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EVAPORATIVE COOLING EFFECTS IN HOT AND HUMID URBAN SPACES

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ABSTRACT. Two different natures of evaporative cooling effects on indoor and outdoor spaces in hot and humid regions are described in view of the devices in traditional architecture with some examples of measured results. One of the evaporative cooling means can be found in a traditional way by spraying water in the garden or fountains to make the air cooled through vegitations. This will give the air of one or two degrees lower in temperature than the ambient air, which was measured with a house in Japan. This will contribute to the improvement of thermal comfort to a considerable extent owing to a certain air movement along the skin surfaces of human body, though the relative humidity of the air becomes higher. The other can be seen also in traditional houses with thatched roofs or tiled roofs. The rain water soaked by those roofs will be evaporated by strong solar radiation whereby the inside surface temperature becomes much lower than the case with the roof which does not soak rain water. This was examined by laboratory experiments and a field study with an earth sheltered building.

1. Introduction

PLEA has been playing an important role in promoting bioclimatic architecture under the serious environmental conditionds where many people are much indulged in abundant lives of so called industrialized age. One of the most dangerous situations in view of the energy supply and demand is a high peak demand of electricity for cooling for a short duration of hot spells in the daytime. The increase rate of this peak demand in the whole households of Japan is equivalent of four nuclear power plants to be constructed every year. To relieve such grave situations architects, urban planners, scientists and engineers must strive for creating new ideas of bioclimatic designs, though policy decision makers should impose very high rate charges for electricity consumption during the summer peak hours.

Bioclimatic solutions are being expected to be effective against the problem concerned. There are several ways of passive cooling to be applied to different situations. From the viewpoint of thermal comfort for people inside or outside with a certain clothing and activity level, it is desirable to have lower dry bulb temperature, lower wet bulb temperature, lower mean radiant temperature and greater air movement.

In the urban spaces where people walk, stand, sit down and work, it is generally difficult to have dry bulb temperature and relative humidity changed by direct means of passive cooling. Radiative cooling does work effectively under hot and dry conditions to have the surface temperatures of ground or building lowered, but less effectively under hot and humid conditions as long wavelength radiation is absorbed by moisture in the atmosphere. Shading is of primary importance, but sometimes avoided in modern buildings where cooling load naturally turns out quite high.

Evaporative cooling is one of the most effective ways of passive cooling for architecture and urban spaces from ancient times in hot regions. It is more effective in hot and dry regions than hot and humid regions in terms of total amount of cooling, but may be

S. Alvarez et al. (eds.), Architecture and Urban Space, 631–636.

ially effective in both regions in terms of the enhanced level in thermal comfort against ere summer conditions.

There are two different natures in the evaporative cooling effects in hot and humid an spaces: use of evaporatively cooled air for urban or inside spaces and sensible ling of inside surfaces by evaporative cooling on outside surfaces.

Evaporatively Cooled Air

OUTLINE OF THE PROCESS

ien the air is cooled by evaporation as we experience the breeze, the adiabatic change urs in every bulk of air which absorbs moisture from sprayed water or evaporated water por from wet surfaces in the surroundings. Then the temperature of the air can be vered down to the wet bulb temperature when perfectly saturated.

This process is called ventilative cooling, because the moist but cool air enters into space to deprive the sweat from the skin surface of a human body. Thus the heat loss ociated with mass transfer from the skin surface to the air makes the body feel cool. Of irse this effect is more pronounced when the air velocity is higher and when the skin faces is wet. If the air is stationary, the evaporation takes place only slightly in the form skin diffusion and the sweat tends to be accumulated on the skin surface. As the air nes in and flows along the skin surface, the evaporation will take place to a large extent l the person feel it a comfortable breeze. It can be maintained that the intermittent air vement makes the person feel cooler than the constant air movement. Fig. 1 shows one imple of air movement in velocity recorded at the center of the room in one of the anese vernacular houses on a hot and humid summer day.

