Comparative studies on different type of roof ponds for cooling purposes: literature review

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ABSTRACT

Bioclimatic approach gives attention to the design of roof since it is commonly the building element which is most exposed. Some of the most favorable roof cooling techniques are roof ponds which appear to influence the thermal behavior of roof through different processes including evaporation, radiation and conduction. Large air-conditioning energy savings were estimated, reaching 100% in a variety of locations. In this paper, the most known types of roof ponds are presented, including uncovered and covered with or without sprays, energy roof (water contained within parapet), coolpool (open pond shaded by sloping louvers), coolroof (with floating insulation), walkable pond with night water circulation (insulation embedded within the pond), wet gunny bags (with a “floating” wetted cloth) and ventilated roof pond. This study provides the background to, and the current status of, all the above as passive cooling technique capable of providing both reduction of energy demand and thermal comfort. After an extensive background statement giving the history and motivation to create different types of ponds, the basic advances and disadvantages are sketched, focused on the comparative performance of the presented techniques. Several researchers have measured the energy reductions caused by different types of roof ponds in a variety of locations and have also suggested simulation techniques. In the presentation of each method, the basic principles have been recalled underlined the time and space scale of its application and analyzed its accuracy and suitability for use in different type of environments. The specific problems of each method are underlined focused on the environmental principles and design considerations. A condensed account of roof pond experience in a number of climates is being presented, including numerical results. Finally discussion and conclusions have been presented, focused attention on the most interesting new guidelines for research on the measurement and estimation of roof ponds.

1. INTRODUCTION

Roof pond is a passive cooling technique based upon the increased heat capacity of cheap and widely available water. In general, the pond is covered during day to prevent heating, and open at night to be cooled. The operation is being reversed in winter for heating. International literature has given a number of variations on the existence or not of an insulating cover, shading louvers, embedded or floating insulation and floating cloth.

2. THE MOTIVATION FOR THE CREATION OF ROOF PONDS

Evaporative cooling can be tracked back several hundreds of years in ancient Egypt and Persia [1,2,3]. The reduction of heat flux through the roofs by using roof ponds was probably first investigated at the University of Texas [1] in the 1920s. In 1940, a number of publications [1,4,5,6] investigates the cooling produced by an open pond and a spray of water on the roof, complemented by Yellot [7, 8]. Two years later, roof ponds appears in international bibliography, when Harold Hay originally patents skytherm. Hay and Yellott [9,10] determine experimentally the practicability of intermittent water spraying and external movable insulation, with and without a closed roof pond.

In 1972 Niles [11] continues experiments on skytherm followed by Jain and Rao [12] who investigates the cooling effect of movable insulation, roof spray, with and without a roof pond. They were the first to experimentally observe wetted gunny bags supervised by an investigation [13] focused on the practical problem of essential requirement of the water spraying. In 1976 roof pool system is being presented [14]. By the end of seventies, several studies [15,16,17] indicate that the cooling effect can be enhanced using a shaded pond of water over the roof and circulating the pond water through the room. In the early 80’s, Sodha proposes a novel concept by a layer of flowing water over the roof [18]. The following year, he replaces the spray system to wet the gunny bags [19]. Chandra [21] was the first to consider the heat transfer mechanism for the building envelope as a whole. In 1985 an experiment [22] proves that the performance of roof ponds be further improved by allowing vapours to escape. Givoni also contributes substantially in the motivation of roof ponds [23, 24, 25,
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Carrasco [27] performs an experimental study of the use of a roof spray system, followed by the use of low emissivity material reduced the underside ceiling surface temperature [28]. By the end of the decade, the concept of using roof ponds has been gathering increasing popularity [29,30].

In the nineties, most of evaporative cooling techniques have been put into practical use [31, 32]. Among all reported roof evaporative cooling techniques by then, a roof covered with wetted gunny bags and a pond with a movable insulation have been widely considered as the most efficient systems for cooling of buildings in spite of the unreliability of the mechanical system [5, 33]. In order to cope with the above problem an improved roof pond with gunny bags floating over the water surface suggested recently [34, 35, 36] which performed slightly better.

