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HYBRID ROOF POND SYSTEM TO REDUCE HEAT IN HOT-HUMID CLIMATES FOR BUILDINGS

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Abstract: **This paper reviews literature systematically using roof ponds on passive heating and cooling of buildings. The key goals were to obtain a detailed understanding of the different roof pond models and their performance, compare the effectiveness of different roof pond variants, assess the performance of different roof pond variants in relation to other passive design techniques, explore the impact of climatic conditions and different design configurations on roof pond performance and identify knowledge gaps. Overall, it identified 19 roof pond cooling systems and 4 roof pond heating systems. In some cases, this review suggests that roof ponds can provide thermal comfort throughout the year while reducing the demand for active heating and cooling systems. They can therefore be used to achieve the goal of carbon-neutral design. Roof ponds with wet gunny bags, shaded roof ponds, ventilated roof ponds and mobile insulated roof ponds have been shown to be more efficient compared to other roof pond cooling systems variants. Comparing performance with other passive approaches has shown that roof pond cooling systems are about as efficient in preserving thermal comfort indoors in many cases. The main factors influencing roof pond quality are meteorological conditions, water depth, roof deck content, and insulating panel thickness. There are several areas of weakness identified in the literature. Future research should among other items, provide further detailed knowledge on the quality of all roof pond types, further explore the suitability of roof ponds with respect to other passive design measures, investigate the efficacy of roof ponds when combined with other passive design measures, evaluate the life-cycle costs of roof ponds and provide more knowledge on their genuine-world application.**

Keywords: **roof pond; passive heating and cooling; passive design; energy saving; carbon-neutral design.**

1. INTRODUCTION

Roof pond is a passive cooling strategy based on the increased heat power of inexpensive and widely available water. In general, during the day, the pond is covered to prevent heating and open for cooling at night. The heating cycle will be reversed in winter. The presence of an insulating sheet, shading louvers, embedded or floating insulation and floating fabric has varied according to international literature [1] Roof ponds can be built cheaply by enclosing water with rigid transparent plastic covers in plastic bags, metal or fiberglass tanks. An indirect heating and cooling system in which the thermal mass, which is liquid in plastic bags, is on the roof of the heated and/or cooled room. [2].

Passive cooling techniques in buildings have been shown to be extremely effective and can contribute significantly to the reduction of buildings ' cooling load. Designed and tested efficient passive systems and techniques. Passive cooling has also been shown to provide excellent thermal comfort and consistency of indoor air, along with very low energy consumption. A lean acclimatization theory can be established if the internal and solar gains of a building are sufficiently reduced. [3]

Passive techniques have developed gradually over time, but throughout the world they have been largely ignored. The explanation for this might be lack of knowledge or the curiosity of people in new and latest technology. Climate responsive design was limited to the size of the HVAC. Some passive techniques have been worked on more than others, such as evaporation and ventilation. On the other hand, the radiation effect attracted less investigators.

Among different elements of building envelope, roof is believed to be the most important when it comes to developing passive measures [4]. This is because it is the most exposed part of a building to direct solar radiation and there is enough evidence indicating that roof alone can be responsible for up to about 50% of heat load in single or two story buildings during summer. Shading the roof, increasing roof thickness, enhancing albedo of roof, insulating the roof and providing false ceiling, vegetating the roof, spraying and flowing water over the roof, and provision of roof ponds are several passive measures for regulating heat gain through the roof [5].This study is focused on the latter type. Using water as an ideal thermal mass (due to its large volumetric heat capacity and the fact that it is cheap and nontoxic) roof ponds are capable of providing passive heating and cooling. Since the invention of roof pond system by Harold Hay and his colleagues in late 1960's, a vast body of work has been published on design and performance of different types of roof ponds [6]

