

DEVELOPMENT AND PERFORMANCE EVALUATION OF AN EVAPORATIVELY COOLED STORAGE STRUCTURE FOR HORTICULTURAL PRODUCE

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An attempt has been made to develop a storage structure for fruits and vegetables by application of the principle of evaporative cooling. A computer program has been developed with C++ for analysing the transient thermal environment of different types of enclosures. This simulation model along with limited field trials were used to study the changes in temperature and relative humidity in an evaporatively cooled (EC) structure, as affected by the different structural, operational, environmental and produce parameters. The analysis revealed that when evaporative cooling was the predominant process of heat transfer on the structural surfaces, the changes in effects of the structural parameters, which included wall thickness, height, length-breadth ratio, etc. were limited to 5%. However, the operational parameters like the rate of evaporative cooling on the surfaces and infiltration/exfiltration rates contributed significantly for the inside environment. With the help of the analysis, an evaporatively cooled storage structure has been designed for storage of fruits and vegetables. The storage structure, which has been constructed of aspen fibre pads, offered lower temperature and higher relative humidity than ambient conditions, which proved to be quite beneficial for short term storage of fruits and vegetables. The shelf life of potato was observed to increase by 3 folds within the structure as compared to ambient storage. Besides, as the type of structure is light weight and easy in construction, it can be easily constructed at any place or conveniently shifted from one place to another.

1. INTRODUCTION

Storage of fruits and vegetables at low temperatures has been an important area of research because at low temperature, these can be preserved in their wholesome state for extended period. Refrigerated or cold storage, which is believed to be the best method for storing the fruits and vegetables in fresh form, is not only energy intensive but also involves huge capital investment. Besides, it is not suitable for rural or on-farm storage where the producer would like to store commodities for a few days to accumulate ample quantities before carrying them to the markets situated far off and in urban areas. For certain fruits and vegetables, the exposure to very low temperatures as in cold stores results in physiological disorders such as freezing injury or chilling injury (Dahiya *et al.* 1997). Power availability and its cost are also other major problems, which

prohibit the cold storages to be recommended for on-farm short duration storage. Hence, a low cost option to maintain lower temperature in a chamber, such as evaporatively cooled storage, has been a matter of prime importance under Indian conditions (Rama *et al.* 1990).

Evaporative cooling is one of the earliest methods evolved by man for comfort cooling of residential buildings and has been extensively utilized for creating a modified atmosphere in an enclosure for crop growing, livestock housing or storage of horticultural produce. Some attempts were also made to use the principle of evaporative cooling for storage or perishable horticultural commodities (Thompson and Kasmire, 1981; Chouskey, 1985; IARI, 1985; Roy and Khurdiya, 1986; Habibunnisa *et al.*, 1988; Rama *et al.* 1990).

However, it was observed that there was a huge gap between the potential cooling and the actually obtained cooling effect in these structures. Though the small structures performed satisfactorily, under field conditions the bigger structures of similar types of construction did not perform well (Chouksey 1985;

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Roy and Khurdiya, 1986; Dash and Chandra, 2000). The effects of these structures also varied for different places and for different weather conditions and under different climatic parameters. Hence, the present study was planned to develop an evaporatively cooled storage structure for horticultural produce and test its efficacy.

2. MATERIALS AND METHODS

2.1 Principle

The temperature and moisture content are the two most important physical parameters that control the decay of food commodities during storage. Higher the temperature, more is the rate of respiration and each increment of 10°C above optimum temperature increases the rate of spoilage by 2-3 folds (Jimenez, 1983). Besides, the high moisture content of the horticultural commodities accelerates the vital activities of the tissues such as transpiration, respiration and ripening, making them highly perishable. Reducing the moisture content of the commodity to a recommended level through drying or dehydration could enhance the shelf life, although it disturbs the general texture and impairs the quality. Very low humidity in the storage space causes undesirable moisture loss from the commodity leading to desiccation and shriveling. Thus, the principal aim of storage in fresh form is to control wilting and shrinkage along with the above undesirable physiological and biochemical changes and disease infections. Therefore, evaporatively cooled (EC) storage structures, which can maintain lower temperature coupled with high humidity, provide enough promise for short-term storage of horticultural produce.

Evaporative cooling is the adiabatic saturation of moist air. It is a thermodynamic process, where a part or all of the sensible heat of moist air is converted to latent heat, thereby, producing a reduction in temperature. The cooling effect produced by the evaporation of water increases with increase in the amount of evaporation (Esmay and Dixon, 1986). Theoretically, the lowest temperature that can be achieved by the evaporation of water is the wet bulb temperature of the moist air (Hall, 1975).

2.2 Plan of study

To obtain the maximum possible cooling effect in an EC structure, it was required to study the effects of different structural and operational parameters and different thermal loads on the structure environment. Two approaches could be tried. Either to study the effect of each individual parameter on the thermal environment of the structure by conducting actual field experiments, or by performing model study with subsequent limited field trials. As the first approach would be time consuming and much more tedious than the second one, the latter was adopted for the study.

