ROOF DESIGN FOR NATURAL COOLING

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ABSTRACT A recent European project explored combinations of radiative and evaporative cooling processes involving the roof for application in the Mediterranean region. The paper introduces the experimental applications which were built and tested as part of the project and the design considerations and applicability data derived from simulation models validated with the experimental results.

1 Introduction

Roofs offer protection from the elements, but can also help exploit ambient energy sources and sinks thus making a positive contribution to environmental design requirements of buildings. The mainstream approach to environmental design has emphasised the roof's *protective* function, i.e. the exclusion or modulation of the external climate. On the other hand, research on natural heating and cooling techniques has highlighted the *selective* mechanisms by which roofs can contribute to space heating, cooling, ventilation and daylighting of buildings. A recent European project focused on roof solutions for natural cooling (ROOFSOL) for application in the Mediterranean region.

Mathematical modelling informed the development of experimental applications based on processes of radiative and evaporative cooling. The experimental applications were built and tested over short periods in summer at standardised test cell facilities in Spain, Italy, Greece and in Israel. The results were applied to the calibration and refinement of simulation models. These were in turn used on parametric studies and to determine the applicability and likely performance of selected roof-based systems across Europe and Israel. A Roof Design Handbook was prepared (Yannas 1998) which comprises sections on the physical principles and the typology of roof-based solutions for natural cooling; on traditional and contemporary roof construction practices and trends in Mediterranean countries; on profiles of some 30 built examples of roof cooling applications; on the test results from the six prototypical applications tested in the project; and on the design considerations resulting from the applicability studies. This paper introduces the last two sections of the Handbook.

2 Roof cooling prototypes

Six experimental applications were tested in the ROOFSOL project. The general characteristics of each are summarised below. Indicative illustrations of the six applications are given on the following pages.

(a) *Planted roof (with several variants):* this covers 400m^2 on the roof of the School of Agricultural Engineers in Madrid; the planting was arranged in 50 parcels and fitted over an existing roof; temperature and heat flux measurements were collected over a period of ten months by CIEMAT and comparisons drawn between different parcels, as well as with reference parcels without planting.

(b) *Sand-filled roof pond*: this was developed and tested by Conphoebus on their fully instrumented PASLINK test cell in Catania, Sicily by replacing the cell's removable roof with a 19 m^2 slab constructed of reinforced concrete and hollow bricks which supports some 2.8m^3 of sand and pebbles cooled by a pvc ring circuit supplied by sprayers.

(c) *Evaporative cooling roof*: a roof pond with floating insulation and sprays built and tested at the CIEMAT experimental facility in Almeria, Spain; the roof pond tray was installed over the test room replacing its retractable roof, was filled with up to 500mm of water and covered with 100mm thick floating polystyrene slabs; sprinkling nozzles were specified to produce droplets in range of 0.5-1.0mm.

(d) *Evaporative cooling roof:* this was developed and tested at the Center for Desert Architecture and Urban Planning (CDAUP) in Sede Boqer, Israel; a shallow roof pond with water contained in a PVC membrane lining and covered by floating 100mm polystyrene insulation. The pond was installed over an existing roof slab of 120mm reinforced concrete; small holes in the polystyrene boards allowed water sprayed above the insulation to trickle back into pond; white pvc panels raised above the pond provided shading, as well as channelling wind; spray nozzles were fitted 50-100cm above water; using a fan, cool moist air from the vicinity of the pond can be drawn inside through an opening at the centre of the roof.

(e) *Water-based radiator and roof pond:* developed and tested by CDAUP in Sede Boqer, this is a shallow roof pond 10-15cm deep, with floating insulation, coupled to an emitter for cooling by longwave radiation; two different radiators were tested and compared to an adjacent reference room, both radiators provided low-cost solutions and high efficiency.

(f) *Water-based radiator and cooling panel*: this was developed and tested at the Center for Renewable Energy Sources (CRES) in Athens; the radiator was made of heavy duty steel pipes fixed on steel plate painted white; the cooling panel consisted of a 120 mm concrete slab with embedded pipes, and 60mm thermal insulation placed between water radiator and concrete slab for the roof to comply with the Greek Building Regulations; water circulated 1900 to 700 hours.