Owing to the moisture absorption the temperature of the breeze through the garden h a lot of moist foliage gets lower than in the field by 1 - 2 °C as shown in Fig.2. This s measured by Kimura et al (1987) at one of the rural houses facing the garden in manashi Prefecture in Japan.

THEORETICAL CONSIDERATION

s rather difficult to estimate the air temperature after evaporatively cooled through itation and evaporation from water surface. From the energy balance the decease in isible heat should be equal to the increase in latent heat with ragard to the air flow n³/h] between before and after the moisture absorption. Thus,

$$C_p\gamma(\theta_1-\theta_2)Q = \gamma r(x_2-x_1)Q \qquad (1)$$

iere

θ_1, θ_2 : air temperature before and after the moisture absorption respectively [°C]

x_1, x_2 : humidity ratio before and after the moisture absorption respectively[g/kg]

C_p : specific heat of the air [J/kg K]

γ : specific weight of the air[kg/m^3]

r : latent heat of water [J/g]

n the air temerature after the moisture absorption becomes

$$\theta_2 = \theta_1 - \frac{r}{C_p}(x_2-x_1) \qquad (2)$$

The higher the humidity ratio x_2, the lower the air temperature θ_2 after moisture orption, which is to be called secondary air temperature hereafter. The value of x_2,

however, cannot be higher than saturated humidity ratio for the temperature θ_2. The lower the humidity ration of primary air x_1, the greater the difference in humidity ratio x_2-x_1, and the lower the temperature of secondary air θ_2, which people would feel. It can be explained clearly that evaporative cooling works more effectively in dry regions than in wet regions.

Having the relationship between temperature and humidity ratio linearlized for the temperature range around 30°C, saturated humidity ratio against air temperature may be approximated by

$$x_s = 22.6 + 1.55(\theta w - 27) \qquad (3)$$

where θw is wet bulb temperature of the primary air.

If the state of secondary air is assumed to reach a half way between the initial and saturated conditions, i.e.,

$$x_2 = \frac{x_1+x_s}{2} \quad \text{and} \quad \theta_2 = \frac{\theta_1+\theta w}{2} \qquad (4)$$

then the temperature of the secondary air may be estimated by substituting equations(3) and (4) into equation (2), namely,

$$\theta_2 = \theta_1 - 2.08\left(\frac{x_1+22.6+1.55(\theta w-27)}{2} - x_1\right)$$
$$= \theta_1 + 1.04x_1 - 23.5 - 1.6(\theta w - 27) \qquad (5)$$

This is an engineering approximation and may be used by architects or urban planners for their practical estimation.

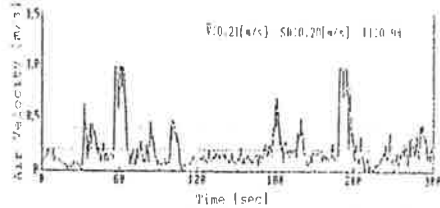

Fig.1 Air velocity in the second floor of a vernacular house in Kawagoe

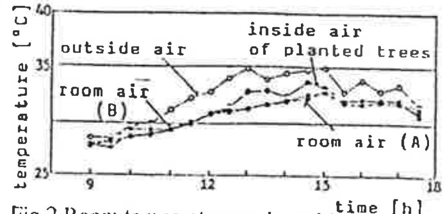

Fig.2 Room temperature and outside air temperature in a rural house

3. Surface Temperature Suppression by Evaporative Cooling

3.1 HEAT BALANCE AT THE SURFACE

Evaporation from a wet surface is accompanied by heat loss from the surface to the ambient air to be resulted in the decrease in temperature of the surface. This is explained by the following equation of heat balance at the surface:

$$q_{r1} - q_{r2} + q_d = q_c + q_e \qquad (6)$$

where

q_{r1} : incoming radiation absorbed by the surface [W/m^2]

q_{r2}: outgoing radiation emitted from the surface [W/m^2]

q_d : conduction to the surface from behind [W/m^2]

q_c : convection from the surface to the ambient air [W/m^2]

q_e : heat loos by evaporation from the surface to the ambient air [W/m^2]

