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"Cooling of Outdoor Spaces"

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COOLING OF OUTDOOR SPACES

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ABSTRACT.

the paper deals with the possibilities of lowering the air and radiant temperatures in different types of outdoor spaces. It deals separately with outdoor spaces adjacent to buildings, where an interaction exist between the thermal conditions in the building and in the adjacent outdoor space, and with "free-standing" outdoor spaces. It discusses the different sources which can be used for cooling outdoor spaces at each of these two types. With respect to free-standing outdoor spaces a distinction is made between the treatments applicable to wide rest areas and those applicable to narrow walkways.

1. Introduction

1.1. Environmental Factors Affecting Comfort in Outdoor Spaces

Many human activities take place in bounded outdoor spaces, either attached to their homes, such as yards and courts, or in "free standing" areas such as public rest areas, walkways, etc.

In hot regions, in summer, outdoor exposure often causes heat discomfort and stress, resulting from exposure to the sun and the high temperatures. In such cases the possibilities of improving the comfort conditions by shading the area and, if possible and practical, also lowering its air and radiant temperatures, should be considered.

There are some basic differences between the environmental factors affecting human comfort in outdoor and in indoor spaces. Inside buildings people usually are protected from direct exposure to solar radiation. Also the longwave radiant temperature of an indoor space usually is not too different from the indoor air temperature. On the other hand people staying outdoors are exposed to several direct and indirect forms of solar radiation.

When an outdoor space is not shaded the people staying there are exposed first to the direct solar beam and the diffused solar radiation from the sky. Reflected solar radiation from the surrounding ground, which depends on the reflectivity (color) of the ground, may add significant heat load, especially in arid region which often have scant vegetation and light color of the soil.

During daytime the ground surface temperature, especially in arid regions, is significantly higher than the ambient air level. This temperature elevation imposes an extra longwave radiant load on the persons on which it impinges, in addition to the direct, diffused and reflected solar radiation.

The physiological severity of the solar and longwave radiant loads depends on the ambient wind speed, temperature and humidity, as well as on the clothing worn by the people. The higher are the temperature and the humidity and the lower is the wind speed, the greater is the physiological heat stress imposed by the radiant load.

The direct solar radiation impinging on people in an outdoor space can be reduced by shading. The effectiveness of a given shading device depends on geometrical factors (in conjunction with the annual and diurnal patterns of the sun paths in the sky) and on the partial transparency of the shade material.

Common shading elements over outdoor spaces (except shade of some plants) are thin and lightweight. Their surface temperature during daytime would usually be higher than the ambient air, depending on their color. In many cases also the underside of the shade element would be at higher temperature than the ambient air, imposing a radiant heat load on persons staying below the shade. The design details of the shading should aim to minimize this extra heat load.
Any cooling scheme of an outdoor space should start, therefore, with minimizing the solar and

the longwave radiant loads. Although such treatments do not comprise a "positive" cooling of the space, they are equivalent from the comfort aspect to actual lowering of the space air temperature.

1.2. Differences Between Cooling Methods Applicable for Buildings and for Outdoor Spaces.

The difference between cooling methods applicable to buildings and those applicable to outdoor spaces is caused by the fact that a building can be closed, minimizing the flow of hot outdoor air through the building. The conductive heat gain can also be controlled by the thermal resistance of the building's envelope. An outdoor space, by definition, is open to flow of the ambient air and therefore the degree by which its temperature can be lowered below the ambient level is quite limited. Therefore, a cooled outdoor space, even when shaded by an impermeable material, has a much higher rate of heat gain by wind flow across the space than a building. Any cooling scheme of an outdoor space should take this factor into account.

Another difference between a building interior and an outdoor space concerns the radiant load. Within a building solar radiation can be eliminated and the mean radiant temperature is usually close to the indoor air temperature. Outdoors the reflected solar and the emitted longwave radiation from the surrounding hot ground can cause significant radiant heat load and therefore should be minimized by the treatment of the outdoor space.

Minimizing the temperature elevation of surfaces in an outdoor space above the ambient air level does not involve, in many cases, expenditure of energy. Planting trees and shrubs within and around the periphery of an outdoor space can effectively reduce the reflected solar and the longwave radiation emitted from the surrounding area.

On the other hand, lowering the surface temperatures of an outdoor area below the ambient air level involves, directly or indirectly, some form of water evaporation and some expenditure of energy.

1.3. Types of Outdoor Spaces, from the Aspects of Relationship to Buildings and Cooling Options.

From the viewpoints of the cooling options for outdoor spaces, and the interaction between the thermal conditions in the outdoor space and inside a building to which the space may be attached, outdoor spaces can be classified into several types.

First a distinction should be made between "free standing" outdoor spaces, which are not attached to a building, and outdoor spaces which are adjacent to a building. Adjacent outdoor spaces may interact with the building thermally, either by modifying the climatic conditions to which the building itself is exposed or by modifying the thermal conditions in the outdoor space by the cooling system of the building.