3 Design considerations and performance data

3.1 Sensitivity studies on generic systems

Mathematical models were developed in the course of the project to help inform the specifications of the experimental applications and to run parametric studies investigating the relative importance of different design parameters. The models encompassed base case forms of planted roofs, water ponds, and water-based and air-based radiators, as well as the variants developed later. The main design parameters of each system became the object of sensitivity analysis.

In the case of the planted roof, the analysis showed that canopy evapotranspiration and air exchange between canopy and ambient had little effect on the heat flux through the roof. On the other hand a well designed planting reduced heat flux and was equivalent to improved thermal insulation. The effectiveness of leaf cavity as shading device, and the thermal diffusivity of the soil substrate were found to be key considerations. With water ponds, the pond characteristics, the thermal and solar optical-properties of the pond cover, the detailing of the spraying system, and the operational conditions (pond covered or uncovered; spraying on or off and schedule of operation) were investigated. With the water–based radiators, plate thickness and radiative properties, thickness of thermal insulation at the back of the radiator panel, pipe layout, water mass flow rate, and use of wind shield were considered. The graphs in Fig.1 illustrate three of the parametric studies performed for water-based radiators to assess the influence of the emittance of the radiator plate, the effect of water inlet temperature, and that of the mass flow rate.

3.2 Climatic applicability and reference cooling loads

Using simulation models validated with the experimental data, the cooling potential and likely performance of roof cooling configurations similar to those tested were assessed for typical residential and office buildings using weather data from some 250 locations. The results were transferred onto a set of maps of Europe (and Israel) which are held on an electronic Atlas with areas of equal performance identified by coloured contours, and numerical results for specific locations given by the positioning of the cursor.

In Figs.2-5, which illustrate these maps, the geographic plot has been confined to the Iberian peninsula section as full view of the maps would provide little legible information in the small size and black and white reproduction possible here. The cursor is positioned on the location of Madrid to provide a numerical indication. The maps of Fig.2 show the kind of climatic applicability data that has been produced. These include dry-bulb cooling degree-days to base temperature of 25°C, wet-bulb and sky temperature degree-days to same base; and wet-bulb and sky temperature depressions. The wet-bulb depressions are given separately daytime and nightime. For the vicinity of Madrid the maps of Fig.2 show that the daytime wet-bulb depression (left map on bottom row) is of the same order as the dry-bulb cooling degree days (top left) indicating promising potential from evaporative cooling for this location. There is a similar indication from the sky depression value (bottom right).

Fig. 3 shows a small sample of the maps which produced to provide reference data on cooling demand and peak temperatures for the reference residential buildings. These maps were produced for typical residential and office buildings (only some of the residential cases shown here). For each building type three thermal categories were defined (and termed "best", "worst" and "average") by varying the level of thermal insulation, orientation of glazing, level of internal gains, and pattern of air exchange. The maps give the resulting cooling demand in kWh/m^2 for indoor setpoint temperatures of 25°C. For non-airconditioned variants of the reference buildings, the maps give the peak indoor temperature, the mean indoor temperature above 27°C (and above 23°C), and the average daily duration of the period with indoor temperature above 27°C (and above 23°C). In Fig.3 the worst case has a cooling demand over 50% higher than the best case. With the free-running variants the peak indoor temperature of the worst building was 4°C higher than that of the best case.

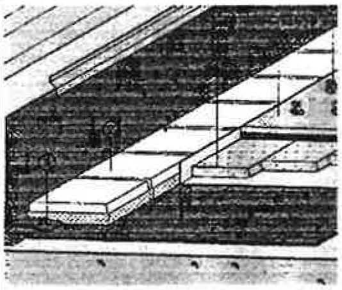
3.3 Variants of the experimental cooling systems

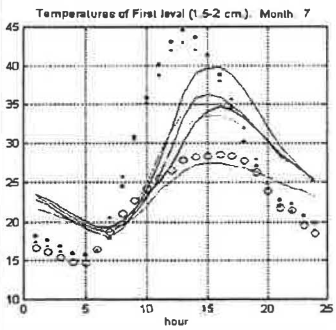
The roof cooling systems selected for assessment were modelled on those developed and tested for the ROOFSOL project. For each system, a base case and a number of variants were modelled and studied. These are described below.

