EFFECTS OF DIFFERENT STRUCTURAL AND OPERATIONAL PARAMETERS ON THE THERMAL ENVIRONMENT OF AN EVAPORATIVELY COOLED STORAGE STRUCTURE

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ABSTRACT

A computer based mathematical model was used to study the effects of different structural and operational parameters on the thermal environment of an evaporatively cooled (EC) storage structure of 1 m³ volume for horticultural produce. The computer model used transient finite element thermal analysis for determining the temperature and relative humidity in the structures. The computer model was tested with experimental data for a twin-walled brick EC structure. The mean deviation of predicted and measured temperatures in the chamber to was 1.4 °C. The analysis revealed that the rate of evaporative cooling on the exterior surfaces of an EC chamber and the infiltration/exfiltration rates through the chamber were the most important parameters affecting the interior thermal environment. Thicker walls reduced the daily fluctuation of temperature in the structures.

The changes in the effects of structural dimensions such as wall thickness, height, length: breadth (L. B.) ratio, and thermal properties of the construction materials were limited to 5% when evaporative cooling on the structural surfaces was the predominant process of heat transfer. For a structure with height 0.5 m, L. B. ratio 1, and wall thickness of 0.025 m, the advantage obtained by changing the air velocity across the structure from 0.5 to 4.5 m/s was 8.4%. The advantage obtained from no-ventilation to ventilation at a rate of 0.1 m³/s through the structure was 5.5%. An EC storage chamber of 1.0 m³ volume was constructed on the basis of the results of the analysis. While the air temperature in the EC chamber of the brick construction remained 4 to 8 °C higher than the ambient wet bulb temperature, it was close to the ambient wet bulb temperature (1-2 °C) in the EC chamber of porous aspen pads.

Keywords: Evaporative cooling, storage structures, modeling, thermal environment, design

1. INTRODUCTION

Evaporative cooling has been found to be an efficient and economical means for

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reducing the temperature and increasing the relative humidity of an enclosure. This effect was extensively investigated for increasing the shelf life of horticultural produce in tropical and subtropical countries (Dash and Chandra, 1999). It was recommended for removal of field heat from the produce on the farm and short duration storage, after it is removed from cold stores before distribution. Several studies have been conducted in the past to observe the feasibility of using evaporatively cooled (EC) structures for extending the shelf life of fruits and vegetables. Thompson and Kasmire (1981) developed an evaporative cooler for vegetables where a wetted pad made of commercially available aspen fibre was used for cooling. Vakis (1981) reported that in Kenya, a cheap cool store for vegetables was made with local grass. The roof and walls were kept wet by dripping water from the top of the roof. Chouksey (1985) reported the design aspects of a solar-cum-wind aspirator ventilated EC structure of 20 tons capacity for potato and other semi-perishables, which had 32 cm thick walls with a cavity of 10 cm in the middle filled with rice husk. Roy and Khurdiya (1986) constructed an EC structure for storage of fruits and vegetables, the side walls of which were made of two layers of bricks with a 7.5 cm thick sand layer in between them. The top of the storage space was covered with khaskhas (a type of local grass) and gunny cloth in a bamboo-framed structure. Habibunnisa et al. (1988) fabricated a metallic EC chamber where the four sides were covered with a cloth, the top ends of which were immersed in water placed in the top tray. These designs and some other designs of EC structures were reviewed by Dash (1999). All these structures maintained a higher RH and lower temperature than the ambient, and extended the shelf life of fruits and vegetables.

However, all these experiments mainly aimed at increasing the shelf life of different types of commodities in the available designs of EC structures. Few studies have been conducted to quantify the modified atmosphere under different climatic parameters, types of storage structures, and to analyze the effects of different input parameters. A close examination of these structures revealed that there was still a gap between the actual cooling effect and the potential cooling. Therefore, the present study was planned to observe the thermal environment within an EC storage structure for different structural, environmental and operational considerations and commodity factors, with a view to developing a suitable evaporatively cooled storage structure for horticultural produce.

2. MATERIALS AND METHODS

2.1 Development of a Mathematical Model

A mathematical model was developed (Dash, 1999; Dash and Chandra, 1999) to study the effects of different input parameters, dimensions and shapes of the structure on the thermal environment within an EC enclosure. Schematic representation of the thermal energy and moisture exchanges in an EC structure is given in Fig. 1. The different factors affecting the thermal environment in the EC structure included: (i) environmental parameters such as ambient temperature, relative humidity, wind velocity, insolation; (ii) structural parameters such as size and shape of the structure, construction materials, wall thickness; (iii) operational parameters such as rate of evaporative cooling on the
Fig. 1: Schematic of thermal energy and moisture exchange in an evaporatively cooled structure

structural surfaces and ventilation/infiltration through the structure; and (iv) produce parameters such as type, load, initial temperature, respiration, transpiration and thermal properties. The following assumptions were made for the analysis.

a. The air inside the structure is well mixed at all times and no temperature and moisture gradients exist.

b. All construction materials and produce are homogenous.

c. The length, breadth and height of the structure were much larger than wall thickness and heat transfer through the walls is essentially one-dimensional. The effects of corners and edges have no significance.

d. Thermal gradient in the ground exists only in vertical direction.