The specific purpose of this systematic review is to synthesize this literature of research. Three study articles on this subject have been published over the past four decades. [7] Kumar's study was written in 1982 when there was still shortage of literature on roof ponds. Givoni and Spanaki, Tsoutsos have done two more recent reviews. The first paper reported studies investigating the potential of different passive cooling systems, including radiant cooling, and indirect evaporative cooling of indoor temperature by roof ponds. In this study, results from several studies based on different roof pond variants (i.e. accessible, with mobile insulation, ventilated, cool-roof, and shaded) are presented. The review by [8] analysis offers a fairly detailed account of roof ponds built for passive building cooling purposes. They compared the performance of several roof pond variants after categorizing different roof pond variants and finally made some recommendations on choosing the desired roof pond system. This analysis builds on previous research by offering statistical data on the literature reviewed, presenting a more detailed account of the various configurations of the roof pond and their results, Investigating the cooling and heating efficiency of roof ponds, providing more information on the comparative performance of different roof pond types, contrasting roof pond performance with other passive measurements, exploring the effects of climatic conditions and different design configurations, and finding expertise and data gaps.

General advantages and disadvantages of roof pond systems.

Advantages

– A great deal of knowledge is available on design and operation of roof pond cooling systems

– These system have proved to be useful in arid, as well as temperate climates. Some variants are also applicable to humid climates

– Roof ponds can also provide co-benefits in terms of storm water management and the stored water can also be used for fire-extinguishing purposes

– Unlike many other passive measures, performance of roof ponds is not affected by building orientation

– Unlike direct evaporative cooling systems, roof pond cooling systems do not increase indoor humidity to an undesirable level

Disadvantages

– Roof ponds increase the weight of the building and are not suitable for buildings constructed according to lightweight construction standards. Retrofitting such buildings to make them more resistant may impose substantial cost premiums

– Roof pond systems can only be installed atop flat roofs (only ventilated roof pond is an exception)

– Unlike other passive techniques such as green roof and high-albedo coating, roof ponds affect the accessibility of roof for other uses (walkable roof pond is an exception)

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– In case of improper maintenance, leakage and water contamination issues may occur

– Most variants can only provide indoor comfort in one-or two-story buildings

2. METHODS AND MATERIAL

This is a desktop study containing literature content analysis related to roof ponds. The process described in Pullin and Stewart (Pullin AS, Stewart GB, 2006) was used to perform literature review. The basic review questions to be answered were: "What are the main variants of the roof pond described in the literature? What are the basic roof pond statistics analyzed in the studies reviewed? How effective are different roof pond variants in the provision of passive heating and cooling (typology, configuration, geographical distribution, etc.). Similar to other passive steps, how do roof ponds work? And what is the major research gaps to be tackled?

3. LITERETURE REVIEW

3.1 Basic principles of passive cooling and heating using roof ponds

Roof ponds offer cooling benefits by indirect evaporative cooling and/or radiant cooling [8]. In both methods, the roof serves as a heat exchange component cooled by surface evaporation, long wave radiation to the atmosphere, or both. It then works as a heat sink that absorbs indoor heat and penetrates heat into the building [6]. Thanks to the thermal coupling of the ceiling to the roof pool, radiation and convection also cools the interior space [6, 9]. The driving forces behind evaporation and radiation are' difference between vapor pressure at water surface temperature and surrounding air vapor pressure' and' difference between water surface temperature and effective sky temperature' [1,10]. Readers interested in more detail on the underlying radiation, evaporation, and convection concepts can refer to Santamouris [11] and La Roche [9].

It is also possible to use roof ponds during winter for passive heating. The pond is exposed to solar radiation during the daytime, and the water's heating storage capacity is used to store solar energy as sensitive heat in the pond. This stored energy is then transferred by conduction to the ceiling below, eventually transmitted by radiation and some convection to the indoor space [9, 12].

3.2. Overview of the reviewed studies

The total number of experimental and/or simulation results studies related to roof ponds was 70. Table 1 provides a brief overview of the main features of these studies. Most of the studies are related to roof pond cooling systems, only two studies have investigated the use of roof ponds in high-rise buildings, and most studies have reported satisfactory agreement between experimental and simulation results (see Table 2).