3. ROOF PONDS

3.1 Overview
Roof ponds can be inexpensively constructed by enclosing water in plastic bags, metal or fiberglass tanks with rigid transparent plastic covers. Moveable insulation panels are usually made of 2” polyurethane foam reinforced with fiberglass strands and sandwiched between aluminum skins. [37].

According to Givoni [38], the necessary condition for applying the technique efficiently is that the wet bulb temperature (WBT) of the air should be lower than 20°C. Further studies described below give environmental principles for the variety of systems.

The advantages of roof pond systems are that performance is independent of building orientation, the provision of both heating and cooling and even when there is a lack of water, brackish water can also be used. Disadvantages are that most of them can only cool the spaces under the roof and the lack of experience by the construction company. Additionally extra attention of the roof required being watertight, able to support 200-400kg/m² [38, 39, 40, 41].

3.2 Analysis of roof ponds types

3.2.1 Uncovered pond with sprays
The spraying system operates during day and nighttime. According to the recently held Roofsol project [39,40] droplet radius is recommended to be in the range of 0.5-1 mm, sprays flow rate from 1 to 1.5 vol/h, while spray height should be at least 0.5 m. Spraying should be stopped when the water temperature is 3-4°C above ambient WBT to avoid warming the pond. Limiting spray operation to nighttime conserves water and prevents the pond temperature from oscillating around the WBT. Nevertheless, spraying is required to maintain a stable water temperature in shallow ponds (<300mm).

For deeper ponds the increase in water temperature during daytime will be less than 7-8°C, even in warm and sunny conditions. Spraying system is usually preferred for larger cooling loads [39, 40]. The usefulness of roof spray cooling was found to be most effective in buildings with lightly constructed, poorly insulated roofs [5]. Open ponds are often preferable due to their simplicity. Disadvantages of the system comprises the demand for continue operation and the susceptibleness to fouling from wind blow dust, leaves, bird droppings, algae and mosquito larvae [38, 39,40].

3.2.2 Uncovered without sprays
In the second variant, the water depth is recommended to be at least 30cm deep [39, 40]. An uncovered pond tends to increase its temperature due to the solar gains until they are compensated by the spontaneous evaporative effect; typical water temperature fluctuation is around 5°C. The heat absorbed is inversely proportion to the bottom reflectance [39, 40].

The system consumes less water due to lack of spraying system.

3.2.3 Covered with sprays
This pond is assumed to be covered only during daytime and that the spraying operates only at night. The design recommendations of the spraying system are similar to the uncovered ponds [39, 40]. Pond depth in the range of 30-50cm is adequate for cooling. Additionally, the higher the conductance of the support roof the higher the cooling effect at night [39].

An additional analysis carried out to assess the effect of the sprays working during daytime, highlighted that the sprays warms the water in the pond when the ambient WBT rises above the pond temperature. This finding suggests that some form of control needs to be fitted to prevent such occurrence [39]. The cooling rate is higher compared with uncovered pond with sprays [40].

3.2.4 Covered without sprays
The system provides a slight cooling effect at all times with negligible temperature fluctuations. An opaque insulated cover is recommended. The emissivity of the cover, the solar absorbance for opaque covers and ventilation of the airspace between cover and water surface does not affect performance [39, 40].