Among the adjacent outdoor spaces a distinction can be made, from the climatic control viewpoint, between outdoor areas which are not surrounded by physical barriers (e.g. walls), and those separated from the general environment by solid walls, about 2 meters high. In the first case lateral wind would make the achievement of air temperature reduction an impractical task while in the second case such air cooling is possible.

Among the "free standing" outdoor spaces a distinction should be made between two main types:

- Wide areas, with a smaller dimension over about 8 meters, to be referred to in the following as "rest" areas.

- Narrow long linear areas, to be referred to as "walkways".

The degree of climate modification that is achievable in these two types is quite different and some of the cooling systems which can be applied to rest areas are not applicable to walkways.

2. General Considerations in Cooling Outdoor Spaces.

When considering the design of an outdoor space in a hot region the first decision to be made is whether to limit the treatment of the area only to shading it or whether, in addition to shading, also to lower its temperature below the ambient air level. For lowering the temperature a source of water would be needed.

Before any technique is applied to lower the air and surfaces (radiant) temperatures in an outdoor space the wind flow through that space should be minimized. A major source of heat transfer into a cooled rest area is by advection of the warmer outdoor air. This heat advection can be minimized by the elements surrounding the boundary of the area: fences, walls, shrubs, etc., as well as by the details of the shading element over the cooled area. The treated area can also be sunken below the level of the surrounding ground, to increase its "isolation" from the ambient environment.

Once a rest area is partially isolated from the surrounding environment several cooling sources can be applied for lowering the air and surfaces temperatures in the area, as discussed below.

2.1. Shade as a Prerequisite for Cooling Outdoor Spaces.

Before considering any means for lowering the air and or the radiant temperature in an outdoor space shade should be provided from the sun. There are two reasons for the primacy of shading:

First, protection from solar radiation has a larger physiological effect, in reducing heat stress, than the effects which can be expected from lowering the temperatures in outdoor spaces.

Secondly, Shading does not involves any expenditure of energy or water, as are almost all the systems which can lower the temperatures in a rest area.

Effectiveness of the Shading.

Materials which commonly are used to shade outdoor spaces are not solid and, in effect, transmit some fraction of the solar radiation. The transmitted radiation raises the ground surface temperatures in the shaded space. In practice, even with "tight" shade materials, about 20% of the radiation impinging on the shade can be assumed to be transmitted. The transmitted radiation causes extra physiological heat load from the direct solar and the longwave radiation emitted from the ground.

Furthermore, even in cases when the whole outdoor area is covered by the shading elements, solar radiation can enter from the sides, especially in the morning and afternoon hours. The narrower the shaded area the greater is its fraction affected by this lateral sun penetration, especially if the area extends in the North-South direction.

The Temperature of the Shade's Underside.

The temperature of the shade's underside during the daytime is above the ambient air level, as a result from the solar radiation absorbed in the shade's material. The temperature of the underside of the shade affects the longwave radiant field to which the persons staying in the area are exposed, and consequently their thermal comfort.

The shade's underside temperature depends on the external color of the material and its thermal conductance. The lighter the color and the lower the conductance the closer will the shade's underside temperature be to the ambient air level.

An exception is the case when shade is provided by a thick layer of leaves, such as by trees or vines with dense foliage. The lower leaves are protected from the sun by the upper part of the canopy and are cooled by evapo-transpiration, so that their temperature is very close to the ambient air level.

2.2. Tradeoffs between Physiological Cooling by Wind and Outdoor's Air Cooling.

In dealing with the issue of comfort in outdoor spaces a conflict may exist between two design approaches:

a) Providing comfort by the cooling effect of the wind.

b) Lowering the air temperature in the outdoor space.

Any lowering of the air temperature in an outdoor space requires to minimize the (warmer) wind penetration. The conflict between the two approaches exists because minimizing the wind penetration to an open space is accomplished usually by fixed devices. The wind blockage can not be turned on and off, as is possible in a building by opening and closing windows. Therefore, once the spaced is semi enclosed, e.g. by surrounding walls, shrubs, earth berms, etc., the wind cooling effect is minimized even during periods when the wind is desirable.

In some cases the comfort state, at the ambient air temperature with moderate wind speed, may be better than at somewhat lower temperature but with lower wind speed. Quantitative comparison of the comfort conditions in the two cases can be done by the use of one of the "Comfort Indices". Generally, it can be expected that in humid regions the wind will have greater effect than the achievable reduction in temperature.

In this case, reflected solar and emitted longwave radiation from the surrounding area can be reduced by the treatment of the area, for instance by covering it with low but dense vegetation, so that the surface temperature is lowered while the wind is not blocked.