Table 1. Main characteristics of the reviewed papers

	Description	F	%	Description	Description	F	%
Type of study	Simulation	30	43	Indication of the amount of the reduced load	Yes	19	27
	Experimental	14	20		No	51	73
	Both	20	29				
	Review/descriptive	6	9	Building height	Low-rise	68	97
Agreement between simulation and experimental results	Yes	19	95		Both low- and high- rise	2	3
	Not mentioned	1	5	Building usage	Residential	16	23
					Services (edu, industrial, commercial)	5	7
Testing season	Summer	50	71		Agricultural/GH	2	3
	Winter	9	13		Test room	29	41
	Both	11	16		Not mentioned (review etc.)	18	26
Concerned load	Cooling	53	76	Consideration of building occupancy	Yes	14	20
	Heating	7	10		No	56	80
	Both	10	14				

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Table 2. Degree of agreement between predicted and monitored values

Type	Description
Correlation coefficients between monitored and predicted values	Correlation coefficients between monitored and predicted data ranged 0.85-0.96
	The coefficient of correlation between predicted and experimental data ranging from 0.94 to 0.98 and standard error 1.76 and 2.80.
	The correlation coefficient was 0.88
	Correlation between predicted and experimental data and standard error values of 0.94 and 1.17, respectively
Maximum deviation between monitored and predicted values (percentage)	Maximum deviation of 4.05% was observed
	Maximum deviation of 7% was observed
	Maximum deviation of 5% was observed
Maximum deviation between monitored and predicted values (degrees Celsius)	The deviation ranges between ±1.5° C
	Agreement of better than + 1.5°C was observed

3.3. Methods of measuring thermal effectiveness

The most common methods used to measure the effectiveness of roof ponds are assessments based on the extent to which the indoor temperature of the test cell changes relative to the indoor temperature of the control cell, the extent to which heat fluxes enter the building through the roof with / without water pond, the extent to which the indoor temperature changes relative to the outdoor temperature and the extent to which the indoor temperature decreases. The least used approaches are level of change in the number of days of cooling degree and extent of the perception of indoor thermal comfort of people. Refer to Table 1 of the Online Supplementary Appendix for further details on these methods and indicators used to assess the thermal efficiency of roof ponds.

Analysis of roof ponds types

3.4. Uncovered pond with sprays

During daytime and nighttime the spraying system operates. It 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, according to the latest Roof Sol project droplet diameter. If the water temperature is 3-4o C above normal WBT, spraying should be stopped in order to avoid heating the lake. Limiting nighttime spray operation preserves water and prevents the temperature of the pond from oscillating around the WBT. Nonetheless, spraying is required in order to maintain a stable water temperature in shallow ponds (< 300 mm) for deeper ponds, the daytime increase in water temperature will be less than 7-8oK, even under warm and sunny conditions. With greater cooling loads, the spraying method is usually preferred. In buildings with lightly constructed, poorly insulated roofs, the usefulness of roof spray cooling has been found to be most effective. Open ponds are often preferable because of their simplicity. System disadvantages Comprises the demand for continue operation and the susceptibleness to fouling from wind blow dust, leaves, bird droppings, algae and Mosquito larvae.

3.5. Uncovered without sprays

The water depth is recommended in the second variant to be at least 30 cm deep. Due to solar gains, an uncovered pond tends to increase its temperature until the spontaneous evaporative effect compensates for them; typical water temperature fluctuations are around 5 ° C. The absorbed heat is inversely proportional to the reflectance at the bottom. Because of the lack of spraying system, the system consumes less water.

3.6. Covered with sprays

It is assumed that this pond will only be covered during the day and that the spraying will only operate at night. The spraying system's design recommendations are similar to the uncovered ponds. The depth of the pond in the 30-50 cm range is sufficient for cooling. Moreover, the higher the support roof conductance, the higher the cooling effect at night.

An additional analysis conducted to determine the effect of sprays working during the daytime, demonstrated that the sprays heat the water in the pond when the ambient WBT increases above the temperature of the lake.