In part of system’s effectiveness, the maximum indoor temperature reaches 21.3°C when the maximum outdoor is 27°C according to Givoni [43]. Etzion observed that indoor maximum temperatures were lowered below the outdoor maximum by 45-50% of the outdoors’ range. The system has the edge on inverted operation in winder for heating but demands further costs for the automatic...
3.2.5 Skytherm
The specificity of the Skytherm system in comparison to the above-described covered pond is that the supporting roof is a metal deck roof in comparison to the concrete roof. The depth of bags is recommended to be in the range of 100-250 mm in spite that simulations reveal that the cooling performance is merely not sensitive to the water depth of pond [36]. To keep the transfer of heat from the pond to the metal deck as great as possible, it is desirable to waterproof the top of the deck with a thin plastic sheet such as double laminated polyethylene carefully sealed at the edges or a fiberglass sheet and a thin coat of asphalt emulsion. [44] It is important to paint the underside of the metal deck since galvanized metal is a poor radiator when bare. Because the ceiling radiates at a relatively low temperature, it can be painted any color [37].

3.2.6 Energy roof
In this system water is contained within parapet and thermal insulation floats on the water under a thin, transparent plastic film. The roof basin is filled with approximately 400mm of water [40] and is supported on a metal ceiling. For summer cooling, water is pumped at night to a distributing tube, which allows it to flow between the insulation and the thermal mass of the roof, dissipating heat from the space below, while the pond is covered. [38]

3.2.7 Coolroof
In this variation, the water is circulated at night over the floating insulation. Cooling water temperature would be about 1 to 2°C above the average ambient WBT. The ceiling temperature in the case of concrete roof would be about 2°C above the water temperature. The insulation panels should be of impermeable to water material, such as extruded polystyrene [43]. According to tests R. Bourne in California, with the outdoor maximum of about 37°C the indoor temperatures during daytime were around 25°C. During the daytime the water was heated by about 5°C but its maximum remained at about the same level as the outdoor air minimum. Givoni proved that the temperature patterns of the system are almost identical to the ventilated pond in spite of the different mechanisms of heat transfer. Cooloof was invented by Dick Bourne of Davis, California in 1980 [43].

3.2.8 Walkable pond
The insulation in this system is embedded within the pond. During the summer, the pond is filled with water to a level about 3cm above the insulation. The insulation plates divide the water into two layers -below and above- with gaps permitting thermosyphonic circulation. The system is applicable specifically for buildings with reinforced concrete flat roofs in desert regions with mild winters (minimum temperatures usually above freezing) [43]. According to Givoni [43], the indoor maximum temperature were lower by about 2°C as compared with a house without any treatment on the roof. Another experiment [47] held in Saudi Arabia showed that the average indoor temperature were about 28°C, when the outdoor ranges of 30-42°C, thus it has been stabilized a little below the outdoor minimum temperature. The system has the advantage over the provision of useful area in the roof. Unfortunately, there is a lack of experience in construction company and in estimation of system’s performance.

3.2.9 Wet gunny bags
The rearmost invented variant of roof pond consists of gunny bags placed on a grid or mesh with polystyrene strips or other floatable materials attached underneath [34]. The insulation inhibits heat dissipation at night and a spraying system becomes essential [40]. The optimal water depth is 20 cm for metal-decked roofs and about 5 cm for concrete roof. [34]. The system first suggested and tested by T. Runsheng, Y. Etzion, and E. Erell in 2002 [35] Experimental results [35], showed that the system performed slightly better than a pond with movable insulation did. The reason is probably the thermal stratification of the water inside the pond [34, 35, 36]. The system is easy to build and control.
3.2.10 Cool-pool
The system consists of an open water pond shaded by sloping louvers, and supported by a concrete roof [48]. Cooled water is then pumped to a storage tube in the building below by concentric thermosyphon tubes in which the cooled water flows slowly downward through a central tube and then warmed by thermal exchange with the indoor air, rises back to the pool again [38, 39]. Karen Crowther and Melzer patented this system in 1979 in the US.