A computer based mathematical model was developed for prediction of thermal environment in an EC enclosure. The parameters included were the structural parameters, i.e., size and shape of the structure, construction materials, wall thickness, environmental parameters, i.e., variations in ambient temperature, relative humidity, wind velocity and solar insolation; operational parameters, i.e., rate of evaporative cooling on the structural surfaces and ventilation/infiltration through the structure; and produce parameters, i.e., type, load, initial temperature, respiration rate and thermal properties. A schematic representation of the EC enclosure with different heat loads has been given in Figure-1. The model used transient analysis for the heat loads and finite element approach for heat conduction through structural components. The computer model has been developed in two segments. The first program configures the structure and computes the solar parameters, and hence was named CONSOL. The second program EVACOOOL determines the thermal environment in the evaporatively cooled structure. The CONSOL output forms a part of the input data for EVACOOOL. The flow charts for the programs are given in Figure 2 and 3. The program was written in C++.

The model was validated with three EC storage structures of 1 m³ capacity, one with brick-sand-brick side walls (Roy and Khurdiya, 1986) and the other two constructed with aspen fibre pads of different length-breadth ratios. Based on the model, the effects of different parameters on the inside thermal

environment of the EC structure were quantified and the design criteria for such structures were developed. An EC structure was constructed on the basis of the results and its performance in relation to maintaining lower temperature and higher RH as compared to ambient, and for extending the shelf life of potato was evaluated.

3. RESULTS AND DISCUSSION

3.1 Design consideration

The computer model developed for the study was validated with observations on temperature and relative humidity from experimental storage structures, as mentioned in the previous section. Under empty conditions, the mean deviation between the observed and predicted values of temperature ranged between 0.56-0.81°C for brick structure and 0.63-1.99°C for pad structures. The predictions for

inside RH were also statistically within acceptable limit. The comparison for loaded structures was better because of the thermal inertia of stored commodity. The model was used to analyse the effects of different parameters on the thermal environment within the structure.

Figure-4 shows the effects of changing the dimensions of the EC storage structure for a particular day during summer, and it was observed that there was only about 5% change in cumulative heat units (CHU) by changing the dimensions. Thus the structural dimensions could be decided on the basis of space availability, cost of construction and operational parameters.

Thermal properties of the materials of construction did not have any significant effect on the storage thermal environment under the evaporative cooling conditions (Figure-5). Increase