In arid regions the choice between the two options may depend on the typical local maximum air temperature. In places where the maximum temperature is below about 30 degrees Centigrade, wind can be very effective as a comfort element. In such regions shading the space, while leaving it open to the wind, might be the best approach to minimize heat stress. In places where the daytime temperatures are higher, the humidity low (e.g. with relative humidity below 50%) and where water is available, lowering the temperature and blocking the wind may be a preferable approach.
This can be accomplished by the various means discussed below (see section 4).

3. Lowering the Surface Temperature in Shaded Outdoor Spaces

Two "treatments" can be applied to outdoor spaces, to lower the surface temperature in the space below the ambient level. They are based, directly or indirectly, on evaporative cooling and include:

- Lowering the temperature of elements surrounding the cooled area.
- Cooling the ground (pavement).

3.1. Lowering the Temperature of Elements Surrounding the Space.

To minimize the radiant heat load, from reflected solar radiation and emitted longwave radiation from the ground around, the cooled area should be surrounded by elements which can be kept at temperature close or below that of the surrounding ground. These elements can be walls, high shrubs, earth berms, etc. The area can also be sunken below the surrounding ground level.

When the elements surrounding the cooled area are plants, or earth berms covered by vegetation, their temperature follows closely the ambient air level and the excess radiant load is minimized.
However, if the surfaces of the surrounding elements, while shaded, can be wetted, their temperature will be closer to the ambient WBT and, in arid regions, will be significantly lower than the ambient air.

In practice, if the surrounding elements consist of built walls, earth berms covered by concrete or stones, etc. it is possible to have running water over their surfaces, for instance in the form of cascades, of thus providing wet surfaces around the cooled area. Such a design was implemented in the "Rotondas" at the '92 EXPO site in Seville by Professors Asiain and Alvarez (Ref. 1).

The water flowing over the surrounding walls need not be of high quality. Where brackish water is available it can be used in this application, as a high rate of water flow can minimize salts and minerals deposition.

3.2. Cooling the Pavement in Rest Areas

As discussed above, even if an outdoor area is effectively shaded, its ground temperature would be somewhat elevated above the ambient air level. Cooling the pavement of a relatively wide shaded area can thus lower the radiant temperature to which the people in the area are exposed, although the effect on the air temperature, at the level of the "occupied" zone, would be negligible.

There is a point in cooling the pavement in a given space only if the dimensions of that area are large enough so that the change in the mean radiant temperature will be significant. This means that the smaller dimension of the area (its width) should be above a given minimum, e.g. above about 8-10 meters. Consequently, there is no point in lowering the temperature of pavements in narrow walkways, where the effect on the mean radiant temperature would be minimal.

A practical method for cooling a pavement, which has been developed by Professors Asiain and Alvarez and applied at the '92 EXPO site in Seville (Ref. 1), is to circulate under the surface, but in thermal contact with the material, cool water. The source of the cool water can be, for example, a pool which is cooled by continuous spray of the water, day and night, as is discussed in more details later on.

To enable water flow underneath, the pavement would usually consist of "plates" supported by "legs". Water flows then through the open gaps between the legs. Critical factors which determine the effective conductance of heat, from the pavement's surface to the cool water flowing underneath, and hence the pavement's temperature, are the actual area of contact between the "legs" of the pavement and the water and the thermal conductance of the legs.

To prevent water overflow above the pavement, and at the same time to insure the flow, an air gap practically exists between the underside of the pavement and the water. Thus the parts of the pavement in actual contact with the water underneath are only the legs. They serve as

the conduction paths for the heat flow to the water. The design detail of the pavement should maximize the potential for this conductive heat flow.

Water flowing over walls surrounding the rest area (as discussed above) can continue to flow under the pavement, into a central pond, as was implemented in the design of "Rotondas" in the '92 EXPO cite by professors Asiain and Alvarez (Ref. 1).

4. Sources for Air Cooling in Outdoor Spaces

4.1. General Considerations.

Once a rest area is effectively shaded and partially separated from the surrounding air, e.g. by being sunken and/or surrounded by walls, trees or shrubs, the air and radiant temperatures in it can be lowered below the level of the outdoor air. Not all the cooling techniques which are applicable in "wide" rest areas can also be applied to narrow linear walkways. Therefore these two types of outdoor spaces should be considered separately.

The air within a semi-confined space can be cooled either by the introduction of pre-cooled air into the space or by direct, or indirect, evaporative cooling of the air inside the space. Air can be pre-cooled by mechanical equipment outside the area and then blown by fans through ducts into the area to be cooled. Direct cooling of the air in a rest area can also be done by the injection of artificial fog which evaporates instantly, drawing heat from the surrounding air and thus cooling it. Other possibilities for cooling the air are by a passive evaporative cooling tower or by a convective cooling tower, systems which are discussed below.

To maximize the physiological benefits from the cooled air it is advisable to introduce it near the ground level. In this way temperature stratification over the rest area would be enhanced, with the cooler air at the level where people are standing and seating.