The pool can lose heat by evaporation whenever the vapor pressure of the atmosphere is lower than that of the pool water, in addition to radiative losses [38, 39]. The maximum cooling occurs for maximum shading and the minimum value of the relative humidity [48]. Choice of suitable protective louvers proved to be a major task, and a chevron (L-shaped) design was found to offer adequate shading and allow greater span widths than could be attained with flat 45° slats, according to J. Hammond tests. The same experiments showed that a small, well-insulated room could be kept between 20 and 25°C during three days in July when the afternoon outdoor air temperature consistently exceeded 38°C [38]. Shaded pond without thermal coupling to the interior is rendered ineffective if the air infiltration is more than 5 air changes per hr. [46].

The system has similar performance to unshaded ponds in terms of temperature with less water consumption [41]. The amount of heat removed per unit of water evaporated is more in than water film and roof pond. [48]. The system effectiveness is not affected by a reduction in roof area [48].

Cool-pool can also be designed for winter passive heating; tubes can be designed to function as a water wall by locating them behind south glazing and blocking circulation to the roof pond. The system does not require daily attention [46] but has a high cost in comparison to other evaporative cooling options of similar effectiveness [38].

3.2.11 Ventilated roof pond
Ventilated roof pond has a secondary lightweight insulated roof over the pond shading the water. Large openings between the water and the shade permit permanent airflow over the water and enhance evaporation. [47].

Water temperature would be about 1 to 2°C above the average ambient WBT. The ceiling temperature in the case of concrete roof would be about 2°C above the water temperature [43]. The water temperature almost follows the average ambient WBT, thus the system provides very effective cooling in dry regions with maximum WBT not exceeding 24°C even when daytime temperature exceeds 40°C [43].

The advantage of ventilated pond lies in the fact that there is not demand for any operation except closing the openings and draining the water in winter [43]. It can also be applied in a tilted roof with a maintained wet lower surface of the cavity over which flows the external air. In this case, the water replenishment is needed only 1 - 2 times a month. [49]

Disadvantages are the requirement of the construction of two roofs and the lack of experience since the technique is recently introduced in the market.

4. COMPARATIVE PERFORMANCE OF ROOF COOLING OPTIONS

4.1 Skytherm
Experiments held in Delhi’s climate [46] showed that the thermal performance of the skytherm system is a shade better than the shaded-pond system. This is because the pond water exchanges thermal radiation with the night sky in the sky-therm system whereas, in the other, it exchanges with the shade which is at the ambient temperature. Other experiments testing ponds in concrete and metal roofs, showed that, independent of the existence of a solar shield for the roof pond, the room temperature was always below 30°C, for Kuwait’s climatic conditions. [41]

A relatively recent validated model [50] indicated that cooling load demand reductions of 79.0%, 58.1% and 43.6% may be obtained by using shaded-pond, pond, and shaded roofs respectively, for the climate of Shiraz in Iran.

4.2 Water spray cooling
Jain and Rao [51, 52] have experimentally investigated in some detail the effect of roof pond and roof spray at the ceiling surface of thick reinforced concrete roof exposed to a hot-day sunny climate. It was seen that, by roof spray, the peak roof temperature decreased from 55°C to 28°C as compared to reduction from 55 to 32°C in the case of roof pond. This was obviously due to more effective evaporation of water at the roof surface. The ceiling surface temperature was observed to undergo a drop of the order of 15°C as compared to 13°C in the case of water pond. The indoor air temperature suffered a drop of the order of 3.5°C as compared to that of 3°C in the case of roof pond. [5]

Numerical computation for the heat flux carried out for the New Delhi’s climate [53] compared evaporative cooling techniques. It was found that, there are reductions in the maximum heat flux entering the room of 48% and 41% for the roof pond and water-sprayed systems, respectively. The corresponding reductions in daily heat input into the room are 20% and 35%, respectively. Similar results came over from a former analysis [54] for the same climate. The study shows that (i)
maximum cooling is achieved by water spray over the roof; (ii) a roof pond system with stationary water is more effective in stabilizing the fluctuations of indoor air temperature as well as the heat flux entering through the roof [54]. Roof ponds proved a more stable roof temperature in comparison to the water spray as expected, according to a simulation held for Washington’s climate [55]. Nevertheless, the wetting effect is not limited to the period of spraying but extends after that since it affects the heat-storing rate and also the roof interior surface temperature.[56]