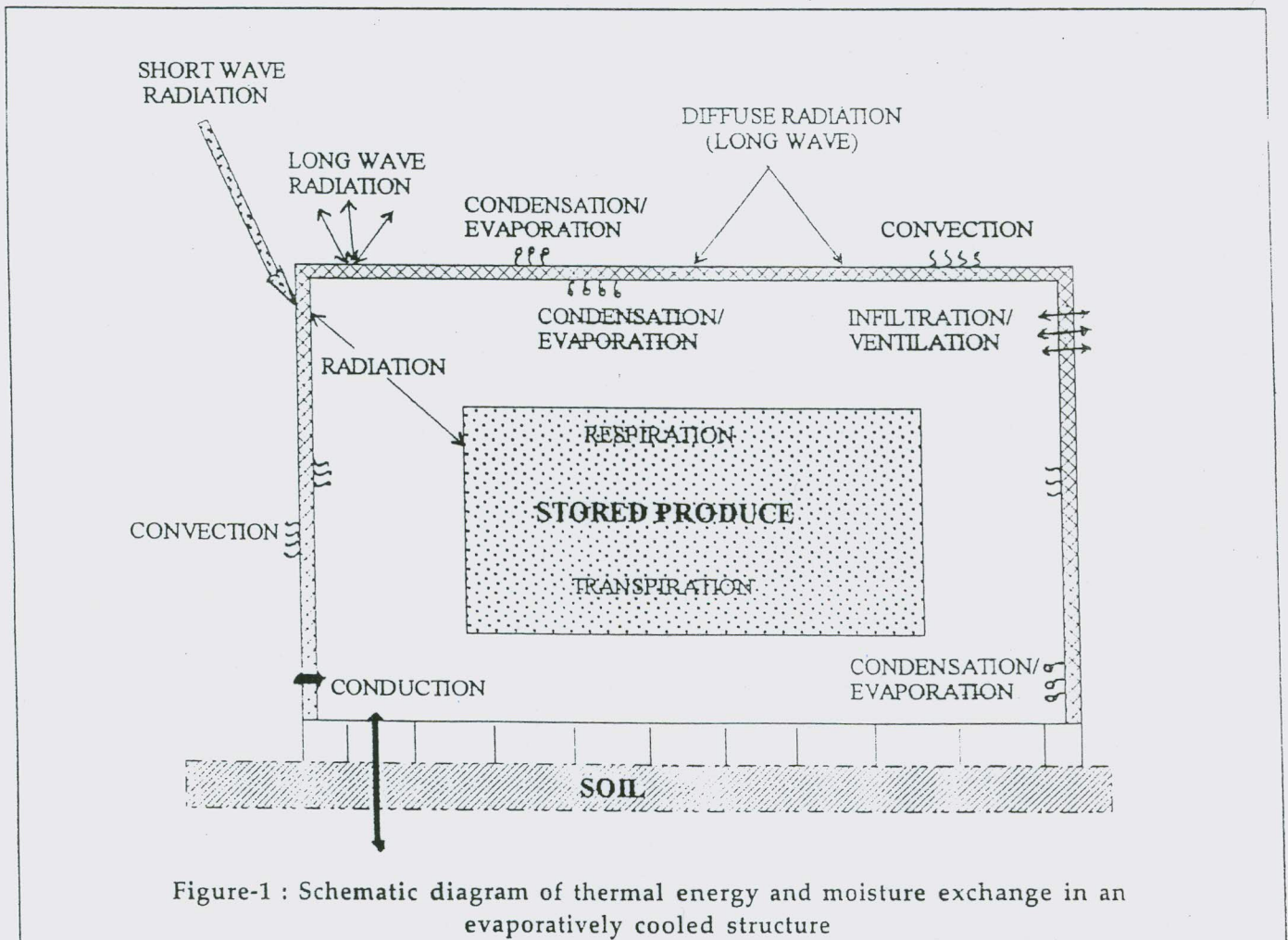


Figure-1 : Schematic diagram of thermal energy and moisture exchange in an evaporatively cooled structure

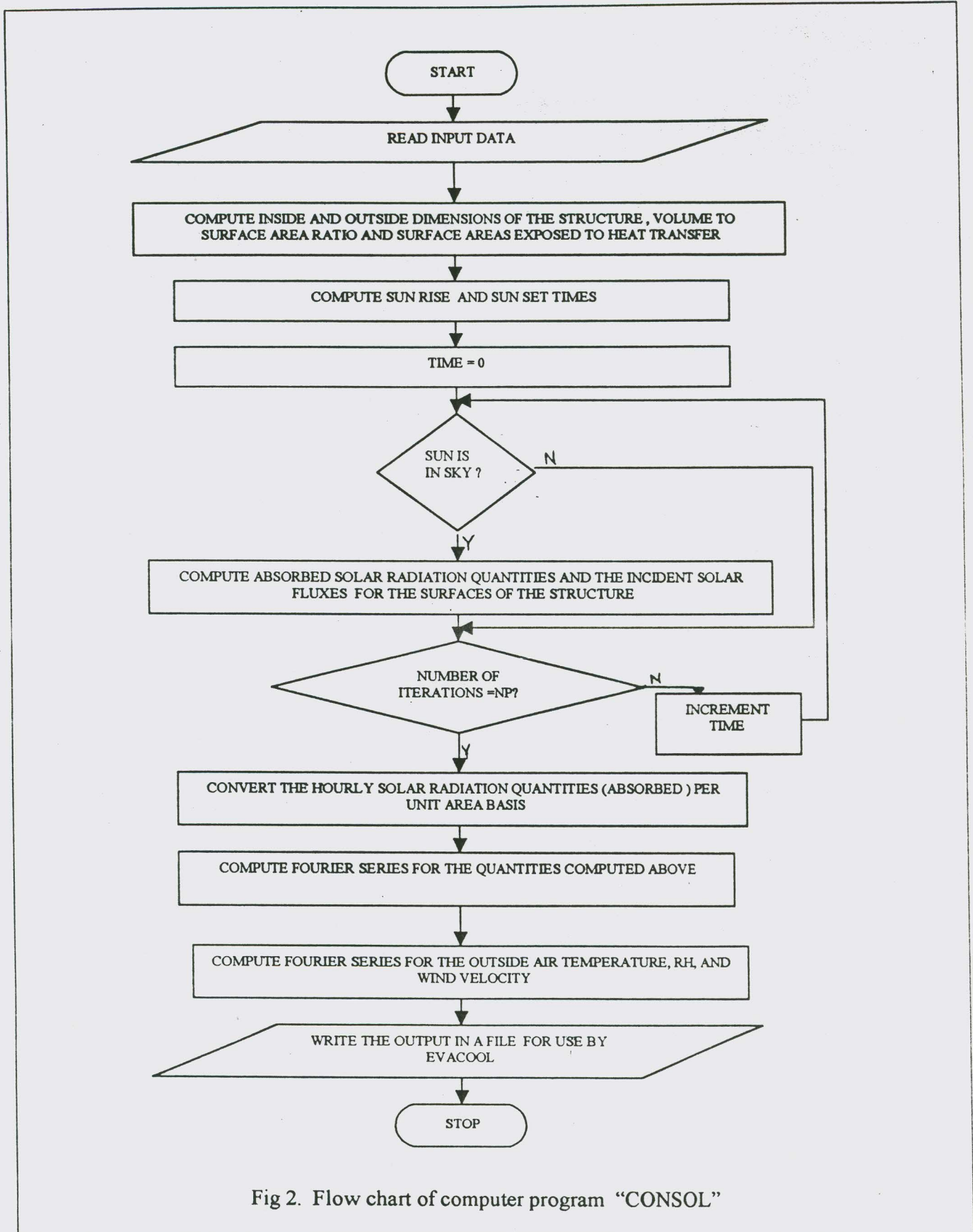


Fig 2. Flow chart of computer program "CONSOL"