3.7. Covered without sprays

Despite small temperature fluctuations, the system provides a minor cooling effect at all times. It is suggested to have a transparent insulated cover. The emissivity of the cover, the solar absorption of transparent coverings and the drainage of the air space between the cover and the surface of the water do not affect performance. As part of the efficiency of the system, the maximum indoor temperature reaches 21.3o C when according to Givoni, the maximum outdoor temperature is 27o C. Etzion observed that maximum indoor temperatures were lowered by 45-50 percent of the outdoor range below the maximum outdoor temperature. The machine has the edge of inverted heating action in the winder, but the automatic requires additional costs.

3.8 Skytherm

Similar to the above-described covered lake, the Skytherm system's simplicity is that the supporting roof is a steel deck roof similar to the concrete roof. It is recommended that the depth of the bags be within the range of 100-250 mm, but tests show that the cooling quality is simply not responsive to the pond's water depth. 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, it is important to allow the transfer of heat from the pond to the metal deck as large as possible. Painting the underside of the metal deck is necessary because when raw, galvanized metal is a weak radiator. Since the ceiling is radiating at a relatively low temperature, any color can be painted.

3.9 Ventilated roof pond

Ventilated roof pond has a secondary lightweight insulated roof above the water shading pond. Wide openings between the water and the shade allow permanent flow of air over the water and increase evaporation. Water temperature will surpass the normal ambient WBT by about 1 to 2o K. In the case of concrete roof, the ceiling temperature would be about 2o K above the temperature of water. The water temperature nearly follows the average ambient WBT, so the system provides very effective cooling in dry regions where the maximum WBT does not exceed 24o C even when the daytime temperature exceeds 40o C.

4. COMPARING PERFORMANCE OF DIFFERENT VARIANTS OF ROOF PONDS

A considerable number of the reviewed papers (13), have provided information on the comparative performance of roof pond variants.

As can be seen, these pairwise comparisons are mainly related to roof ponds designed for passive cooling purpose. This is expected given the limited number of reviewed papers focused on roof pond heating systems .Skytherm provides better heating benefits than open roof pond [12, 13]. Under mild winter conditions of Delhi, India, performance of Skytherm was compared with that of an open roof pond without water spray. By preventing heat loss at night, Skytherm provided a better performance. Indoor air temperature achieved by Skytherm was always about 2ºCwarmerthan that achieved by open roof pond, indicating that nighttime insulation increases heating efficiency of the system [12]. Overall, Skytherm offers a reasonably well performance with moderate water requirements. However this system needs supplementary mechanical control and has comparatively high maintenance costs [8].

It can be seen from Table 6 that open roof pond only performs better than covered pond with an additional insulation layer [14]. Study conducted under hot-arid climatic conditions of SdeBoker indicates that cooling provided by Shaded RPWGB and RPWGB is comparatively better than that provided by the other variants [14]. Cooling performance of the RPWGB was similar to that of the pond with movable insulation and without water spray. Although the water temperature near the bottom of RPWGB was about 2 ºC higher than that of the roof pond with movable insulation, it facilitated better daytime heat loss from the interior building into the pond. However, roof pond with movable insulation (no spray) may perform better under different building conditions. In a more recent study conducted in SdeBoker, cooling performances of RPWGB and roof pond with movable insulation were compared in three different buildings featuring different thermal mass, insulation level, and roof material [4].It was found that the best performance in terms of cooling and temperature stabilization is achieved in the well-insulated building with massive walls and a metal-deck roof. Unlike the case of

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poorly insulated building, RPWGB performed better and indoor temperature achieved by it was always about 0.95ºC lower. When these two roof pond variants were applied to a poorly insulated building with a metal-deck roof, cooling performance was considerably less effective and the building experienced higher indoor temperature swing. In this case roof pond with movable insulation performed better than RPWGB (indoor temperature was always about 2.3 ºC lower). This can be explained by higher thermal conductivity of the gunny bags that results in transfer of more solar heat gain into the pond compared to roof pond with movable insulation [4].