4.3 Cool-pool system
The cool-pool system is more efficient than water-film and roof-pond techniques, according to numerical calculations made for New Delhi’s climate [48]. This is because in a cool-pool system the net amount of heat lost by convection, radiation and evaporation from water surface to the surroundings is taken from the room interior, whereas in other cases the part of the incident solar radiation which is absorbed by the roof surface also adds to the cooling load of the building. This results in a relatively lower indoor air temperature and consequently a smaller water requirement in a cool-pool system. The amount of heat removed per unit of water evaporated is more in the case of a cool-pool system [48].

5. MATHEMATICAL MODELLING OF ROOF PONDS
Dunkle [57] was the first to quantify heat flux followed by Yellot [8] who quantified the effectiveness of water sprays on roofs. Jan and Rao [55, 58] continued a set of experiments on the effects of a roof pond, roof spray and wetted gunny bags. Thereupon, Balcomb [59] and Prasad [60] predicted the indoor temperature using a simple thermal network analysis. Treat and Rogers [61] investigated the performance of water plastic bags. The latter [62] simulated the performance of roof ponds. R. Yadav and Rao [46] estimated the hourly indoor temperatures based on the steady periodic heat-transfer analysis to predict the thermal performance of roof ponds. Sodha [53, 63] provided an analytical base to the open roof pond taking into account the effect of relative humidity, valid only for large water depths (15 to 20cm). He has also analyzed the performance of a thin moving water film over the roof [18, 64, 65.] cool-pool system [48] and was also the first to provide a formula applicable on multi-storey buildings [63]. Tiwari presented a number of investigations on roof ponds [5, 67] and a periodic thermal model [54, 68, 69] taken time dependency of a number of parameters in good agreement with theoretical results. He was the first to consider the heat transfer mechanism for the building envelope as a whole [21]. A number of several investigators also offered much to the simulation of roof ponds. A summary of the algorithms for calculating thermal performance of skytherm is given in Pittinger, White and Yellot [38]. Yadav [46] also introduced a method to estimate the hourly indoor temperature based on a steady periodic heat transfer analysis for roof ponds. Clark [70, 71] presented quantitative assessment of passive cooling rates of roof pond systems [41]. Vieira [72] carried out an energy saving analysis of dehumidified roof pond residences. The above models mainly deal with large computer codes. [54] Some computer models for calculating the thermal load in the presence of a roof pond were available by the mid 70’s, however, the lack of the effects of different parameters explicitly hindered their practical applicability [73, 74, 75]. A mathematical model presented by K. Al Jamal et. Al [41] took into account almost all design and weather parameters followed by Somasundram’s & Carrasco’s [76]. The next investigation [77] uses periodic boundary conditions, and includes the effect of wind velocity and ambient water-vapour pressure. In the 90’s the thermal response of the roof with intermittent stepwise spraying variation modeled [56] and preliminary the effects of roof spray evaluated [55, 27]. By the end of the decade, a validated computer program [44] calculates hourly cooling load requirements.

Recently Yilmaz [78] and Shah [79] compared the expressions on water evaporation given by the up to date literature [5, 79, 80, 81, 82, 83, 84]. Both indicated significant discrepancies. The following analysis [85] offered more accuracy to the quantification of the evaporation rate. Tang and Etzion [34, 36, 86] proposed an effective method on the evaporative water losses from ponds. Recently, a thermal model based on the periodic analysis [87] for hourly variation of passive roof cooling options developed validated with the experimental values of Nahar et al. [33].

6. CONCLUSIONS
Considering the promising results can be concluded that roof ponds adequately handle the cooling loads. International literature indicates wetted gunny bags and movable insulation as the most efficient roof ponds.

REFERENCES