The heat balance of the enclosed air within the EC structure was obtained as,

$$\rho_a V_i C_{pa} \left( \frac{\partial T_i}{\partial t} \right) = \sum_{m=1}^{n} h_{s_m} A_{s_m} (T_{s_m}^{(i)} - T_i^{(i)}) + h_p A_p (T_p^{(i)} - T_i^{(i)}) + \rho_a VR C_{pa} (T_{inf}^{(i)} - T_i^{(i)}) \quad \ldots (1)$$
The first term on the right hand side of the equation represents the heat exchange of inside air with the structural cover surfaces and floor. The second term is the convective heat exchange within the produce. The third term is the contribution from infiltration and ventilation, both of which are included in the term VR. The thermal storage in the air was neglected.

The moisture balance of the inside air at any time was written as

$$\rho_a V_i \left( \frac{\partial W_i}{\partial t} \right) = \sum_{m=1}^{n} D_k A_s (W_{s_m}^{(t)} - W_i^{(t)}) + D_k A_p (W_p^{(t)} - W_i^{(t)}) + M_{tr}^{(t)} + \rho_a VR (W_{inf}^{(t)} - W_i^{(t)}) \quad \ldots (2)$$

The first and second terms on the right hand side represent the contribution of condensation/evaporation on the inner surfaces of the walls and that for the stored produce, respectively. The third term is the moisture flux due to transpiration from the stored commodity. These fluxes depend on the temperatures of the respective surfaces. The last term represents the moisture contribution to the air due to infiltration and ventilation. Employing an appropriate finite difference approximation for the time derivatives in Eqns. (1) and (2) and by determining the surface temperatures at any time level, these equations can be solved for inside temperature and humidity ratio at that time level. The RH of the enclosed air and other psychrometric quantities were calculated using appropriate psychrometric equations (Albright, 1990).

For solids with defined initial and boundary conditions, the temperatures in different regions can be determined using the energy conservation principle (Holman, 1997). However, an analytical solution was not feasible in this case because some of the boundary conditions, such as, thermal radiation, condensation and transpiration, were non-linear functions of temperature. Therefore, the finite element method was used, which could also be conveniently extended for irregular shaped enclosures and material heterogeneity. As the heat and moisture balances in an EC enclosure are time dependent, transient thermal finite element analysis was used.

The environmental thermal forces that would affect the EC structure were grouped under three categories: (i) the specified temperature boundary condition that exists at a certain depth in the ground, (ii) the convection boundary condition that exists on different surfaces of the structure, and (iii) the normal flux boundary condition. Transpiration from the commodity, condensation/evaporation from the commodity and structural surfaces, and radiation fluxes were included under the normal flux boundary conditions. The heat transfer coefficients for the structural surfaces were determined as per ASHRAE (1997) and Holman (1997). The thermal radiation exchange was considered as per Albright (1990). The rate of condensation and heat flux due to condensation were determined as per ASHRAE (1997). The moisture loss from the stored commodity due to transpiration was included in the model by using the transpiration coefficient (Sastry et al., 1978).
2.2 Development of a Computer Program

A computer program was developed in Fortran-77 using the above analysis to predict the thermal environment in an EC structure. The program consisted of two segments. The first program 'CONSOL' configures the structure and computes the solar parameters. The second program 'EVACOOL' determines the thermal environment in the evaporatively cooled structure. The CONSOL output forms a part of the input data for EVACOOL. In addition to the geometry of structural configuration, the thermal and radiation properties of structural materials, initial and boundary conditions, and environmental conditions in the area are used as input data/parameters for the programs. The computer program EVACOOL gives the air temperature and RH inside the EC structure at any instant of time as output.

2.3 Experimental Validation of the Model

The model validation was carried out with a top loading type EC storage structure of 1 m³ capacity (Fig. 2). The inner dimensions of the structure were 1.41 m x 1.41 m x 0.5 m. The side walls (35 cm thick) were made of two layers of brick with an annular gap of 10 cm filled with riverbed sand (Roy and Khurdiya, 1986; Roy and Pal, 1991). The floor of the structure was made of a single layer of brick spread over 5 cm soil layer on the ground. The top cover of the structure was made of 2.5 cm thick hessian cloth suitably supported on a wire mesh frame. The whole structure was saturated thoroughly before the start of the experiment and drip laterals were used for continuous wetting of the sand layer throughout the experiments.