In hot-arid conditions of SdeBoker, RPWGB also performs better than ventilated roof pond. Only during early night hours water temperature at the bottom of the ventilated roof pond was lower than that of the bottom of RPWGB. This is explained by the inverse thermal stratification in the RPWGB during early night hours due to the limited openness of the supporting PVC grid that resists instant sinking of cooled water into the pond. Although due to this phenomenon, heat flux (from interior building) into the RPWGB was lower compared to the ventilated roof pond during the period from late afternoon to early evening, the overall diurnal heat loss was about 20% higher in the RPWGB. This is explained by the fact that fixed shading eliminates long wave nocturnal radiation into the sky, reducing the cooling potential of ventilated roof pond [14]. Even better performance can be achieved by placing an insulation layer within a certain distance (about 20 cm) over RPEGB. During daytime hours temperature near the bottom of shaded RPWGB was about 4ºC lower than ambient WBT. The total daily heat loss from building into shaded RPWGB was about 50% higher than that into the ventilated roof pond, indicating the significant

Improvement achievable by shading RPWGB [14]. Major advantages of RPWGB and shaded RPWGB (over other systems such as skytherm, pond with movable insulation, Cool-roof, Energy-roof, etc.) are that they don't require supplementary mechanical equipment and have low operational and maintenance requirements [8]. Main drawback is that this system uses a large amount of water [15].

Ventilated roof pond has also proved to be a viable option given its performance and cost effectiveness. Cooling performance of this system (in arid and temperate climates) is comparable to that of Skytherm, pond with movable insulation (no spray), and Cool-roof [6, 14, 16]. Comparison of the cooling performance of ventilated roof pond and Cool-roof, under arid and warm-temperate climates, showed that both systems were able to maintain indoor temperature between about 23-24 ºC and this was around 3ºC cooler than outside ambient temperature[6, 16]. Very similar results were found when ventilated roof pond was compared with Skytherm under the same climatic conditions [16]. Much the same as what was said about RPWGB, ventilated roof pond does not need mechanical operation and has minimum maintenance requirements [8]. However, since cooling is mainly produced

by evaporation, it consumes a large amount of water [16]. Skytherm, Cool-roof, and pond with movable insulation without water spray consume comparatively less amount of water [16], making them more desirable for arid areas which are usually water stressed.

Not much is available on the comparative performance of shaded roof ponds. Under warm-temperate conditions of New Delhi, Yadav and Rao [17] performed simulations to compare the cooling performance of an open roof pond, a shaded roof pond without water spray (metal and concrete deck), and a Skytherm (metal and concrete deck). It was found that the first system was not very effective. The Skytherm and shaded roof pond (both metal deck) were the most effective. When the ambient outside temperature was over 40ºC, simulated indoor temperatures for shaded roof pond and Skytherm were about 28 and 26.8ºC, respectively [17]. More information on the comparative performance of different shaded roof pond variants is provided in Section 5.1.6. Shaded roof pond variants (except for the one with water enclosed in watertight bags) are water intensive. Those using operable louvers also need mechanical operation and have comparatively high maintenance costs.

Only one of the reviewed papers has discussed comparative performance of Cool-pool system [18]. Simulation study conducted in warm-temperate climate of New Delhi showed that, compared to an open roof pond, Cool-pool system provides a better indoor thermal comfort. The Cool-pool system provided the maximum amount of cooling at 16 h, when cooling produced by the open roof pond was minimum. This shows the importance of covering the roof during sunshine hours. Average indoor temperatures achieved by the open roof pond, and Cool-pool systems on a light roof were 35.3, and 33.3 ºC, respectively. Better performance of Cool-pool system is because, unlike open roof pond wherein some incident solar insolation is added to the cooling load of the building, in the Cool-pool system almost all the heat loss through convection, evaporation, and radiation is from the indoor space and additional load from solar radiation is negligible. As a result, water requirements of the Cool-pool are also relatively lower. Water consumption of the Cool-pool system was almost half that of open roof pond. Additional advantage of this system is its suitability for buildings with limited roof area [18]. Compared to other systems Cool-pool has higher mechanical and maintenance requirements. Further studies on needed on the comparative performance of this system with respect to other effective variants such as RPWGB, Skytherm, and ventilated roof pond.

5. COMPARING PERFORMANCE OF ROOF PONDS AND OTHER PASSIVE TECHNIQUES

Overall, six different roof pond variants have been compared with other passive cooling and heating measures. Again, the main focus has been on passive cooling techniques.