Lowering the air temperature in an outdoor space by compression air conditioning, delivering cool air to the space, would be very expensive due to the required high rates of air flow. Therefore evaporative cooling in one form or another would usually be, directly or indirectly, the ultimate cooling source. This factor limits, in effect, the applicability of lowering the temperature of outdoor spaces to arid regions where water supply is available.
Fortunately, brackish water can be utilized for several systems applicable to outdoor space's cooling. Such water sources are available in many arid and desert regions.

The depression of the Wet Bulb Temperature (WBT) below the air Temperature (DBT) in summer during the hot hours of the day is the most direct quantitative criterion for assessing the potential of evaporative cooling in a given location. The expected temperature drop of air exiting from an evaporative cooling system, below the ambient air level, would be about 60-80% of the WBT depression (DBT-WBT).

4.2. Mechanical Evaporative Cooling

Mechanical evaporative coolers can cool large quantities of air, to a temperature very close to the ambient WBT, with relatively low expenditure of energy, as compared with compression air conditioners. It is a conventional technology for cooling of buildings, which is used often in arid regions. Because of its relative low cost and low energy consumption it can also be applied in cooling of open spaces, provided that they are partially isolated from the surrounding area.

It should be noted, however, that mechanical evaporative coolers use large quantity of high quality water. Brackish water, which is available in many arid and desert regions, can not be used in mechanical evaporative coolers because it will clog the wetted pads through which the air is drawn. This is in contrast with some other techniques of evaporative cooling where also brackish water can be used.

Mechanical evaporative coolers are noisy. To minimize noise in the rest area it is preferable to install the evaporative cooling machine outside the area to be cooled. The cooled air can be directed by ducts to the rest area. To derive the most physiological benefits from the cooled air it is advisable to introduce it near the ground level, at the "occupied" zone of the space.

4.3. Artificial Fog

Artificial fog can be generated by injecting water at high pressure through very minute orifices. If the water droplets are small enough, and the WBT depression below the air temperature is large enough, the droplets evaporate almost instantly. The evaporation of the droplets cools the air without forming liquid water over people staying nearby, although the fog is visible.

Fog generators consume large quantity of energy, relative to their cooling effect, and need water of low mineral content (or water treated chemically), (Mee Inc., personal communication).

Even with very light wind the fog is carried away downwind. When the winds in a given region are light and the direction is more or less constant, fog generators in the form of a line, located upwind of the area to be cooled, can provide measurable cooling effect.

Artificial fog is especially an attractive cooling technique for local "spot" cooling of small areas where people congregate, such as in front kiosks along walkways.

4.4. Passive Evaporative Cooling Towers.

A passive evaporative air cooling tower, attached to a building, has been developed and tested by Cunningham and Thompson at the Environmental Research Laboratory of the University of Arizona in Tucson (Ref. 2). The system consists of a down-draft tower which has at its top vertical wetted cellulose pads impregnated with anti-rot salts and rigidifying saturants. Water is distributed at the top of the pads and is collected at the bottom by a sump and recirculated by a pump. The complete system in Tucson included also a solar chimney on the opposite side of the building, to enhance the air flow rate through the cooling tower and the building. Such a passive evaporative cooling tower can be used also to provide cool air for outdoor semi-confined rest areas.

Analysis of the test results of Cunningham and Thompson, done by Givoni, has shown that the solar chimney did not affect the performance of the cooling tower and that the air flow rate was almost independent of the wind speed. It was concluded that the
air flow through the pads is generated mainly by the temperature difference between the (cooler) air inside and the (warmer) air outside the tower. This temperature difference is proportional to the WBT temperature depression (DBT-WBT).

A mathematical model has been developed by Givoni (unpublished yet), expressing the expected performance of an evaporative cooling tower attached to a building as a function of the meteorological conditions, the details of the tower and the thermal properties of the building. In this model the pads are assumed to have a flow resistance equal to that of 10 cm. thick cellulose pads, the same as the ones used in the Arizona experiments.

The model calculates the tower exit air temperature (Texit), flow rate (Flow), the speed (Speed), and the indoor air temperature (Tin, when the tower is used to cool a building). The main equations of the model dealing with the performance of the tower itself (without a building) are:

Texit = DBT - 0.87 * (DBT - WBT); (C)

Flow = 0.0368 * Aevap * sqrt(H * (DBT - WBT) / 1.5); (m^3/sec)

Speed = Flow / Atower; (m/sec)

where:

Aevap = area of the evaporative pads, (sqm)
H = height of the tower, (m)
Atower = cross area of the tower, (sqm)

Figures 1 and 2, drawn from the data of Cunningham and Thompson, show the measured and calculated performance of this cooling system during two days and one night. Figure 1 shows the exit air temperature and Figure 2 the exit air speed.

It can be seen that when the outdoor temperature maximum was 40.6 deg. C and the WBT 21.6 C the tower exit air temperature was 23.9 C. The corresponding speed of the exit air at that time was 0.75 m/sec.

