond configuration.

- Water depth should be at least 30cm, to reduce temperature fluctuations resulting from daytime solar gains. Water temperature will increase due to the solar gains until compensated by spontaneous evaporation; typical water temperature fluctuation is around 10K.
- The colour of the pond floor should be light, to reduce solar absorptance. However, the effect of this factor was relatively small, since even in a pond that is only 30cm deep, most of the incoming radiation is absorbed by the water.

4.1.2 Uncovered, with spray:

The spraying system operates day and night over an uncovered pond to provide a cooling effect. The design of the pond is similar to that with no sprayers. In addition, the design and operation of the spraying system should consider the following factors:

- The water spraying system should circulate the equivalent of about 1.0-1.5 volumes of the roof pond per hour.
- The minimum height of the spray should be 0.5m, to create a sufficient time of fall for the drops to cool to the ambient wet bulb temperature.
- Average droplet radius should be 0.5-1.0mm. Generating finer drops requires higher pressure at the sprayers and thus requires more pumping energy. Fine drops are also more likely to drift beyond the perimeter of the roof pond.
- Limiting spray operation to night-time can conserve water. However, daytime operation may be required to maintain a stable water temperature in shallow ponds (<30cm depth). For deeper ponds, the increase in water temperature during the daytime may be less than 7-8K, even in warm and sunny conditions.

4.1.3 Fixed cover, no spray:

The pond is shaded at all times. There is no spraying. In this configuration, the pond cover prevents overheating of water, whilst spontaneous evaporation lowers water temperature below the average ambient air temperature. The design and installation of the cover should be as follows:

- The cover should be installed at a sufficient height to allow unrestricted airflow above the surface of the water, typically about 30cm.
- If airflow is unrestricted, the main function of the cover is to shade the surface of the pond. It should therefore be opaque to solar radiation. Its solar absorptance (upper surface), thermal conductance and the long wave emissivity of its lower surface have a negligible effect on the temperature of the roof pond.

4.1.4 Operable cover, with spray:

The pond is covered during the daytime only, while the spraying system operates at night. In this configuration, the pond cover reduces fluctuation in pond temperature due to solar absorption during daytime while spraying lowers pond temperature at night. The cooling output of such a pond is higher compared to an uncovered pond with sprays.

- The thermal properties of an operable cover should conform to the recommendations for a fixed one. However, removal of the cover at night increases the structural complexity and requires a mechanical system and control mechanism.
- The design of the spraying system is the same as that in an uncovered pond.
- The spraying system should be operated at night only, to conserve water. However, changing environmental conditions may create a situation in which ambient wet bulb temperature increases above the temperature of the water in the pond. In this case, water spraying would lead to an increase in water temperature – and should be stopped.

4.2 Radiative cooling

The main obstacle to implementing radiative cooling as a means of cooling buildings is the imbalance between incoming solar radiation during the daytime and the net long wave radiation balance throughout the 24-hour daily cycle. There are two ways of overcoming this problem: The radiating surface may be covered by means of an insulating cover that is removed only when cooling is both required (during the summer) and possible (at night). Alternatively, the radiator may be exposed at all times, and a suitable heat transfer medium is circulated through it at the appropriate time. The roof itself may be insulated at all times.

4.2.1 Movable insulation

The radiator is insulated from the environment when heat exchange is not required, and insulating panels must be removed to enable cooling.

- Thermal mass may be provided by water bags, a roof pond or structural concrete. In all cases, the storage mass must be located on an exposed roof and is cooled directly.
- The radiating roof must be rectangular, to accommodate movable insulation panels with regular dimensions. The dimensions are limited by

the size of insulation boards and by mechanical considerations.

- A storage space must be provided where the insulation panels may be stacked when the roof is exposed for radiative cooling. Typical solutions provide storage over a service space or a garage.

4.2.2 Water as the heat transfer fluid

The radiator is always exposed. Water is circulated as a heat exchange fluid when cooling is required, if environmental conditions are suitable.

- Radiators may be constructed of any material if its thickness is small. The surface colour has little effect on cooling output, because even dark coloured radiators cool down very quickly after sunset. Colour may therefore be dark if the radiators are also used as a backup heating system.
- Pipes should be as closely spaced as possible.
- Pipe diameter should be able to accommodate the desired flow rate, but should not be greater than about 10mm.
- The length of the pipes may be suited to roof dimensions. Longer pipes allow for faster flow rates, since the temperature difference between inlet and outlet depends on the length of time a fluid is exposed in the radiator.
- The storage mass may be either a water reservoir or concrete cooling panels.

If ambient air is warmer than the desired outlet temperature:

- Back insulation and a windscreen are required to reduced convective heat gains from the environment, so as to achieve a temperature lower than ambient air.
- The water flow rate should be slow to achieve low outlet temperatures.

If ambient air is colder than the desired outlet temperature:

- Back insulation and windscreen hinder cooling.
- The water flow rate should be relatively high to maintain a relatively warm radiator and thus to emit more heat to the environment.

4.2.3 Air as heat transfer fluid

The radiator is always exposed. Air is circulated as a heat exchange fluid when cooling is required, if environmental conditions are suitable.

- The radiator should be made of a highly conductive metal sheet.
- The air gap should be 1-2cm.
- The length of the radiator is limited by friction and power of fans.
- Back insulation and a windscreen are required in order to achieve air temperature lower than ambient. (Otherwise it would be simpler to employ ambient air directly to cool the building interior…)
- Storage mass is essential: Air may be pumped through a rock bed or through concrete cooling panels.
- Air speed should be designed in accordance with the length of the radiator panel, to allow sufficient time for it to be cooled to below ambient air temperature – about 5-10 seconds in a typical installation.

5. DISCUSSION AND CONCLUSIONS

The paper has suggested a methodology for evaluating the potential for several passive cooling techniques in most European locations. Recommendations have been made for the design of roof ponds cooled by evaporation and for radiative cooling systems.

As the case study for Seville shows, most of the cooling required to maintain thermal comfort could be provided by passive means, even in one of the warmest locations in Europe. However, the same study also shows that the details of the specific design adopted may have a great effect on its performance. Furthermore, the design of a building where installation of a roof pond is considered may be quite different from that of a building with no pond, not just in terms of the structure required to support the mass of water but also with respect to its insulation and thermal mass.

Very few architects, if any, have the necessary experience to be able to design a building for passive cooling, other than ventilation, without requiring the assistance of computer software. The RSPT package allows the architect to estimate the cooling requirements of a specific building, to optimise a solution based on a natural cooling technique, and to predict the improvement in terms of either energy conservation or improved thermal comfort.

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