Under humid continental climate of Muncie, Indiana, passive heating performance of a Skytherm (placed under a pitched roof) was compared to that of other passive measures, namely, “direct gain”, “Trombe wall”, “water wall”, and “Sunspace” [19]. Promising results on the effectiveness of Skytherm were obtained from the experiments. Arguing that less than 10ºC of temperature swing is necessary for providing thermal comfort, the author found that except for the Sunspace, the other strategies met this criterion. However, the best performance was gained by Skytherm followed by Trombe wall, and water wall. The highest and lowest variations of operative temperature were for direct gain and Skytherm, respectively. Minimum and maximum temperature swings for these two passive measures were 7.8-10.3 ºC and 1.2-1.4 ºC, respectively.

Many studies have compared cooling performance of open roof pond with that of other passive techniques. It can be seen that “open pond without spray”, roof garden”, and “inverted earthen pots over the roof” have exhibited similar levels of performance under arid and temperate conditions. Performance of “water spray on the roof” is similar or slightly better than that of “open pond without spray”. There is, however, one study indicating better performance by the former [20]. Given the similarities between the studies in terms of parameters such as relative humidity, roof deck material, building type, etc., this can be explained by the lower depth of the open pond used in that study. Deeper open ponds provide better performance. Other reason may be differences in water spray type (continuous/intermittent) and spray flow rate. These information is not provided in the concerned studies. Under temperate conditions, open roof pond has been found to perform slightly better that “water flow over the roof”. However, performance by “active mass cooling” and a combination of “vegetated pergola” and “thin water layer over the roof” has been slightly better than open roof pond. Better performance has been achieved compared to “night flushing”, “vegetated pergola over the roof”, and “shaded roof”.

In a simulation study conducted under warm-temperate conditions of Stellenbosch, Vorster and Dobson [20] compared cooling performance of an open roof pond with other cooling systems namely, roof spray, active mass cooling, and night flushing. It was found that the open roof pond can reduce peak temperature from 33.97 to 28.41 ºC. This resulted in 51.07 and 40.62% reductions in the peak cooling load of the room and total heat energy transferred to the room, respectively. Corresponding values for roof-spray, active-mass cooling, and night flushing techniques were, respectively, 59.36 and 72.24%, 51.39and 58.58%, and 5.50 and 31.67%. This indicates that open roof-pond provides better performance than the night flushing technique. It should, however, be noted that the former is more costly and requires maintenance. Under hot-dry conditions, Jain and Rao [21] conducted experiments to compare the outside roof temperature achieved by applying open roof pond and wetted gunny bags (daytime only) systems. Temperature reductions (as compared to the bare roof) were in the order of 23 and 27 ºC, respectively. In terms of heat flux through the roof, it was found that roof pond can reduce peak heat gains in the order of 85% and wetted gunny bags can even reverse heat flux [21].

For the hot-arid conditions of Al Maadi, Egypt, Dabaieh, Wanas [22] performed simulations to investigate thermal performance of various combinations of different roof shapes and materials. Performances of 16 different combinations were compared to that of a flat bare roof without any treatment. Results showed that an open pond combined with a high-albedo roof coating provides one of the best performances (ranked fifth after "vault+albedo", "ventilated vault+albedo", "flat roof+albedo" and” ventilated vault+air gap+ albedo".

Roof pond with movable insulation, without water spray has performed better than measures such as “water spray on the roof”, and “well-insulated roof”. However, performances achieved by measures such as placing “pieces of white glazed tiles stuck over the roof" and covering the roof with "wetted gunny bags" have proved to be better. In a simulation and experimental study comparing cooling performance of two identical test cells with different roof configurations in the hot-humid climate of Maracaibo, Venezuela, Rincon, Almao [35] found that,taking 25 ºC as the reference comfort temperature, average daily thermal load reductions offered by roof pond with movable insulation with respect to the reference cell (with well-insulated roof) were 41 and 66% in August and January, respectively. Under hot-arid conditions of Jodhpur, India, Nahar, Sharma [15]conducted experiments to compare a roof pond with movable insulation to other passive measures applied to the roof namely, Sania over the roof, cement– vermiculite thermal insulation over the roof, roof painted with white cement, roof provided with air void insulation, pieces of white glazed tiles stuck over the roof, and roof covered with wetted gunny bags. It was found that only the two latter measures performed better than the roof pond. However, the roof covered with wet gunny bags has considerable water requirements (50 l/m2 per day) [15] under hot-humid climatic conditions of Maracaibo, González and Givoni [24] compared cooling performance of a reference test cell with a highly reflective roof to that of a Skytherm. Simulation and experimental results showed that cooling performance of the test cell with Skytherm is better and the indoor temperature provided by it is always about 2ºC cooler. Again it should be noted that Skytherm has higher construction and maintenance costs which have not been considered in the study.