4.5. Passive Convective Cooling Tower

The following air cooling system has been proposed by the author for the '92 EXPO, but has not been tested yet (except for rudimentary preliminary tests) at the time of the writing of this paper.

If a source of cool water is available near the area to be cooled, e.g. from a nearby river or from a cooled pond (see next item), then air can be cooled convectively by a fine spray of the water falling down a vertical shaft (a convective tower). The falling fine drops, having a very large surface area, entrain a large volume of air. The temperature difference between the ambient air and the air column in the shaft enhances the flow by the thermosyphonic effect. Thus an air current is created which is cooled by a combination of evaporative cooling and convective heat transfer from the air to the water droplets.

As a source for the water for such a cooling tower a cooled pond, as described in the next item, can be used. As evaporation from the droplets takes place in the air, brackish water, if available, would also be suitable for this system.

4.6. Cooled Ponds as a Source of Cool Water.

For several of the cooling techniques for rest areas discussed above, such as cooling of surrounding walls, the pavement, or a convective cooling tower, a source of cool water is needed. A water pond near the rest area, with some "treatments", can provide it.

A pond with sufficient depth, e.g. above 60 cm., will have a very small diurnal temperature swing due to its high thermal inertia. Its average temperature will depend on the balance between solar heating, radiant heat loss to the sky, convective heat exchange with the ambient air, and the cooling by evaporation. The relative magnitude of these factors can be controlled and changed by some treatments of the pond.

Solar heating can be minimized by shading the pond, e.g. by trees around the pond. The average temperature of a shaded pond would be about the same as the average WBT as the evaporative loss is balanced by the convective gain. Shading may be a practical design solution in a small pond, in a private courtyard next to a building, but it may be less practical in the case of a larger pond near a public rest area.

Without shading the effect of solar radiation is mostly balanced by the increased evaporation from the pond's surface, due to the elevated vapor pressure of the warmed water, and the longwave radiant loss to the sky. Consequently, in practice, the average temperature of an exposed "deep" pond is above the average WBT and close to the diurnal average of the DBT.

When the objective is to cool the water of an unshaded pond below the average DBT the evaporative heat loss should be increased above the rate which takes place from the surface of the water. The evaporation rate can greatly be increased by a continuous (day and night) very fine-drops spraying of the water.

The fine drops increase many folds the surface area of the water, thus increasing greatly the evaporation rate. During daytime the evaporation from the spray brings the water temperature close to the average daytime WBT. During the night the combination of evaporation and radiation to the sky would cool the water to a temperature close to the minimum WBT. With a sufficient depth the pond's temperature will be close to the average ambient WBT.

In arid regions the water temperature would thus be significantly lower than the daytime air temperature, providing a cooling source for some of the systems discussed above.

5. Issues Specific to Outdoor Spaces Adjacent to Buildings

In the case of open spaces adjacent to a building but not separated by relatively high walls from the surrounding area it is possible, by plants' shading (trees and pergolas), to minimize the radiant temperature in the area itself, as well as the radiant load on the adjacent windows and walls. But it is not practical to lower the air temperature in the open area, except by artificial fog. Greater climatic control is possible in enclosed open spaces.

Open spaces adjacent to buildings and enclosed by walls (courtyards) and internal patios are very common in many hot regions, mainly in developing countries. Houses with courtyards are considered the most "appropriate" in many hot regions, especially in deserts. This notion is based on the fact that such courtyards are very common in such regions and were so since centuries, and millennia.

However, when analyzed from the viewpoint of their impact on thermal comfort and energy consumption (Givoni, 1987), it is found that their performance depends greatly on the detailed design of the courtyard. With some details courtyards can provide pleasant outdoor environment and also improve the indoor thermal conditions. With other details courtyards may actually elevate the indoor temperature and cause poor ventilation in the rooms located on the leeward side.

By applying some specific design details and cooling systems to courtyards adjacent to buildings it is possible to lower, in summer, the air and the radiant temperatures within the courtyard, below the level of the ambient air. A cooler courtyard provides, of course, a more comfortable environment for children's play and other outdoor activities in an area adjacent to the buildings.

In winter, of course, a sunny courtyard is much more pleasant and healthy than a shaded one. The trees should also not shade completely the building's walls, and mainly the windows, facing the courtyard. Therefore, deciduous trees and vines, with thick foliage in summer but as "bare" as possible in winter, should be used for shading.

When adequately treated, such adjacent open spaces can modify the climatic conditions of the ambient environment next to the "skin", and openings, of the building and thus improve also the indoor climate. Such modifications may include:

- Lowering the temperature by various forms of evaporative cooling which can be installed in the courtyard.

- Shading the building walls adjacent to the open space, by the shade elements in the courtyard, without blocking the sun in winter.

- Increasing the insulation value of adjacent walls by dense and high shrubs and vines, which create a semi-dead air-space next to the wall's surface. This last effect can be significant and beneficial, both summer and winter, in the case of walls having very low thermal resistance, such as metal or asbestos-cement buildings which are common in many developing countries.