Fig. 2: Schematic representation of the evaporatively cooled structure used for validation of the model
The environmental conditions (temperature, RH, solar radiation and wind velocity) were measured at the experimental site. The azimuth and tilt angles for the structural surfaces were measured for inclusion in the model. Suitable radiation shape factors were determined for surfaces exchanging radiation with other surfaces and surroundings. The amount of total and diffuse radiations for different major cities of India have been tabulated by Tiwari and Suneja (1997). It was observed that a reciprocal quadratic model adequately represented the relationship between the total and diffuse radiation at any time of the day (Dash, 1999). The equation was used in the program to obtain the amount of diffuse radiation at any time during the course of experiments. The physical and thermal properties of the materials used for construction were either measured or obtained from published literature. The evaporation coefficients for the structural surfaces were measured by recording the weight loss of the materials exposed to similar environmental conditions in the vicinity of the structure.

When commodities are loaded in the structure, the internal heat generation would depend on such factors as amount of produce, density, specific heat, thermal conductivity, heat of respiration and transpiration. However, as the EC structures are generally intended to accommodate a variety of commodities, it may not be specifically designed for any particular produce. It was, therefore, decided that the model should be validated initially under no load conditions. However, the computer model was later validated with commodity in storage (Dash, 1999).

The temperature predictions using the computer program were in close agreement with the observed temperatures in the EC structure. The maximum and mean deviations of temperature remained below 2 °C and 1.4 °C respectively during the test days in the month of April, representing summer conditions in New Delhi. For the test days the maximum and mean deviations between the predicted and observed RH were lower than 12 and 5% respectively. The agreement between the simulated and experimentally observed temperatures and RH of the inside air also indicated that the theory and assumptions used in the model were acceptable. The model was used to compare the effects of individual parameters on the thermal environment of several EC enclosures with the aim of finding optimum values for storage of horticultural produce.

The testing indicated that evaporation from the external surfaces of the brick walls of the EC chamber was greatly constrained; it was only about 5% of the potential evaporation. As a result, inside air temperature was 4-8 °C higher than the ambient wet bulb temperature. The model indicated that at the ideal situation of 100% potential evaporation the gap between the ambient wet bulb temperature and the EC chamber temperature could be reduced to less than 2 °C. The ideal condition of 100% potential evaporation meant that the walls were always saturated and that the diffusion through the walls was not limiting. In fact, when the walls are completely saturated with water and water is added continuously to the walls, there will be more water on the surfaces than the actual evaporation that would take place from the surfaces. Under this condition, the diffusion through the walls will be inconsequential, and the evaporation on the surfaces will be dependent only on the vapor pressure gradient between the surface moisture and the surrounding air.
2.4 Analysis of Effects of Structural and Operational Parameters

A parameter called Cumulative Heat Units (CHU) has been proposed for the comparative study of the effects of different parameters on the thermal environment. It is defined as the daily sum of the product of the average temperature $T_i$ of the enclosed air during a time step and the time step $\Delta t$ in hours. Its unit is degree-hours.

$$\text{CHU} = \sum T_i(t) \Delta t \quad \ldots (3)$$

The CHU is important for evaluating the shelf life of the commodity. The smaller the CHU, the lower the commodity temperature and the better its shelf life will be.

For studying the effects of different structural and operational parameters on the thermal environment of EC structures and to decide the design considerations for construction of such structures, the below mentioned parameters were considered. The simulations were carried out for an EC structure with 1 m$^3$ volume for a typical summer day under Delhi conditions, for which the environmental data were obtained from the automatic weather station at Indian Agricultural Research Institute, New Delhi. The initial simulations were carried out for a structure the sidewalls of which had similar physical and thermal properties as those in the structure mentioned in section 2.3. However, the effects of changing the sidewalls were studied by changing the wall thickness and materials of construction. The long axis of the structure was oriented in the east-west direction and the top surface was shaded. The air velocity in the vicinity of the structure was assumed to be constant throughout the day at 2.5 m/s. The structure was assumed to be empty with thorough air mixing inside it to avoid uncertainties in the effects of the produce parameters.

2.4.1 Height of the structure

As the capacity of the structure was only 1 m$^3$, making the structure of the top loading type would help easy loading and unloading the produce and reducing the cost. However, for convenience of operations and other maintenance practices at the farmer’s field, the height for a top loading type EC structure should not exceed 2 m. Similarly, to accommodate the common fruits and vegetable crates available in the market with reasonable air gaps both at top and bottom, it was decided that the structure height should be at least 0.5 m. Hence, for the simulation studies, the heights of the structure considered were 0.5, 1, 1.5 and 2 m.