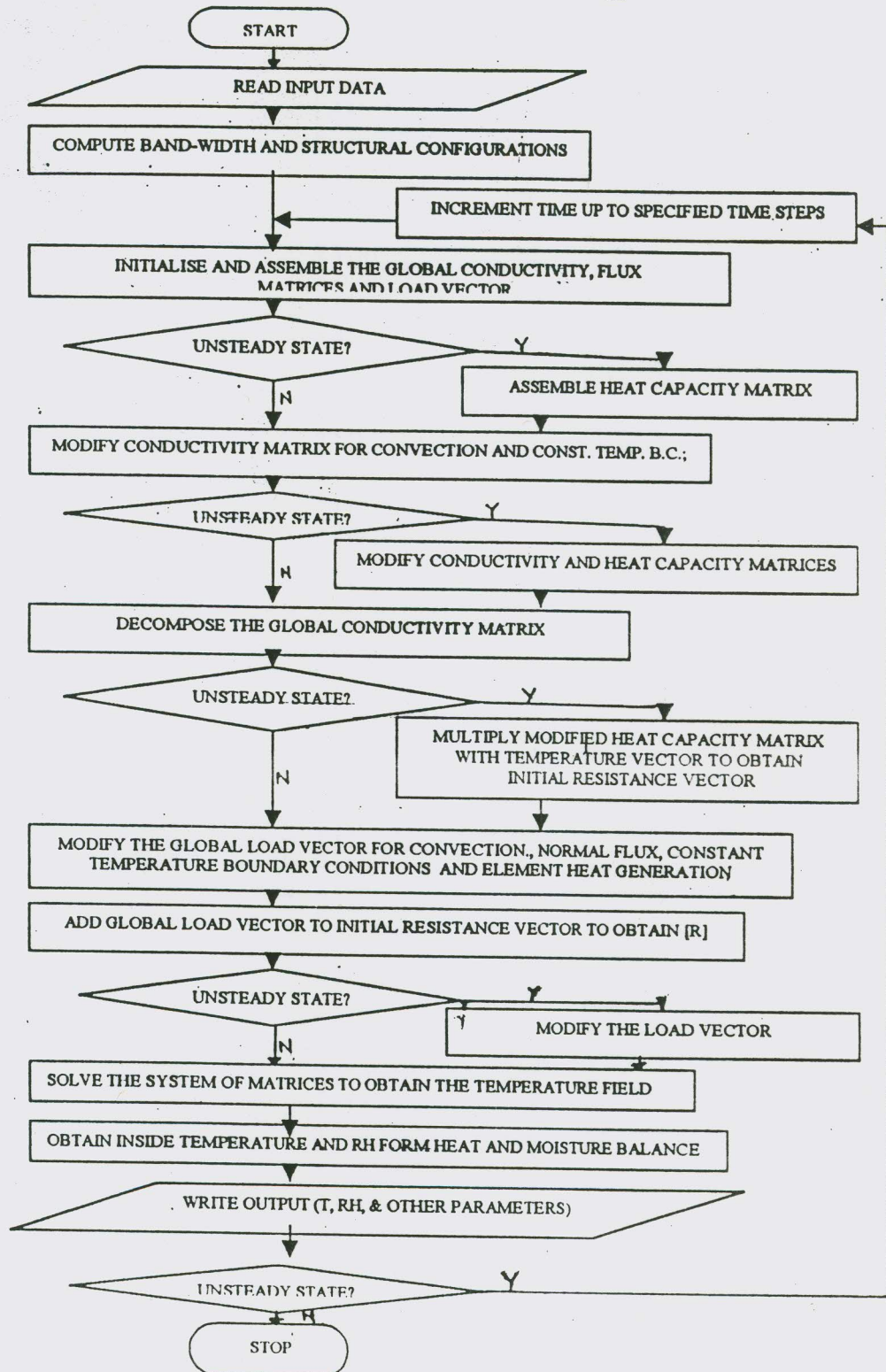


Fig 3. Flow chart of computer program "EVACOOOL"