Modifications of the climatic conditions next to the skin of the building can be achieved only if the courtyard is separated from the "general" environment. Separation is required not only laterally, by high walls around the yard, but also above it, by built elements or by tree canopies, which separate the confined cool air in the yard from the warmer air above.

5.1. Thermal Interaction Between a Building and a Courtyard

The possibilities of thermal interaction between a building and an adjacent courtyard depend to a large extent on whether an evaporative cooling system is used, or is not used, to cool the building.

Evaporatively Cooled Buildings

Evaporative cooling offers the best possibilities for utilizing the cooling system of the building for cooling the courtyard, because it cools very large quantity of air and exhausts the cooled (and humid) air from the building (once through flow). The cool exhaust air can be directed into the courtyard and lower its temperature, before it is discharged to the "general" environment.
Such integration of the cooling systems of the building and the courtyard is most effective in the case of an internal patio, surrounded on all sides by the rooms of the building. When it is desired to utilize the exhaust air to cool a courtyard the duct system, distributing the cooled air within the building, should be designed accordingly.

In this way the cooling system is utilized twice: first it cools the building interior and then the outdoor space, which can serve as a more pleasant area for rest and outdoor activities. The cooled courtyard, in turn, reduces the heat gain of the building across the adjacent wall and windows.

Buildings cooled by compression air-conditioning systems have very low rates of air change. Therefore, when a building is cooled by such a system, the courtyard has to be cooled by different systems.

Un-conditioned Buildings

Even when a building, located in a hot arid region, is not cooled by a mechanical system it still can be kept during the daytime at a significantly lower temperature than the outdoors by appropriate design. Such design should include solar control, external reflective colors of the walls and the roof, and building materials of suitable thermal resistance and heat capacity.

An adjacent cooled courtyard should then utilize separate cooling systems, applicable to outdoor spaces, such as mist generators, wet walls, fine spray fountains, etc., as discussed above. The temperature of the air in the courtyard would then be lower than the outdoor air.

The cool air from the courtyard can be used as the source for the ventilation of the building through openings in the separating walls, either by natural (thermosyphonic) or by forced ventilation, e.g. by an exhaust fan at the other side of the building.

In comparing direct evaporative cooling of the building itself with evaporative cooling of an attached courtyard, it should be noted that a courtyard can be cooled by systems which are not applicable for indoor use, such as wet walls, fine droplets fountain, mist generators, etc. Furthermore, a mechanical evaporative cooler has to use high quality water to minimize clogging of the wet pads where the evaporation takes place. On the other hand, some of the systems suitable for courtyard cooling can use water not suitable for mechanical evaporative coolers, such as brackish water, which is often available in arid regions.

5.2. Cooling Options for Courtyards.

In a private courtyard, internal or adjacent to the building, practically all of the cooling systems discussed in section 4 can be applied, to lower the temperatures of the air and the surfaces enclosing the courtyard.

Shading.

The function of shade elements in a cooled courtyard is not only to block the sun but also to provide some separation between the cooled air volume below the shading and the hotter ambient air above. Shading of courtyards, which fulfills these two functions, can effectively be provided by trees with high trunks and wide canopies and/or by pergolas of vines with relatively thick foliage.
Such shading, together with the building itself and the walls surrounding the courtyard, can "isolate" the air mass within the yard and minimize the mixing by the wind of the cooled air with the warmer ambient air. With such partial separation a desirable thermal stratification is created during the daytime, with cool air below and warmer air above, preventing thermal air currents.

At the same time water vapor, generated by various evaporative cooling systems which may be applied in the courtyard, can diffuse through the trees canopies to the ambient environment. In this way evaporative cooling can proceed continuously without causing excessive humidity.

During the night the plants canopy blocks direct radiant heat loss from the courtyard to the sky, as the radiation is emitted from the upper layer of leaves. However, whenever the air below the canopy is warmer than the air above it rises, and the air cooled by contact with the upper leaves can sink down, creating natural convective cooling of the courtyard.

Deciduous trees and vines can shade the courtyard in summer while admitting the sun in winter, rendering the courtyard comfortable year round.

Effect of Plants Shading on Wall's Temperatures and Building's Energy Use.

Although many articles and books were written on the climatic effects of courtyards on the thermal performance of adjacent buildings, very few actual measurements have been taken to validate the theoretical ideas presented in those publications. Some experimental studies have been conducted, however, dealing with the effect of plants on the surface temperature of walls and on their effect on the energy consumption by air-conditioning (Ref. 5-11). Of particular relevance to the subject of this paper are the studies of Parker in Florida (Refs. 8-11), on the effects of plants around buildings on the wall's temperature and the use of energy for air-conditioning.

On hot sunny late-summer days the average temperature reduction of walls shaded by trees or by a combination of trees and shrubs was 13.5-15.5 °C. Climbing vines reduced the surface temperature by 8-9°C.