(a) **Roof Pond:** a pond surface area equal to the building roof area was assumed with thermal coupling to the spaces below; the pond support had the same composition as the roof structure but no thermal insulation; the water depth was of 30cm and an opaque cover was provided, separated from water by a ventilated air gap; spraying system with water flow rate of 1 water volume per hour. Three operational variants were considered: cover on during daytime only, sprays not used (Roof Pond 1); cover on at all times, cooling by sprays at night (Roof Pond 2); cover on during daytime only, sprays at night (Roof Pond 3). On multi-storey buildings the roof pond was assumed to combined with a cooling panel based on the Roof Pond 3 variant; further operational variants considered as a function of the number of water changes per hour of pond volume through spraying.

PLANTED ROOF VARIANTS

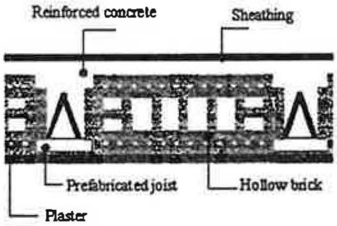
CIEMAT
Madrid, Spain

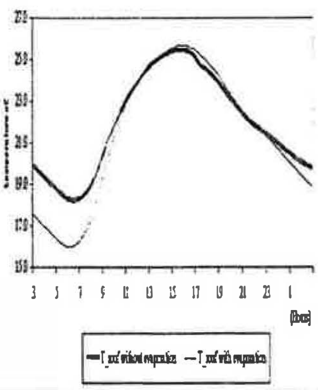




SAND-FILLED ROOF POND

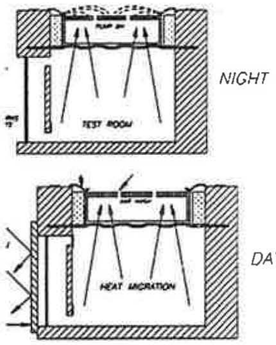
Conphoebus
Catania, Italy

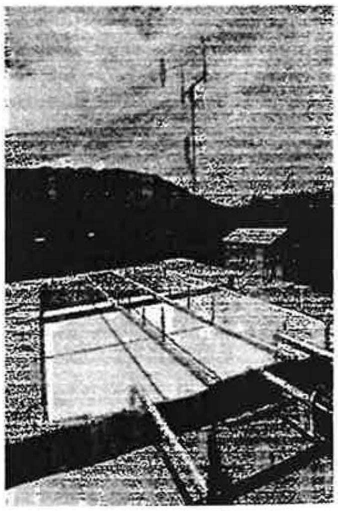




EVAPORATIVE COOLING ROOF

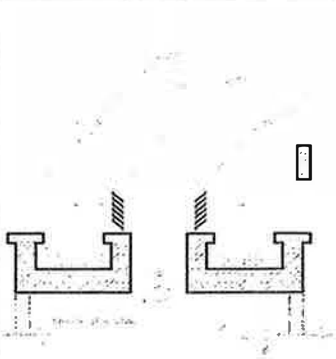
CIEMAT
Almeria, Spain

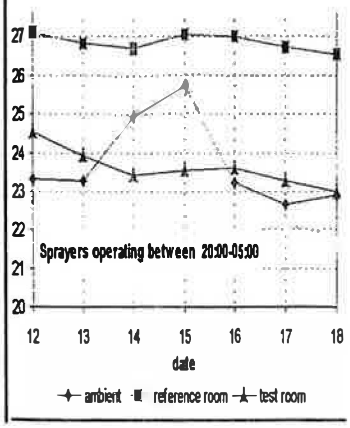




EVAPORATIVE COOLING ROOF

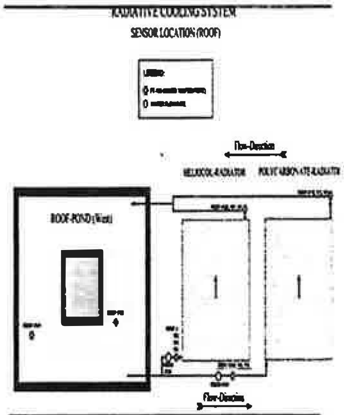
CDAUP
Sede Boqer, Israel

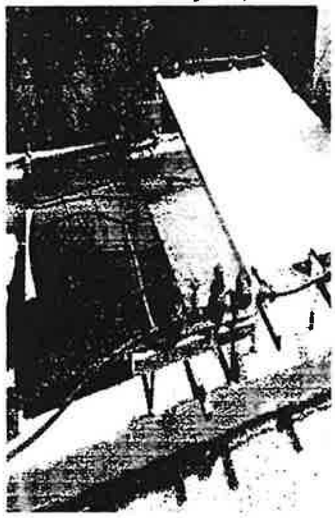


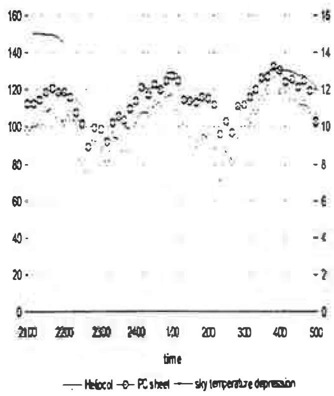


WATER-BASED RADIATORS & ROOF POND

CDAUP
Sede Boqer, Israel

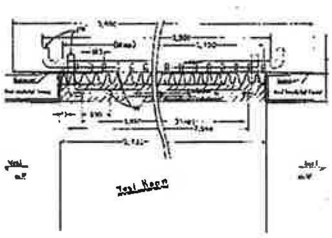