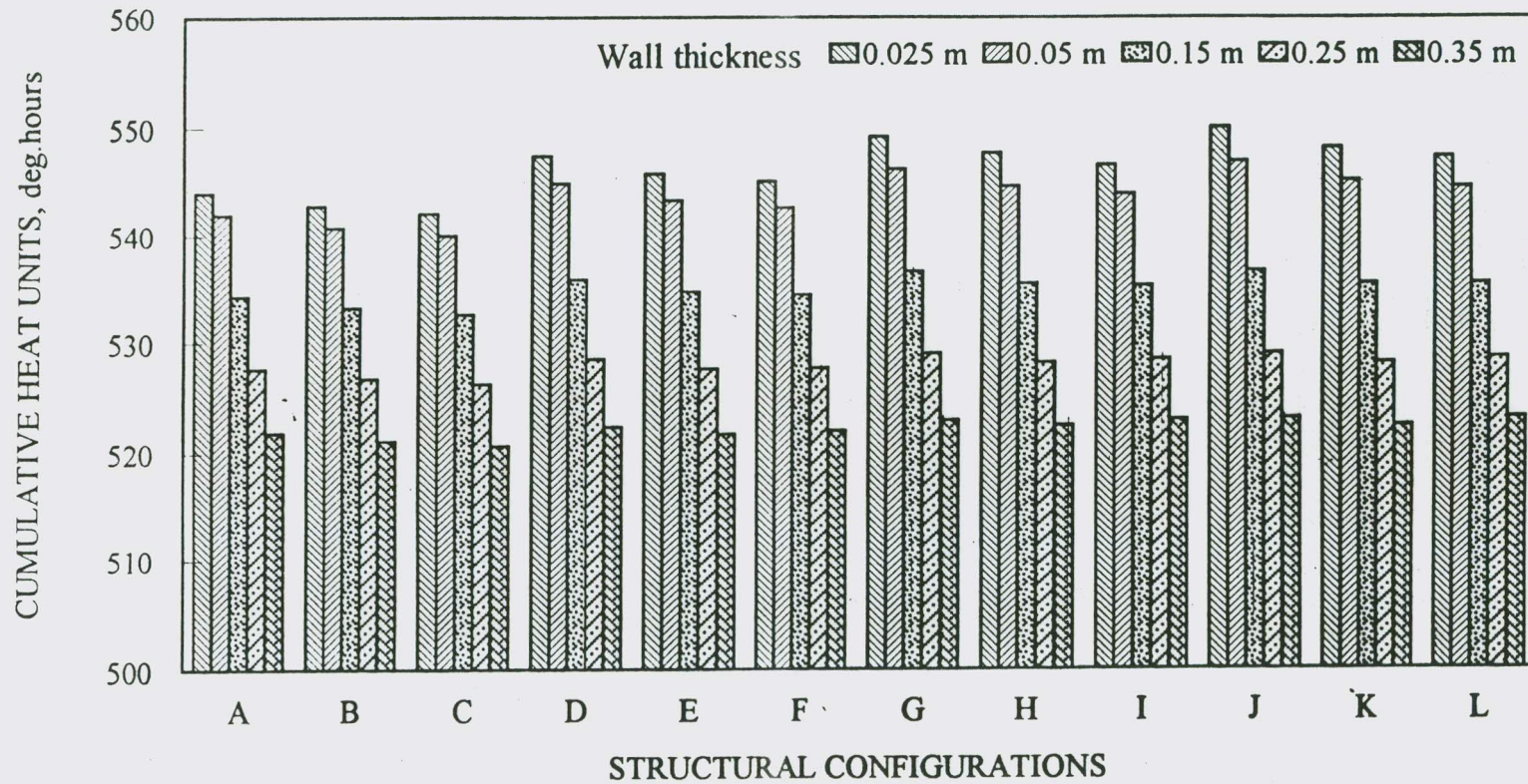


Fig 4 Cumulative heat units in a 1 m^3 EC structure as obtained by changing the height and L.B. ratio for different wall thicknesses (ambient air velocity 2.5 m/s)

A: height 0.5 m, L.B.ratio 1 D: height 1.0 m, L.B.ratio 1 G: height 1.5 m, L.B.ratio 1 J: height 2.0 m, L.B.ratio 1
 B: height 0.5 m, L.B.ratio 2 E: height 1.0 m, L.B.ratio 2 H: height 1.5 m, L.B.ratio 2 K: height 2.0 m, L.B.ratio 2
 C: height 0.5 m, L.B.ratio 3 F: height 1.0 m, L.B.ratio 3 I: height 1.5 m, L.B.ratio 3 L: height 2.0 m, L.B. ratio 3

in air velocity on the outside surfaces of the structure increased the evaporation coefficient and efficiency of evaporative cooling, and decreased the CHU. For a structural configuration with height 0.5m, length-breadth ratio 1 and wall thickness 0.025m, the advantage obtained in CHU by changing the air velocity to 4.5 m/s and 2.5 m/s from 0.5 m/s were 8.4% and 6.1%, respectively. For a porous structure, it would also increase the infiltration through wet walls, which in turn would further reduce the inside temperature. Increase in ventilation/infiltration through the EC structure decreased the CHU in an asymptotic manner. The net advantage obtained from no ventilation to ventilation at a rate of 0.1 m³/s was 5.5% (Figure-6).

The structural orientation had a negligible effect on the internal thermal environment of a well ventilated EC structure. The gains obtained by changing the long wall from east-west to north-south was limited to only 0.6%. The CHU was lowered by 8.1%, 8.23%, 3.2% and 4.8% by shading the structure during the months of January, April, July and October, respectively (Figure-7). The simulation studies under different weather conditions indicated that the RH inside an EC structure, with sufficient infiltration and ventilation, would remain close to 100% throughout the year and the maximum advantage of evaporative cooling could be obtained under low ambient relative humidity conditions (Figure-8).

The above analysis provided an insight into the heat transfer processes in the EC structures and it was observed that evaporation on the surfaces and infiltration through the structure were the two most important processes in the thermal balance of EC structures. Porosity of walls permitted more efficient thermal exchange between the storage interior and evaporatively cooled air and the EC structure made of thin and porous walls maintained cooler environment as compared to impervious walls of any thickness. Thicker walls in a storage structure resulted into reduced daily fluctuations in inside air temperature due to higher thermal inertia. The studies on brick EC structure revealed that there was negligible evaporation on the outer surfaces, though the sand layer was kept saturated all the time. Further, the effect of wall thickness and thermal

properties of the construction materials were also observed to be insignificant.