In the main study the tested building was an insulated double-width mobile home serving as a children day-care center, in Miami. Energy uses for air conditioning were compared in two periods, before and after landscaping, during days with similar weather conditions. The landscaping consisted of trees and shrubs around the building.

Average daily rate of energy consumption for air conditioning in the period without plants' shading was 5.56 kWh/h and after landscaping it was reduced to 2,28 kWh/h on hot summer days. The effect of planting was even more marked during the afternoon hours (the peak load period): the average rate of energy use was reduced from 8.65 to 3.67 kWh/h.

Cooling a Courtyard Adjacent to a Building.

Taking into account the effects of un-cooled, landscaped, yards on the exposure conditions and thermal performance of buildings, the impact of enclosed (walled) courtyards, shaded by trees and cooled by some of the cooling systems discussed above, where the air temperature would be lower than the ambient, on the energy use of buildings and on the peak demand for electricity for air-conditioning, can therefore be expected to be quite significant.

Several features of an enclosed courtyard adjacent to a building can be designed as cooling elements, among them :

- the walls surrounding the yard,

- a shaded water pond with spray fountains,

- the pavement of the court.

The surfaces of the walls facing the courtyard can be cooled by provision of closed cycle flow of water, flowing down over the surfaces, and eventually into a pond in the courtyard. The cooled surfaces of the walls facing the courtyard lower the radiant and the air temperatures, to which persons staying in the courtyard are exposed.

A pond in a shaded courtyard, with fountains generating fine-drops spray, can maintain the water temperature near the diurnal average WBT.

If so desired, the water flow from the walls can continue under the pavement of the courtyard, to further lower the environmental radiant temperature in the space.

6. Specific Considerations in Cooling Free-Standing Rest areas

Rest areas, as distinct from walkways, are relatively wide. They can also be designed with a cross section and boundary conditions which would help in controlling their micro-climate. The degree of climate modification that is achievable in rest areas is therefore greater than what is possible in narrower and longer walkways.

In hot regions the objective of micro-climate control would be to minimize the solar radiation and lower the radiant and air temperature as much as is practical. Special geometrical configurations and treatments of the boundaries of rest areas can facilitate the achievement of these objectives.

6.1. Impact of Design Detail of Rest Areas.

Shape of the Cooled Area.

For a given size of a cooled rest area a shape close to a circle or a square configuration would be the best one, as it maximizes the smaller dimension of the area.

A wider area enables to achieve greater difference between the micro-climate of the rest area and the ambient climate. Overhead shading is more effective the wider the area because lateral sun, penetrating from the sides, affects relatively smaller fraction of the area, and people within it have more opportunities to move to the shaded parts. More techniques for lowering the air and radiant temperatures can be applied in wide areas than is possible in narrow ones.

Cross Section of the Area

A sunken cross-section, with special treatments of the surrounding banks, discussed below, can protect persons within the rest area from the reflected solar and the longwave radiation emitted from the hot ground around. A sunken area can also help, by enhancing stratification, to maintain air temperature within the space at lower level than the ambient air, when cooling is applied.

6.2. Treatment of the Ground and Surrounding Boundaries

As mentioned above, the only way by which the air and radiant temperatures in an open space can be lowered below the ambient air level is by the use of some form of direct or indirect water evaporation. Therefore, if water is not available, except for growing trees and shrubs, all that can be done to reduce thermal stress in rest areas is to minimize the solar load by providing effective shade, by trees or by built elements. In this case some wind is helpful in enhancing comfort as long as the air temperature is below about 38 deg. C., and the boundaries of the rest area should, therefore, enable wind penetration.

On the other hand, when water is available and when it is possible to lower the radiant and air temperatures in the rest area below the ambient level, the rest area should be separated physically by some means from the surrounding ground and the wind speed should be minimized.

Physical separation between the rest area and the surrounding ground can help in creating a micro-climate different than the ambient one. Such separation can be provided by "green" or built fences, and by earth berms, around the area. The surrounding elements should be treated so as to minimize their surface temperature. Trees and shrubs maintain surface temperatures of their leaves close to the ambient air by evapo-transpiration. Earth berms should be covered by vegetation to maximize their effect. Built fences could be wetted, to lower their surface temperature.

The ground of the rest area, if paved, can also be cooled by conduction when cooled water flows below the pavement. A cooled pavement can effectively lower the radiant temperature to which the persons in the rest area are exposed.

6.3. Summary of Cooling Techniques Applicable to Rest Areas

The following cooling techniques can be considered for lowering the temperatures in rest areas. Details were given in section 3.

- Mechanical Evaporative Cooling, with ducting of the cooled air into the rest area.

- Artificial Fog.

- Passive Evaporative Cooling Tower.

- A Cooled Pond, which can serve also as a source of cool water for the following cooling techniques:

  - Passive Convective Cooling Tower.

  - Cooled walls around the rest area.

  - Cooled Pavement in the rest area.