2.4.2 Shape of the structure

The containers generally used for handling fruits and vegetables in the market are of the box type. Hence, the overall configuration of the structure was decided to be of rectangular box type, so that the inner space could be efficiently utilized. Moreover, the construction of a structure with rectangular cross section is much easier than that with any other cross section and farmers can easily construct such a box type structure at their place. If properly oriented, the structures with permeable walls would also permit more
ventilation/infiltration through the structure.

To observe the effect of shape of the structure on the inside thermal environment in the simulation studies, the length-breadth ratios considered were 1, 2 and 3. Thus, for any particular wall thickness, with 4 levels of heights and 3 levels of length-breadth ratio, there were 12 configurations.

2.4.3 Wall and cover thickness

For initial simulation studies, five thicknesses of the wall were considered, i.e., 0.025, 0.05, 0.15, 0.25 and 0.35 m. As the structures were of the top loading type, the top cover in all the configurations was considered to be made of a porous pad, in this case, hessian cloth layer of 0.025 m thickness. In addition to convenience in operation and maintenance, this would also reduce the weight on the side walls. The top surface should be kept wet for evaporative cooling and hence if the top surface is made thick, the load on the side walls would be substantially increased. The earlier small capacity EC structures of Roy and Khurdiya (1986), and Roy and Pal (1991) were also of the top loading type for the same reason. Habibunisa et al. (1988), Rama et al. (1990) and Umbarkar et al. (1991) also used top loading type EC structures for increasing the shelf life of the produce.

2.4.4 Structural material properties

For studying the effects of different individual parameters on the thermal environment within the EC structure, the thermal properties of the different components of the structure and its accessories, soil and other relevant objects were taken from ASHRAE (1997), Holman (1997) and Hilllel (1998). For simulation studies, the side walls of the structure were considered to be constructed of two layers of brick with a 10 cm sand layer in between, as used by many researchers (Roy and Khurdiya, 1986; Roy and Pal, 1991; Umbarkar et al., 1991) for studying the shelf life of different horticultural products under evaporative cooling conditions. The floor of the structure was considered to be made of a brick layer on a 5 cm thick soil; and the top cover of hessian cloth. For the experimental validation of the model, the thermal properties of the materials were experimentally measured. However, as mentioned below, it was subsequently observed that the thermal conductivity of structural materials had a negligible effect on the thermal environment in EC structures having sufficient infiltration, which obviated the need for measuring the actual parameters under field conditions.

3. RESULTS AND DISCUSSION

3.1 Effects of Structural Dimensions

3.1.1 Wall thickness

Fig. 4 exhibits the thermal conditions that would be expected in a 1 m³ structure
with 0.5 m height and an L. B. ratio of 1 for different wall thicknesses under both evaporative cooling (100% potential evaporation) and no-evaporative cooling conditions. It was observed that in structures without evaporative cooling on the outer surfaces, the inside air temperature followed the ambient dry bulb temperature profile. However, in structures with evaporative cooling the inside air temperature approached the ambient wet bulb temperature. This indicated that evaporative cooling on the outer surfaces provided a substantial cooling effect.

The simulated range of air temperatures in a 1 m³ EC structure with different configurations and different wall thicknesses on a typical summer day (June 2, 1998) is presented in Fig. 4. It was observed that the difference between maximum and minimum temperatures inside the enclosure reduced as the wall thickness increased. For structures with 0.025 and 0.05 m thick walls, the inside air temperature almost followed the ambient dry bulb temperature profile. But as the wall thickness increased, the daily fluctuations reduced, i.e., the maximum temperature decreased, the minimum temperature increased and the curve smoothed. This was because the thicker walls, due to increased thermal capacity, provided adequate buffering against the penetration of the daily environmental fluctuations into the storage chamber. A similar effect was also observed under no-evaporative cooling conditions (Fig. 3).

The cumulative heat units (CHU) obtained by changing the configurations of a 1 m³ structure for the above test day have been plotted in Fig. 5. If the temperature in the enclosure remained the same as the ambient wet bulb temperature, the CHU would have been 505 degree-hours. It was observed that the CHU decreased with the increase in wall thickness for any particular height and L. B. ratio. This was because the thicker walls, for the same interior volume and surface area, resulted in increased surface area for evaporation and, hence, increased heat loss from the structure. Therefore, the simulations suggested that a storage structure with thicker walls was better for maintaining lower temperature if full potential evaporation took place from the outer surfaces of the structure. However, full potential evaporation can not be obtained if the walls do not remain under saturated condition at all times as observed with the experimental structures made up of brick side walls (Dash, 1999).