The term(q_{r1}- q_{r2})is large when strong solar radiation is flaling on the surface and becomes negative during the night with greater value for drier atmosphere. The radiation exchange (q_{r1}-q_{r2}) is negligible when the surface is in the shadow and when the sky is overcast. Thus the convection loss q_c can be positive or negative depending on the temperatures of ambient air and the suface, as expressed by

$$q_c = \alpha_c(\theta s - \theta a) \qquad (7)$$

where

α_c : convective heat transfer coefficient along the surface [W/m^{2}K]

θs : surface temperature [°C]
θa : ambient air temperature [°C]

Under the summer conditions the ambient air temperature is higher than the surface of the streets or roofs in the daytime and lower in the nighttime. Namely, the convection loss is positive in the nighttime and negative in the daytime. The absolute value of the convection loss is minimal for the shaded surfaces, where evaporation loss dominates accordingly.

Heat loss by evaporation is associated with mass transfer between the wet surface to the ambient air to be expressed by

$$w = kx(xs - xa) \quad (8)$$

where

w : rate of mass tranfer [g/m^2h]
kx : coefficient of mass transfer based on humidity ratio [$g/m^2h(g/kg)$]
xs : saturated humidityratio [g/kg]
xa : humidity ratio of ambient air [g/kg]

Then the heat transfer by evaporation is given by

$$qe = rw \quad (9)$$

The surface temperature should be determined by the conditions so that the heat balance as expressed by equation (6) can be maintained. For simulation unsteady state heat transfer through the solid with which the surface temperature is concerned must be involved to give the rate of surface heat flow qd.

.2 IMPERFECTLY WET SURFACE

If the surface is not perfectly wet, it may be assumed to be partially wet. Namely, the surface is assumed to be evenly distributed with partially wet surface and partially dry surface. The ratio of wet surface area to the total surface area may be comparable to the relative humidity very close to the surface, which can be measured by hygrometer or through humidity transducer.

It is quite difficult to identify the correct figure of the relative humidity for partially wet surface like soil surface or grass covered surface. It is possible, however, to infer the value by assumption to a certain degree.

In fact evaporation loss especially during the night is so great that the surface temperature can be suppressed remarkably. This effect must be regarded significant in the hot and hmid regions where radiation loss cannot be expected substantially. This resembles with the case that a person sweat very much under the hot and humid conditions when the air temperature is as high as skin surface temperature with no air movement.

Figure 3 shows the results of comparison of the soil surface temperature of an earth sheltered building in Japan made by Kimura et al (1988). This verifies that the evaporative cooling effect can be approxiamted by mass transfer formula where the humidity ratio of the soil surface was inferred by the measured relative humidity close to the surface multiplied by the saturated humidity ratio for the surface temperature. Conduction is relatively easy in estimation, as the soil temperature under the surface can be easily measured. The temperature of the ceiling surface can be

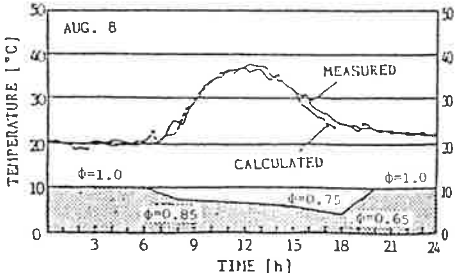

Fig.3 Comparison of roof surface temperature between calculated and measured results in the room of an earthe sheltered building

lower than outside and stable throughout the day.

This principle may be applied to the buildings and urban spaces where earth covered surface can be used. It is generally desirable to have about 30 cm of soil thickness for obtaining good evaporation effect, but the soil of 20 cm thick even can offer quite stable, low temperature underneath.

Thatched roof has much the same effect as soil. The rain water soaked by thatch will be evaporated by strong solar radiation afterwards. The evaporation loss continues after sunset and the upward heat flow through roofs will make the inside surface temperature lower. This is the reason why the houses with thatched roof is generally cool as being popularized by people at large.