3.2 Construction of the structure

Experimental studies revealed that the wet surface of the evaporating walls should be directly exposed to ambient air for full potential evaporation. If the side walls are made permeable to allow sufficient infiltration of saturated air, then the performance of EC chamber would be better than that for structures with impermeable side walls made up of brick (Roy and Khurdiya, 1986). Hence, the side walls could be made of any permeable material with a good water holding capacity. For the present study, the side walls of the EC structure were constructed from aspen fibre pads (2.5 cm thick) for adequate infiltration of moist air. Plastic laterals with drippers were used for wetting the surfaces of the structures to obtain full potential evaporation, simultaneously. The produce was kept inside the structure in a specially fabricated container leaving 5 cm gap from all sides.

The above analysis also indicated that if evaporation was a 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 was limited to less than 5%. Therefore, the selection of dimensions of the structure would be essentially dependent on operating parameters like ventilation rate, rate of evaporation from the surfaces, ease of construction, loading and unloading, etc. For an outdoor structure, the height should be limited to 0.5 m to minimise solar irradiation on the surfaces of the structure. Similarly, to allow more infiltration of saturated air into the structure, its long side should be kept across the prevailing wind direction. For indoor structures, without appreciable air flow in the vicinity of the structure, lower length-breadth ratio would reduce cost.

The aspen fibre pads were sandwiched between two layers of welded wire mesh. The different components of the structures were pre-fabricated in the workshop and were assembled on the experimental site. The pad layers were carefully tied to the frames of the structures without leaving any

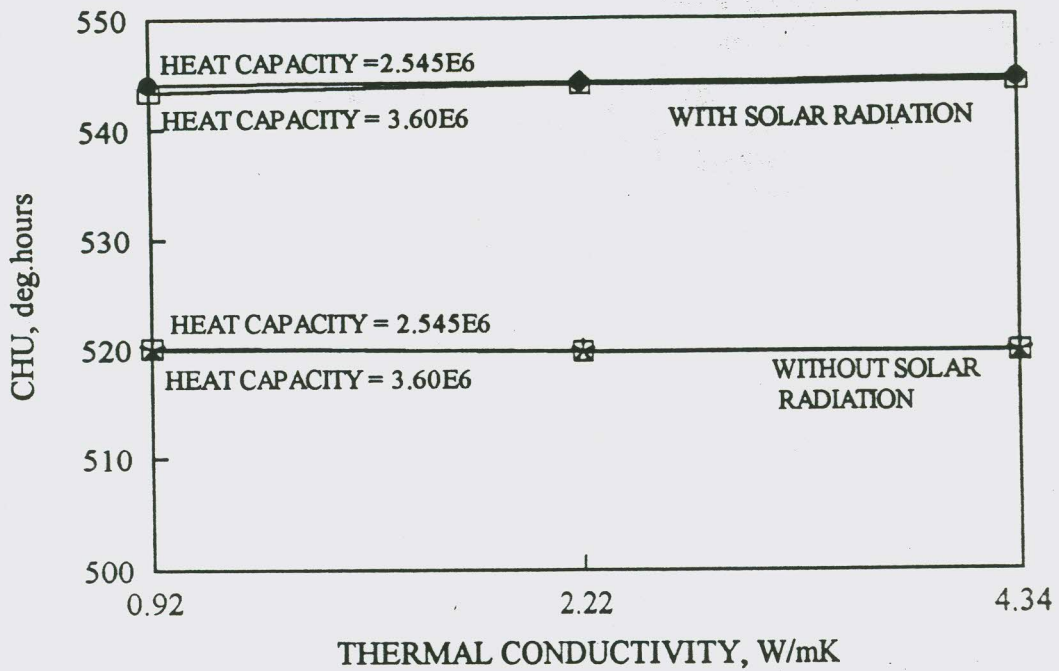


Fig 5 Cumulative heat units in a 1m³ EC structure with height 0.5m, L.B.ratio 1 and wall thickness 0.025 m as affected by varying thermal properties of wall materials