7. Specific Considerations in Treating Linear Walkways.

7.1. Differences Between Rest Areas and Walkways

Even when a walkway is shaded by an overhead device, the protection which can be provided from direct and indirect solar radiation is less than what is achievable in a wide rest area. Near noon time an overhead shade provides good protection from the sun in all cases. However, the situation is different in the morning an mainly in the afternoon hours, which often are the hottest, when the more oblique sun rays can reach the walking people. When the sun reaches a certain part of a narrow walkway the people may have less options to move to the shaded parts than is possible in wider rest areas.
The effectiveness of an overhead shade a walkway depends to a large extent on its orientation. An East-West walkway can provide somewhat better shade in summer than a North-South one. However, in both cases overhead shade can not provide complete protection from direct solar radiation in narrow walkways.

Also the protection from indirect solar radiation: reflected solar and emitted longwave radiation from the hot surrounding ground, is more difficult and often less effective than in wider rest areas.
However, with some design details, discussed below, it is possible to minimize this lateral radiant source.

Cooling of the air over a whole long walkway is practically impossible, except in small selected sections where people may stay for some time (e.g. in front of a kiosk along the walkway).

Appropriate cooling systems for walkways are discussed below.

7.2. Treatments and Cooling Techniques Applicable to Walkways

Practical treatments of walkways can include the following:

- Overhead shading by man-made materials, such as canvas, plastic sheets, etc., or by trees along the walkway and plants' pergola. This is obviously the first thing to do and will not be discussed further on.

- Reducing the lateral radiant heat load.

- Cooling the air over the walkways in selected places.

Reducing the Lateral Radiant Heat Load.

The lateral reflected and emitted radiation can be reduced by two types of treatments. The first is to lower the "natural" reflectivity and the surface temperature of the land areas along the sides of the walkway. The second is to install barriers. built or of plants, along the walkway and thus blocking the radiation before it reaches the people.

The albedo (reflectivity) of the natural ground, often of light color in arid regions, is usually about 0.4 to 0.6, so that the reflected solar radiation from the ground is significant from the thermal stress aspect. The surface temperature of exposed and untreated soil during the summer daytime hours, especially between 10 a.m. and 4 p.m., is significantly higher than the air temperature, increasing the emission of longwave radiation.

Covering the land along the walkway by any kind of dense vegetation: lawns, low shrubs, flowers, etc. reduces both the surface temperature of the ground and its reflectivity. Wide (e.g. about 10 meters) strips of "green" land along the walkway will thus reduce significantly the lateral reflected and emitted radiation.

A second option for reducing the lateral radiation reaching the people on a walkway is to block it by built or "green" fences along the walkway, about 1 meter high. With such a height the barrier blocks most of the lateral radiation while not blocking the view, and the wind, over it.

Care should be taken, however, to insure that the temperature of the fence's surface facing the walkway would not be elevated significantly by absorbed solar radiation.

The surface temperature of Green fences, e.g. of shrubs, is kept close to the ambient air level by the natural process of evapo-transpiration. Built fences exposed to the sun, on the other hand, may have a higher temperature, even of the surface facing the walkway, and may need some treatments to prevent it.

Maintaining a white color of the external surface of the fences insures reflection of most of the impinging solar radiation. The color of the surface facing the walkway is not important because this side is shaded by the overhead shading device.

Strips of trees with wide canopies along a walkway can reduce significantly the lateral direct solar radiation. If the strips are wide enough they effectively reduce also the reflected and emitted radiation from the shaded ground underneath.

Applicable Techniques for Cooling the Air over Walkways.

As discussed above, several of the cooling systems which can be considered for wide rest areas are not effective, or not applicable, to narrow walkways, such as for example: cooling the walkway's pavement, cooling the air over the whole walkway, etc.

However, for selected small segments of a walkway, the following cooling systems can be applied.

Mist Generators.

Mist generators produce under high pressure very fine water droplets, so small that they actually float in the air and evaporate in few seconds. The evaporation process draws heat from the ambient air and cools it. In an open environment the cooled air mixes with the general air volume so that the resulting temperature is about halfway between that of the

ambient air and the WBT.

Even with very light wind the mist is carried away with the air flow. Therefore only localized cooling, at selected places along a walkway, is practical with this system.

Perforated Bricks Wet Walls.

This cooling system for walkways has been proposed by the author for walkways at the '92 EXPO, but has not been tested yet at the time of writing of this paper. It consists of fence-like walls built with perforated bricks, with the bricks' holes horizontal and perpendicular to the wall, so that the wind can flow through. When the wall is wetted the bricks are cooled by evaporation and air flowing through their holes is cooled by a combination of convection and evaporation.

A rudimentary prototype was built at the '92 EXPO site in Seville. Although temperature measurements were not taken subjective sensation of the persons present was that of a significant cooling effect. This cooling sensation could result from the combination of cooler air and lower radiant temperature next to the wall.

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