3.1.2 Height

If the L. B. ratio and thickness were kept constant, increasing the height of the structure increased the CHU (Fig. 5), which was because of the increased surface area of the side walls. An analysis of the different heat loads indicated that the higher surface area of side walls of the structures with more height caused extra heat gain by convection, long wave radiation exchange and solar irradiation, which more than offset the effect of extra evaporation from the surfaces.

As the side wall surface area for evaporation increased with increase in the height of the structure, the incremental change in CHU reduced, i.e. the increase in CHU by changing the height from 1 m to 1.5 m was lower than that obtained by changing the height from 0.5 to 1 m. In the simulations, the thickness of the top cover had been kept constant at 0.025 m to reduce structural load on the sidewalls and for convenience in handling the produce, whereas the thickness of the sidewalls was changed. The rate of
heat removal from the top cover was more than that from sidewalls due to its lower thickness. As the height of the structure increased, the top surface area decreased for the same volume. For a 1 m$^3$ structure if the height of the structure is changed from 0.5 to 1.0, 1.5 and 2 m, the top surface area decreased from 2 to 1, 0.67 and 0.5 m$^2$, respectively. Hence, the increase in CHU was not proportional to the increase in the surface area; rather, the incremental change decreased because of asymptotically reducing top surface area. The results indicated that the designed height of the top shaded EC structure should be kept as low as possible to maintain a cooler environment inside the structure.

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**Fig. 3:** Simulated air temperatures in a 1 m$^3$ structure (height 0.5 m, L. B. ratio 1) for different wall thicknesses, with and without evaporative cooling.
Fig. 4: Simulated range of air temperatures in a 1m$^3$ EC structure with different heights (0.5 m – 2.0 m), L. B. ratios (1, 2 and 3) and wall thicknesses (ventilation rate: 0.001 m$^3$/s)

3.1.3 Length-breadth ratio

The CHU decreased with the increase in L. B. ratio of the structures. However, in the case of structures with more height or thickness, the change was less than for structures with less height and thinner walls. The net advantage in CHU also reduced
Fig. 5: Simulated cumulative heat units in a 1 m³ EC structure as obtained by changing the height and L.B. ratio for different wall thicknesses (ambient air velocity 2.5 m/s)
with the increase in L. B. ratio. It was found to be mostly due to the effect of convection and partly due to solar irradiation and the long wave radiation exchange. The relative contributions of the convection and radiation components in the thermal balance of the EC structure indicated that convection was the most important phenomenon in the heat gain for the walls of the structure, as compared to the heat gain by solar radiation and long wave radiation exchange (Fig. 6).

![Bar chart showing CHU values for different conditions](image)

- A. No convection and radiation exchange on outer surfaces
- B. No radiation exchange on outer surfaces
- C. No insolation on outer surfaces
- D. All components viz. convection, long and short wave radiation exchanges present

Fig. 6: Simulated cumulative heat units in a 1 m³ EC structure under four boundary conditions

The advantage obtained by changing the length-breadth ratio in structures with a particular height was less than 1% (Fig. 5). For a height of 0.5 m, L. B. ratios up to 7 were tested with the consideration that the width of the chamber should not be less than 50 cm to accommodate at least one produce basket. It was observed that as the L. B. ratio increased, the CHU decreased in an asymptotic manner (Fig. 7). In structures with 0.025 m wall, the CHU decreased from 544.1 degree-hours to 540.8 degree-hours when the length-breadth ratio was changed from 1 to 7, indicating a change of only 0.6%. For structures with 0.35 m wall, the net advantage was still lower. However, as the length-breadth ratio is increased the cost of construction will be increase, and hence increase in length-breadth ratio may not be recommended.

The study indicated that if the top surface of the structure was made of a thinner material than the sidewalls, and the sidewalls were not shaded, then the height of the structures should be kept at a minimum. This would be advantageous in two ways. First, the effect of insolation on the sidewalls would be reduced, and second, the heat from the structure could be taken out in a more effective way through the top cover. However, if the structure was kept in a room or in an orchard so that sidewalls would not be expected to receive considerable insolation and if some mechanical ventilation was possible, the
height of the structure could be increased. Putting a close shade on the sidewalls might, however, act as a deterrent to the device, because it would restrict air flow to the vicinity of the structure, and hence reduce the rate of evaporation and infiltration. Fig. 5 indicates that for the configurations under consideration, the smallest advantage was obtained by using the structure with height 2.0 m, L. B. ratio 1 and wall thickness 0.025 m; the greatest was in the case of a structure with height 0.5 m, L. B. ratio 3 and wall thickness 0.35 m, and the difference was merely 5.3%. The structures with height 0.5 m in general offered lowest CHU as compared to other heights, i.e., the height of the top shaded EC structure should be kept as low as possible. The advantage obtained by changing the configurations in a 0.5 m height structure was limited to less than 5%. The additional benefit obtained by increasing the L. B. ratio from 1 to 3 for all heights was limited to a maximum of 0.5%, and was considered to be negligible.