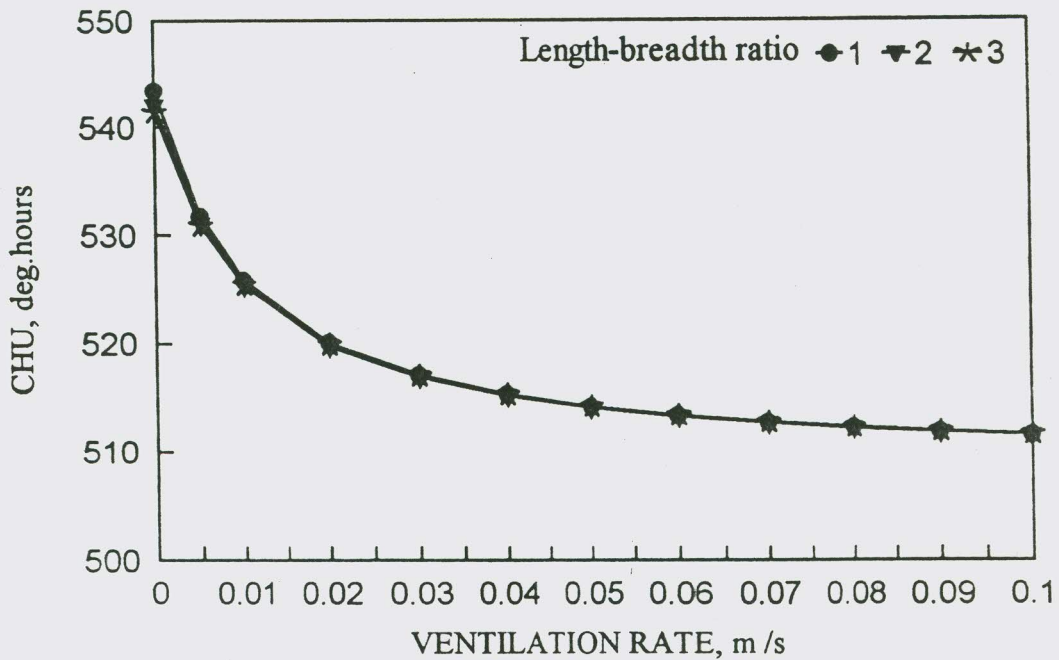


Fig 6 Cumulative heat units in a 1 m³ EC structure with 0.025 m thick wall and 0.5 m height as affected by ventilation rate through the structure

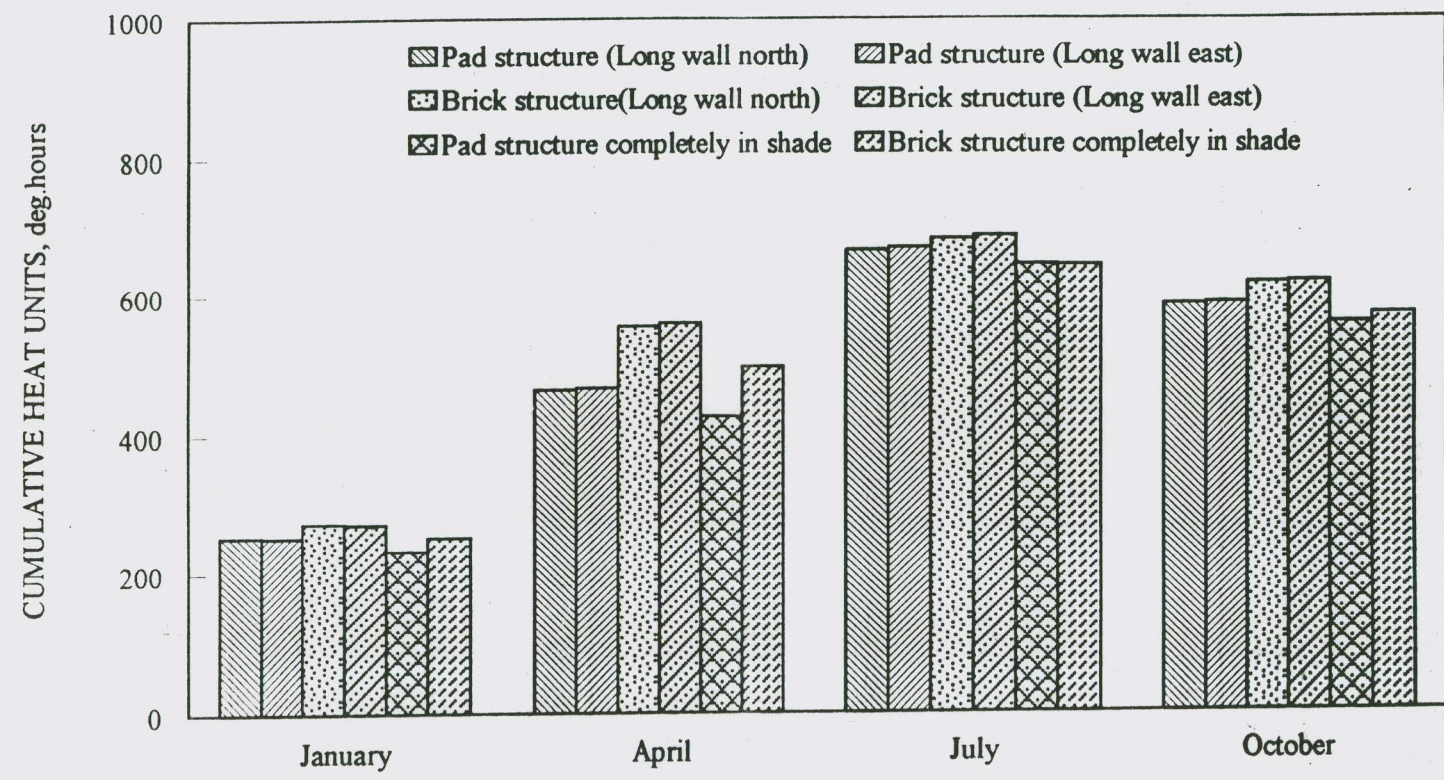


Fig 7 Cumulative heat units in 1 m³ EC structures made of permeable pad/ brick side walls for different weather conditions and orientations