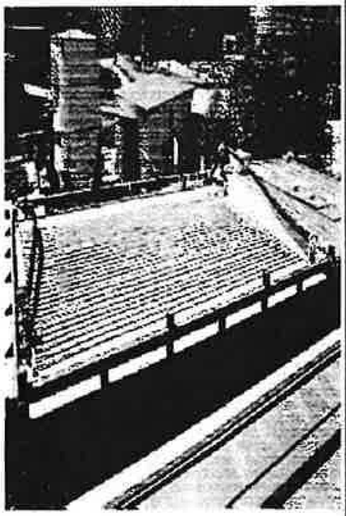


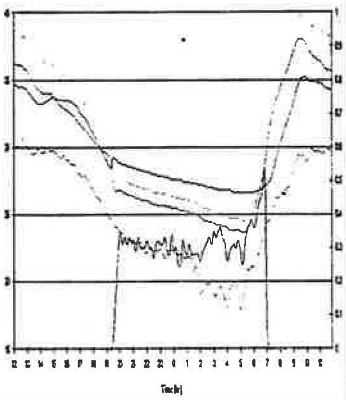


WATER-BASED RADIATORS & COOLING PANEL

CRES
Athens, Greece







(b) **Roof pond & cooling panel** : a cooling panel of 6 cm thick concrete is attached to the ceiling with parallel tubes of 3/4" in diameter spaced 10cm apart and centred in the concrete; water from roof pond circulated through one or more cooling panels depending on number of floors served; one variant was assumed to have a panel with perfect thermal coupling with the roof or ceiling (Cooling Panel 1), second variant assumed to be adiabatic on its upper side (Cooling Panel 2).

(c) **Sand & pebbles roof pond:** pond surface area equal to building roof area and thermally coupled with spaces on top floor; pond support of same composition as roof structure but without thermal insulation; pebble layer of 50mm, no pond cover; on one variant the pond contains 50.87 kg/m^2 pebbles and 30.43 kg/m^2 water (Sand & Pebbles Pond 1), second variant has 92.5 kg/m^2 pebbles and 14.43 kg/m^2 water (Sand & Pebbles Pond 2).

(d) **Water radiator & cooling panel:** surface area of radiator assumed equal to roof area; water circulated at night, flow stopped during daytime; cooled water feeds one or more cooling panels situated in ceilings.

(e) **Water radiator & roof pond:** the pond is covered by a radiator which it supplies with water; pond support left uninsulated; no spraying system; water is circulated at night and stopped during daytime; three radiator variants based on those tested in the project.