Cool-pool system has been compared with water flow over the roof. Results of simulated study conducted under warm-temperate conditions of New Delhi, India, showed that it was more effective in reducing indoor room temperature. Average indoor temperatures achieved by water film, and Cool-pool systems on a light roof were 35.3, 33.3ºC, respectively. For heavy roofs, the corresponding values were 35.6, and 33.7ºC, respectively. The similar performance of heavy and light roofs can be explained by the large thermal storage of the walls of the building [18].

As expected, RPWGB has performed better than wetted gunny bags over the roof. Due to creation of thermal stratification in the pond, the thermal comfort provided by the RPWGB is always better. Thermal stratification is important because it eliminates heat convection from the top of the pond to its bottom and the conduction is also very slow because of the poor heat conductivity of water. As a result, thermal stratification minimizes heat transfer to the bottom of the pond and keeps water at the bottom at a low temperature, facilitating better heat loss from the interior building into the pond [25].Another effective factor is that RPWGB is less sensitive to increasing absorptivity of the gunny bags compared with the roof covered with wetted gunny bags [26].

Finally, ventilated roof pond has performed better than massive buildings and shaded roofs. Kruger, Cruz [27] compared cooling potential of a ventilated roof pond with that provided by a high thermal mass building in the hot-arid climate of SdeBoker Israel. Simulation results showed that ventilated roof pond provide greater maximum temperature depression. Lower efficiency of the high mass building in terms of

Reducing the maximum temperature was explained by the lower nocturnal local wind speed and the considerable time needed for a high-mass building to cool down at night. In the room with ventilated roof pond the cooling degree days were almost eliminated as no indoor temperature was registered above the maximum adaptive thermal comfort limit. The high-mass building was also effective in reducing the number of cooling degree days. In terms of total indoor comfort, the high mass building performed better due to the fact that its indoor minimum temperature is almost always above the lowest adaptive comfort limit as prescribed by ASHRAE Standard 55 for SdeBoker's climatic conditions. Since using ventilated roof pond alone drops the minimum indoor nighttime temperature below the lower adaptive comfort limit in SdeBoker (in summer), it is suggested that ventilated roof pond and high thermal mass should be combined to counter this problem.