3.2 Effects of Material Properties

In the simulation studies mentioned in the previous section, the thermal properties of the construction materials were assumed to be the same for all structural configurations, i.e., for a wall of two layers of brick with a 10 cm sand layer between them (total thickness 0.35 m). However, the materials chosen for a 0.025 m wall and a 0.35 m wall may not be the same. A 0.025 m thick wall could be constructed of either a metallic sheet with evaporative pads/jute cloth on the outer side, or it may be a layer of porous pads for allowing infiltration. It could also be constructed of a wire mesh covered with evaporative surfaces, as previously adopted by Rama et al. (1990). Under such a condition, i.e., if the wall is constructed of a 1 mm thick mild steel plate or perforated sheet with 0.024 m thick jute cloth/pad layer on it (assuming total thickness of wall to be 0.025 m), then the thermal conductivity of the wall is expected to be 2.22 W/(m.°K). For a 2 mm thick metallic plate and 0.023 m pad, the thermal conductivity would be 4.34 W/(m.°K).
Hence, to study the effect of change in material properties, the thermal properties of the construction materials for sidewalls were changed in the above range for a 0.5 m height structure with an L. B. ratio equal to 1. Only 0.025 m thick walled structures were considered, because it would not be economical for constructing a thicker wall with metals having high thermal conductivity. It was observed that the thermal conductivity and heat capacity of the materials did not have any significant effect on the internal thermal environment of the EC structure (Fig. 8). These observations clearly indicate the insignificance of thermal conduction in the overall heat balance of the thin walled EC structures. For thicker walls, as used by Roy and Khurdiya (1986), experimental studies revealed that there was negligible evaporation on the surfaces of the walls. This was because of the negligible diffusion of water through the brick walls in spite of the saturated condition of the sand layer. In that case, only the evaporation from the top surface and infiltration through it contributed to the lower temperature within the structure, and the sidewalls served mainly as a barrier to the outside temperature fluctuations.

![Graph showing simulated cumulative heat units](image)

**Fig. 8**: Simulated cumulative heat units in a 1 m³ EC structure with height 0.5, L. B. ratio 1 and wall thickness 0.025 m as affected by varying thermal properties of wall materials

### 3.3 Effects of Operational Parameters

#### 3.3.1 Air velocity

Fig. 9 (a and b) shows the CHU obtained within structures of different configurations for two air velocities, viz. 0.5 m/s and 4.5 m/s. The rate of evaporation varied directly with the outside heat transfer coefficients and the CHU in all the structures under consideration decreased with the increase in outside air velocity. For a structure with height 0.5 m, L. B. ratio 1, and wall thickness 0.025 m, the advantage obtained in
CHU by changing the air velocity from 0.5 to 4.5 and 2.5 m/s were 8.4 and 6.1% respectively. The variations of CHU for all structures at these two air velocities were in a pattern similar to that observed previously for the outside air velocity of 2.5 m/s. However, in the case of structures with permeable walls, the air velocity outside the structure would also affect infiltration and, thus, enhance the influence on internal thermal environment.

![Graph showing cumulative heat units](image)

**Fig. 9:** Simulated cumulative heat units in a 1 m³ EC structure as obtained by changing the height and L. B. ratio for different wall thicknesses for different air velocities outside the structure.
3.3.2 Ventilation and infiltration

Thompson and Kasmire (1981) observed that in an evaporative cooler for vegetables when the average air velocity across the aspen fibre pad was maintained at 0.25-0.38 m/s, the air entering the structure was nearly saturated, i.e., the temperature was almost equal to the wet bulb temperature. An effort was made to study the effects of higher ventilation rate at 100% saturation. The ventilation rate variation would indicate the effective porosity of the walls and top cover. In an EC chamber of brick construction, the ventilation and infiltration is mainly through the top cover by way of opening and closing, and material of construction of the top cover. However, in the case of an EC chamber made of other materials the effective porosity may be different, e.g. if aspen fibre pads are used as walls of the EC chamber, then the effective porosity of the chamber would be significantly higher than that for EC chamber using brick construction. With thicker walls like the brick-sand-brick wall (Roy and Pal, 1991), the ventilation rate cannot be increased unless the wet sand layer is replaced by a more porous material and a sufficient gap is kept in the brick construction like that used by Umbarkar et al. (1998). Therefore, the effect of increased ventilation was observed only in the case of structures with 0.025 m thick walls with 0.5 m height for different L. B. ratios.