Fig.4 gives indications of the maximum contribution that might be expected from a sample of the above roof cooling systems; the figures are in units of kWh/m^2. For residential buildings in the location of Madrid the most promising configuration is a combination of roof pond with cooling panel. However, all of the roof systems considered are shown to have a cooling potential higher than the cooling demand of even the worst of the building specifications. This suggests that the simplest and cheapest of the systems could suffice. Comparing the relative yield of the different roof systems it can be seen that the water roof pond alone can provide twice as much as the sand and pebbles pond and the radiator and roof pond combination. Use of cooling panels on the other hand seems to improve performance of the roof pond very substantially owing to the much faster evacuation of heat from the occupied spaces.

Fig.5 shows maps of "actual performance". The roof pond with cooling panel was found to be best overall and could cover 100% of the cooling demand maintaining the indoor effective temperature within comfort. However, this system is the most complex; a simpler alternative could provide a reasonable performance at lower capital cost. The figure illustrates the energy savings which may be expected from the base case roof pond variants. Cover during daytime only and spraying at night performs slightly better than the other two operational schedules. For the best building specifications cooling energy savings ranged between 36% and 53%. For the worst case savings rose to 47-57%. Regarding thermal comfort, the improvements compared to the reference cases were not substantial in terms of a lower peak temperature, but there was a considerable reduction in the number of hours above 27°C.

The following are some general conclusions on the performance of the systems :

- Roof pond variants did not differ much in performance; the simplest case had a daytime cover and no spraying system, which was cheaper than the other options and provided satisfactory performance in most situations. For locations with larger cooling loads, however, the other two variants may be preferable.

- the sand and pebbles roof pond had a less good performance and in some locations its contribution was negative, which means it was inferior to the reference insulated roof.

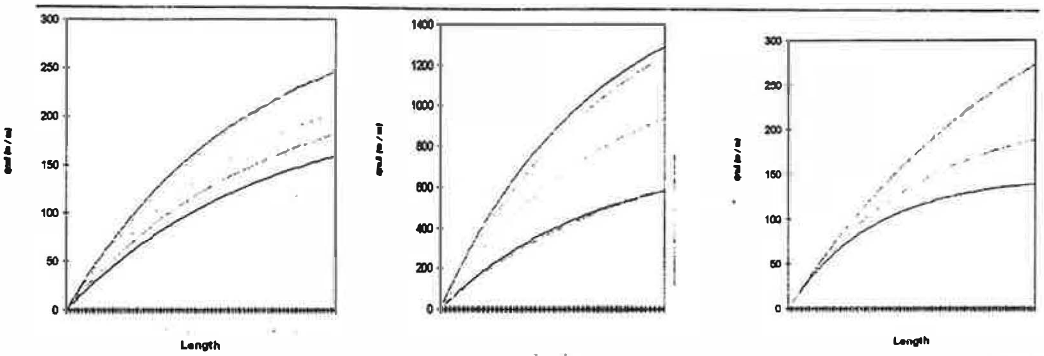


Fig. 1 Results from three of the sensitivity studies for water-based radiators investigating the influence of the radiator plate longwave emissivity (lef), the combined effect of water inlet temperature and radiator selectivity (centre) and of the mass flow rate (right)

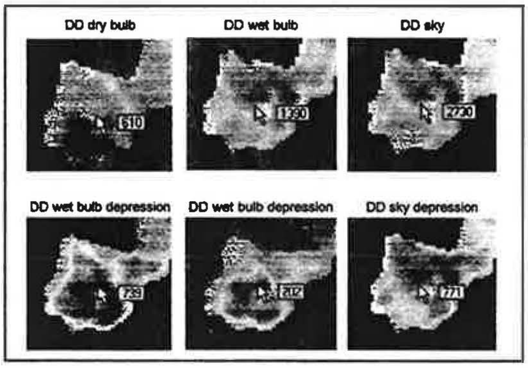


Fig. 2 Degree days and temperature depression maps (cursor showing data for Madrid, Spain)

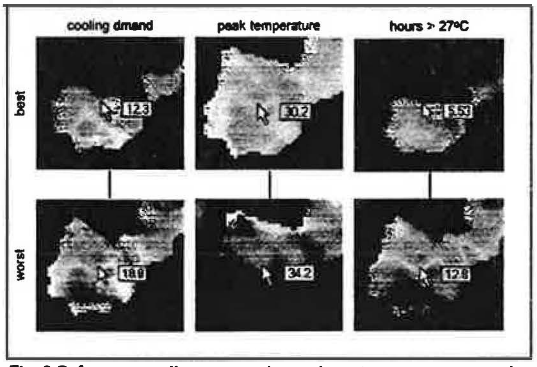


Fig. 3 Reference cooling energy demand, peak temperatures and hours with temperatures above 27 C for air conditioned and free-running residential buildings