The porous roof tiles have similar effects of evaporative cooling, though the amount of soaking rain water may be much smaller than in the case of thatched roofs. Figure 4 shows the results of measurement made by Kimura (1984) with experiments on roof tiles to be compared with steel plate roof. The obvious difference was found between them. The effect of the small air spaces between the roof tiles and seathing board underneath was found to be ventilated as it was warmed up by strong solar radiation. This is the device of avoiding excess heat of solar radiation and may be somewhat effective in storing solar energy in the winter daytime within the roof tile.

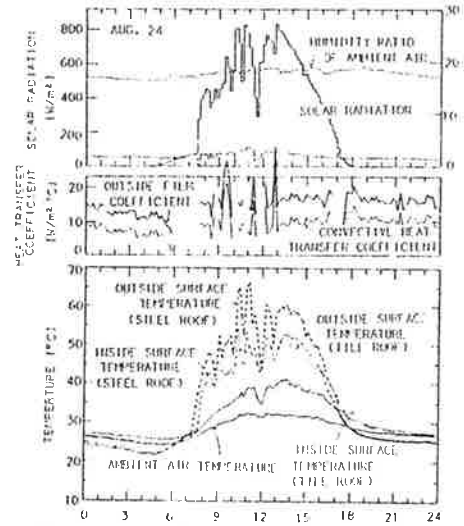

Fig.4 Experimental results without roof spray in comparison between tiled roof and steel plate roof

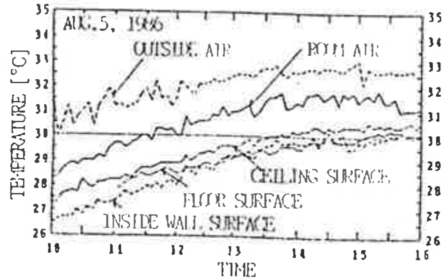

Fig.5 Diurnal variation of temperatures in the 2nd story of a massive house in Kawagoe on Aug.5, 1986

Kimura (1988) presented the results of a field measurement made at the massive house in Kawagoe located at 40 km north-west of Tokyo as shown in Fig.5. It was found that the room air temperature during the daytime on a hot day in mid summer was 1 - 2 degrees lower than the air temperature outside and more interestingly the mean radiant temperature in the room of the second floor turned out 2°C lower than the room air. This is very much owing to lower temperature of the ceiling surface which must be cooled by evaporation.

3.3 INTERIOR SURFACE TEMPERATURE

Further implication of evaporative cooling effect of the surface may be extended to the interior or shaded exterior surface which is made of relatively porous material so that moisture may be absorbed and desorbed at the surface concerned.

The porous material such as clay wall embraces a lot of minute pores where moisture is absorbed in its hygroscopic state. This moisture may be desorbed when drier air comes along the surface. This process is another phase of mass transfer and the surface temperature can be lowered by desorption of water vapor. This is not the evaporative cooling and may be called desorption cooling, but the effect is not so much great as evaporative cooling as it does not involve latent heat loss.

In some cases the water vapor absorbed by a porous material may change to the form of water droplets. If the water state within the pore continues, mold and mildew may develop in natural course. The smaller the pore, the more the mold and mildew, because the probability of water formations is much greater than wood or straw matt floor of large pores.

On the contrary the interior surfaces with vinyl cloth or oil paint do not absorb and desorb moisture and no cooling effects can be expected.

4. Concluding Remarks

Two types of evaporative cooling for hot and humid urban spaces are described: the air cooled by evaporation and the surface cooled by evaporation. Physical background for both cases are explained with some measured results.

In the modern urban spaces under hot and humid climate, green areas are being minimized with the result that the ambient and temperature tends to rise. It is recommended, therefore, to provide foliages and water surfaces to increase the heat loss by evaporation for avoiding excess accumulation of heat within the massive ground surfaces.

Roofs of buildings occupying a large area of urban spaces also had better be covered with evaporative surfaces by soil or equivalent. Heat loss by evaporation from the roof would in turn makes the interior cooler as the ceiling surface temperature becomes lower.

Various arrangements of evaporative cooling process in the urban spaces for hot and humid regions will help make the peak demand of electricity reduced considerably owing to the passive approach.

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