The CHU decreased in an asymptotic manner with the increase in the ventilation rate (Fig. 10). The net advantage obtained from no-ventilation to ventilation at a rate of 0.1 m$^3$/s was 5.5%. However, under these high ventilation conditions the change in L. B. ratio did not have any influence on the CHU. Although the thick walls performed better under constant infiltration conditions, the performance of a permeable thin wall was better than the thick wall because of higher infiltration/ventilation. Therefore, providing higher ventilation or infiltration through wet surfaces so that the air would get saturated before entering the chamber, is highly desirable to get the maximum benefit of

![Graph showing CHU vs Ventilation Rate](image)

**Fig. 10:** Simulated cumulative heat units in a 1 m$^3$ EC structure with 0.025 m thick wall and 0.5 m height as affected by ventilation rate through the structure
evaporative cooling. It was possibly due to this that Umbarkar et al. (1991) observed better performance when they used brick batt in place of sand in the annular layer between two layers of bricks for the side walls of the EC chamber developed by Roy and Khurdiya (1986).

3.4 Construction of the EC Structure

The above analysis indicated that if evaporation was the predominant process of heat transfer and there was sufficient infiltration of saturated air, the dimensions did not matter and the effects of ranges of dimensions of the structure would essentially be dependent on operating parameters such as the ventilation rate, and the rate of evaporation from the surfaces, and other factors like the ease of construction, loading and unloading. Experimental observations revealed that there was negligible evaporation on the surfaces of the sidewalls for the brick structure, though the sand layer was kept wet all the time (Dash, 1999). The wet surface should be directly exposed to ambient air for full potential evaporation. If the sidewalls are made permeable to allow sufficient infiltration of saturated air, then the performance of the EC chamber would be better than that in the case of structures with impermeable side walls. Further, as the thickness and thermal properties of the sidewalls were also insignificant, the thickness of the material used for construction could be decided depending on the availability and strength of the material.

Two other functional requirements for outdoor EC structures were defined, first to minimize insolation on the surfaces of the structure, and secondly, to allow maximum draft of ambient air on the outer surfaces. These two requirements demanded contradictory set-ups. However, simultaneous shading on the top surface and minimizing the height of the structure was a reasonable compromise. Similarly, no significant change was observed with the change in L. B. ratio. But if the long side of the structure were kept across the prevailing wind direction, then it would allow more infiltration into the structure, which would decrease the inside temperature. For indoor structures, without appreciable air flow in the vicinity of the structure, a lower L. B. ratio would reduce cost. The dimensions of the EC structure should also take into account the dimensions of the crates (fruits and vegetable containers) available in the market for maximum utilisation of inner space.

With the above considerations, it was decided that the 1 m$^3$ structure be constructed with an inner height of 0.5 m and side walls made of wood-wool pads. The wood-wool pads were sandwiched between two layers of welded wire mesh having an effective thickness of about 2.5 cm. It was not necessary to fabricate the structure on site. Rather, the different components of the structures were pre-fabricated and later assembled on the experimental site. The pad layers were carefully tied to the frames of the structure without leaving any gap at the joints. The top cover of the structure was made of a 2.5 cm thick layer of hessian cloth kept on a welded wire mesh frame. The floor was made of a single layer of brick on a 0.05 m thick sand layer. The structures of this type would be lightweight and can be shifted from one place to another without much difficulty.

Reduction of solar radiation was achieved by shading with plywood boards.
Plastic laterals with drippers were used to keep the surfaces of the structures wet for evaporative cooling. The spacing and discharge rate of the drippers were chosen based on preliminary trials to keep the surfaces wet at all times and to minimize the water loss to the ground. The top surface of the structure was kept wet by controlled sprinkling of water. Care was taken that no water entered through the top surface into the structure.