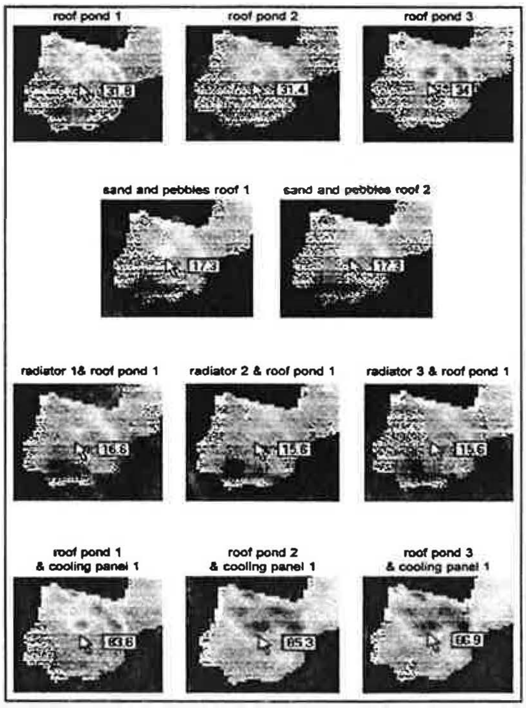


Fig. 4 Maximum potential contribution from the roof cooling systems

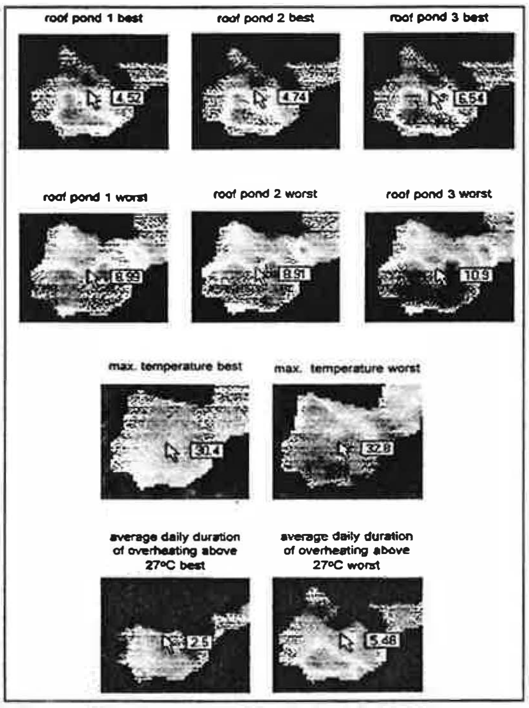


Fig. 5 Cooling energy savings from roof pond variants (top two rows of maps) and peak temperatures for free-running building with roof pond (lower two rows of maps)

- the roof pond and water radiator was limited in practice by the radiator surface area which could not be larger that that of the roof pond; as no spraying system was considered, the overall performance was less good than that of the roof pond on its own.
- the roof pond with cooling panels gave the best performance and the cooling panel is especially suited to multi-storey buildings; the use of a small pump to drive the cooled water from the roof pond to the cooling panel has a negligible economic and energy cost.

Acknowledgment

This paper is based on the findings of a research project partially funded by the European Commission DG-XII. The project was coordinated by Felix Tellez and Guillermo Schwartz of CIEMAT. The experimental applications illustrated in the paper were developed and tested at CIEMAT in Madrid and Almeria, Spain; CDAUP, Sede Boqer, Israel; Conphoebus, Catania, Italy; and at CRES, Athens, Greece. The mathematical modelling and sensitivity studies were pursued at GISE-ENPC Paris, and at the Universities of Malaga and Seville. The applicability maps were developed at the University of Seville. The Handbook was produced at the Architectural Association Graduate School, London.

References

Yannas, S. (Ed. 1998). *Roof Solutions for Natural Cooling Design Handbook and Directory*. European Commission DG XII ROOFSOL Project. Architectural Association Graduate School, London.