6. CONCLUSION

Implementation of passive design techniques can contribute to climate stabilization by providing significant savings on energy consumption in the built environment. Roof ponds are relatively simple passive design elements capable of minimizing energy use in buildings. A vast body of work has been published on roof ponds, indicating the availability of a substantial amount of knowledge on their structure and performance. Reviewed studies have employed either analytical, experimental, or both methods to determine the effectiveness of roof ponds. Good agreement between the results indicates validity of the models used in these studies. This systematic review listed different variants developed for cooling and heating purposes. Overall, 19 different roof pond cooling variants were discussed. Open roof ponds, ponds with movable insulations, and ventilated roof ponds are major roof pond cooling types that have received comparatively higher attention in the literature. Little information exists on performance of Energy-roof, walkable roof ponds, shaded ponds, and shaded RPWGB. More research is needed on these variants. Results showed that all variants (except Roof pond with additional insulation layer) are capable of enhancing thermal comfort in arid and warm-temperate climates. It was found that Skytherm, Cool-roof, and ventilated roof pond can even be effective in humid climates. Effectiveness of Skytherm can be explained by the fact that water is enclosed in watertight bags and therefore its performance is less affected by relative air humidity. This implies that "shaded pond with water enclosed in water tight bags" may also be suitable for use in humid climates. Future research is needed to verify this assumption empirically. Cool-roof uses nighttime intermittent water spray over the roof to enhance evaporation. This can explain its effectiveness in humid climates. However, since this system has only been examined in two humid climates, this result should be treated with caution and further research is necessary to better understand the performance of Cool-roof in humid climates. Effectiveness of ventilated roof pond in humid climate can be attributed to its use of fans to enhance water evaporation. Unlike roof pond cooling systems, the literature on roof pond heating systems is limited. This is probably because of their limitations compared to other passive heating techniques. In addition to the cost and maintenance issues, roof ponds are argued to only be capable of providing sufficient heating for climates where outside air temperature does not fall below 5ºC[9]. Other passive techniques such as direct gain and Sunspace need less maintenance and can be applied in any climate and to any building, regardless of its height. Of the four different variants mentioned in the study, Skytherm and "roof-integrated water solar collector" proved effective in temperate climates. It was also argued that creating non-convective zone in the water pond can make the Skytherm applicable to freezing conditions as well. This review indicates that limited evidence on the comparative performance of different roof ponds is available in the literature. Several studies include comparisons between two or more roof pond cooling systems. However, variants such as Energy-roof, walkable roof pond, Cool-roof, and Cool-pool have not received due attention. Results show that, under arid and warm-temperate conditions, RPWGB, shaded roof ponds, ventilated roof ponds, and roof ponds with movable insulation provide better performance than other types (descending order of performance). However, there are also other factors such as initial costs, maintenance and functioning costs, need for mechanical support, water consumption, and type of target building that should be taken into account. For instance, high water requirement of RPWGB, shaded roof ponds, and ventilated roof ponds undermines the viability of using them in water-stressed areas. When making comparisons between different roof ponds variants, future research should also take these factors into account and provide quantitative and/or qualitative information related to each of them. Research on comparing roof pond systems with other passive techniques is also limited. Of the roof pond heating variants, Skytherm is the only one that has been compared with other common passive heating systems such as direct gain, Trombe Wall and Sunspace. It has proved more effective than these systems.

As for the cooling variants, only a limited number have been included in the comparisons .Comparing performance of RPWGB, Cool-pool, ventilated roof pond, and Skytherm to other passive strategies showed that, in many cases, these roof pond variants perform better or are about equally effective in maintaining indoor thermal comfort. These findings are promising. However, it would be rash to conclude that roof pond systems always perform better than other passive techniques. Such a conclusion would only be supported if other issues such as cost, maintenance, resource consumption, and applicability to different climates were also considered in the comparative analyses. This is a major gap in knowledge that needs to be addressed. This review also discussed several factors affecting performance of roof ponds. Increased humidity has negative impacts on performance of roof pond cooling systems. It was argued that keeping water in watertight bags (dry roof ponds) and enhancing evaporation by using fans to blow air over the water surface can be used to mitigate the impact of humidity. Wind enhances evaporative cooling. However, it reduces long wave radiation to sky. It is therefore necessary to work on strategies for minimizing its negative impacts on long wave radiation. Regarding the optimum water depth, values between 5 and 75 cm were recommended for different roof pond systems. Results showed that values approaching the lower limit are more appropriate for covered ponds. Upper limit is recommended for uncovered roof ponds. Regarding appropriate roof deck thickness and material, these recommendations can be made: For covered ponds designed for heating and cooling purposes metal deck performs better. Due to high conductivity of metal, deck thickness does not have a significant impact. For covered ponds that have concrete deck, thinner deck is desirable (both heating and cooling). For open roof ponds designed for cooling and heating purposes, thicker and thinner concrete slabs are recommended, respectively. About the effects of thickness and emissivity of the roof pond cover, existing evidence indicates that cooling and heating effectiveness of Skytherm improves with increasing thickness up to about 3 cm, after which it remains constant. Effects of emissivity have been found to be negligible. Effects of these parameters on the performance of other covered roof pond variants should also be studied in future research.

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