### 3.5 Thermal Environment Within the Improved Structure

The performance of the EC structure was compared with a structure with brick-sand-brick walls (Roy and Khurdiya, 1986; Roy and Pal, 1991) of similar volume to observe the effectiveness of the improved design. Fig. 11 (a & b) shows the temperature obtained in two structures, one made up of wood-wool pad walls and the other with

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**Fig. 11:** Comparison of the observed air temperatures within the EC structures made of brick and porous pad on two test days.
brick-sand-brick walls during two test days for comparison. It was observed that the inside air temperature in the brick walled structure was about 14-15 °C lower than the ambient dry bulb temperature. Still there was a gap of 4-8 °C between the observed air temperature and the wet bulb temperature. However, in the pad structures, the gap was reduced by increased infiltration and higher rates of evaporation from the surface. As the structural surfaces permitted easy passage of air and there was no wind barrier, the ventilation/infiltration rate approached about 10 times the one obtained in the brick structure. As the side walls were kept wet by drip laterals, the infiltrated air remained saturated all the time. This resulted in a lower temperature in the pad structures as compared to the brick structure. Thus, it was possible to reduce the gap between the inside temperature obtained in the brick structure and the wet bulb temperature by using the improved EC structure. The average daily temperature fluctuations in the brick structure were about 3 °C, whereas they were more than 8 °C for the pad structures. However, the daily mean air temperature in the brick structure was higher than that in the pad structure.

The relative humidity inside the brick structure ranged between 70-95%, as against 98-100% inside the pad structures under no load conditions (Fig. 12). The conditions would also be similar when the loads of produce inside the structure were very small when compared to the total volume of the structure, because the moisture production due to respiration and transpiration would be much lower than the moisture contribution of infiltrated air. The pad structures maintained higher relative humidities because of the higher infiltration rate and because the air entering the pad structures was almost saturated. The relative humidity in the brick structure was lower because of the relatively higher inside air temperatures. However, the range of RH obtained in both types of structures was favorable for the reduction of transpiration, and the increase of the shelf life of perishables with the application of suitable fungicides and sprout suppressants (Roy and Pal, 1991; Hegde, 1996).

3.6 Advantages of the Improved EC Structure

As the rate of decay of the stored commodity is directly proportional to the storage temperature, the improved EC structure would increase the shelf-life of the commodity by maintaining a lower temperature than the previously reported EC structures. The economics of both types of EC structures revealed that the costs of storage in the two structures were almost equal. However, as the structures made of wood-wool pad walls are lightweight, they can be conveniently moved from one place to another and can be used as temporary storage structures for short-term storage or during transportation in trucks/rail cars. They can be installed within a short time at any place to meet immediate demands.

4. CONCLUSIONS

The rate of evaporation on the surfaces and infiltration/exfiltration rates were the two most important parameters that affected the thermal environment of the EC structure.
Fig. 12: Comparison of the relative humidities obtained within the EC structures made of brick and porous pad on two test days

When evaporative cooling was the major component of the heat balance, variations in materials and dimensions for impervious structures had no significant effect on the resultant thermal environment.

When the air velocity outside the structure was higher, the evaporation from the surfaces of the structure and infiltration of saturated air in to the structure increased. The resultant air temperature in the structure decreased.

The advantage obtained in the cumulative heat units from no-ventilation to ventilation at a rate of 0.1 m³/s was 5.5%. Permeable, thin and saturated walls provided a lower temperature in the structures due to higher infiltration. An EC storage structure constructed of porous aspen pads maintained lower air temperature and higher RH than
an EC structure made with brick side walls. However, the brick structure reduced the
daily temperature fluctuations as compared to the pad structures.

The model could be used as a design aid for development of evaporatively cooled
storage structures under any given set of environmental, operational and structural
conditions.

<table>
<thead>
<tr>
<th>Symbols/abbreviations Used</th>
<th>Superscripts/subscripts Used</th>
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<tbody>
<tr>
<td>A  - area of the surface, m$^2$</td>
<td>(t) - at t$^\text{th}$ time step</td>
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<tr>
<td>$C_p$ - specific heat, J/(kg °K)</td>
<td>a - air</td>
</tr>
<tr>
<td>$D_k$ - evaporation coefficient, kg/m$^2$s</td>
<td>i - inside environment</td>
</tr>
<tr>
<td>h - heat transfer coefficient, W/(m$^2$°K)</td>
<td>inf - infiltrated air</td>
</tr>
<tr>
<td>M - rate of moisture transfer, kg/s</td>
<td>m - represents a particular surface</td>
</tr>
<tr>
<td>n - number of surfaces</td>
<td>p - stored produce</td>
</tr>
<tr>
<td>T - temperature, °C</td>
<td>s - any surface of the structure</td>
</tr>
<tr>
<td>t - time, s</td>
<td>tr - transpiration</td>
</tr>
<tr>
<td>V - volume, m$^3$</td>
<td>VR - ventilation and/or infiltration rate, m$^3$/s</td>
</tr>
<tr>
<td>$V_R$ - ventilation rate, m$^3$/s</td>
<td></td>
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<tr>
<td>$W$ - humidity ratio, kg/kg of dry air</td>
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<tr>
<td>$\rho$ - mass density, kg/ m$^3$</td>
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