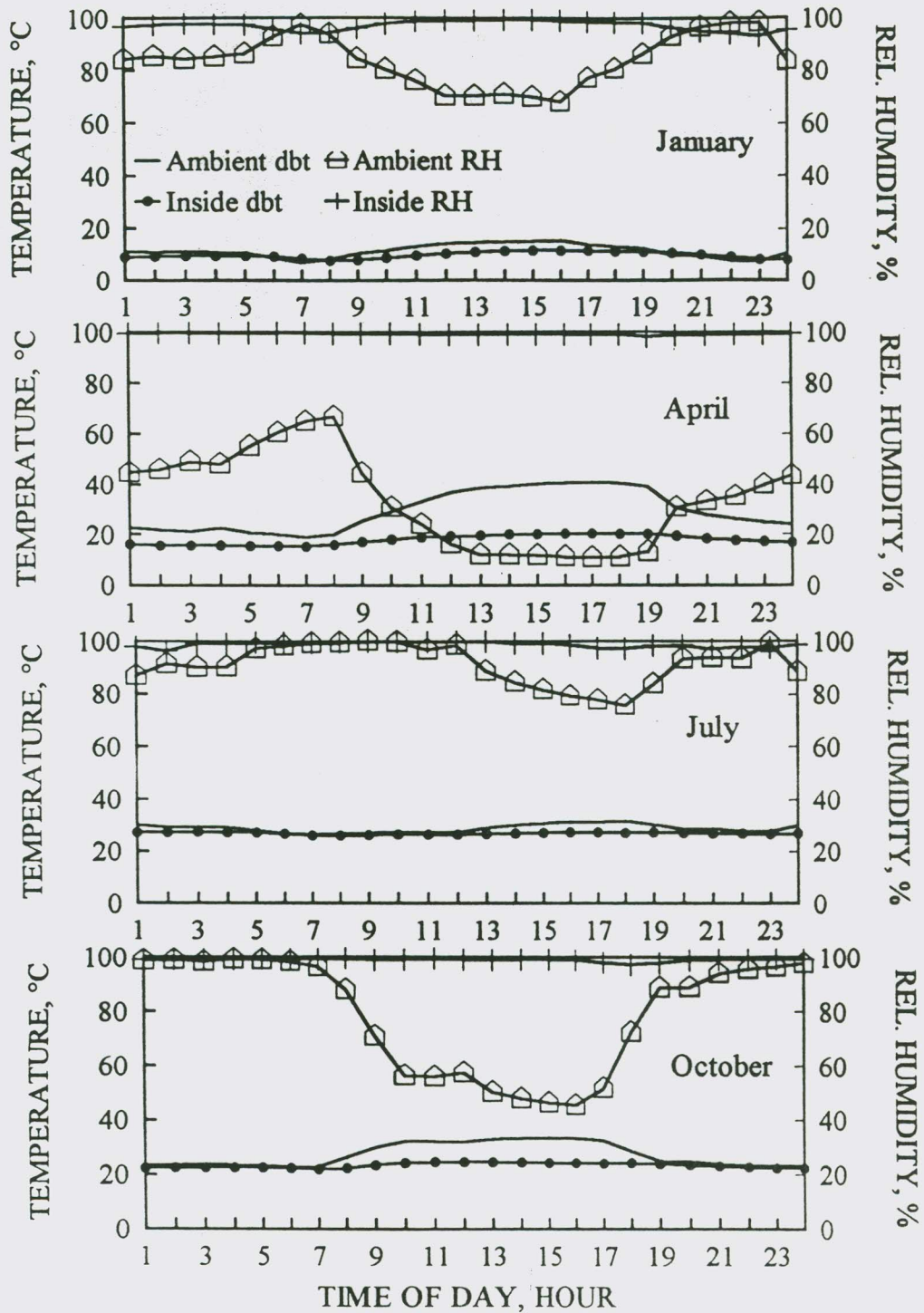


Fig 8 Simulated thermal environment in a 1 m^3 EC structure with permeable walls during different times of a year (representative days for each month are taken for simulation)

gap at the joints. The floor of the structure was made of a single layer of brick spread over 5 cm soil layer on the ground. Thus, the floor of the structure was 12.5 cm above the ground level. This was done to prevent moisture seepage through walls and accumulation of water on the floor of the structure. The top cover of the structure was made of 2.5 cm thick layer of hessian cloth kept on a welded wire mesh frame to avoid direct entry of water into the structure and to keep the cover wet for longer time. Due to its better water holding capacity, the frequency of wetting was reduced. The top surfaces of the structures were shaded all the times.

the other with a brick-sand-brick wall, as recorded on a test day, for comparison. The average daily fluctuations of temperature in the brick structure was about 3°C, whereas, it was 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. In the pad structures, the temperature approached the wet bulb temperature by increased infiltration and higher on-surface evaporation. As the structural surfaces permitted easy passage of air and there was no wind barrier, the ventilation/infiltration rate approached almost about 100 times of that obtained in the brick structure.

3.3 Performance evaluation of the EC structure

Figure-9 shows the temperature obtained in two structures, one made up of porous pad walls and

The relative humidity inside the brick structure ranged between 70%-95%, as against 98%-100% inside the pad structures under no load conditions. When

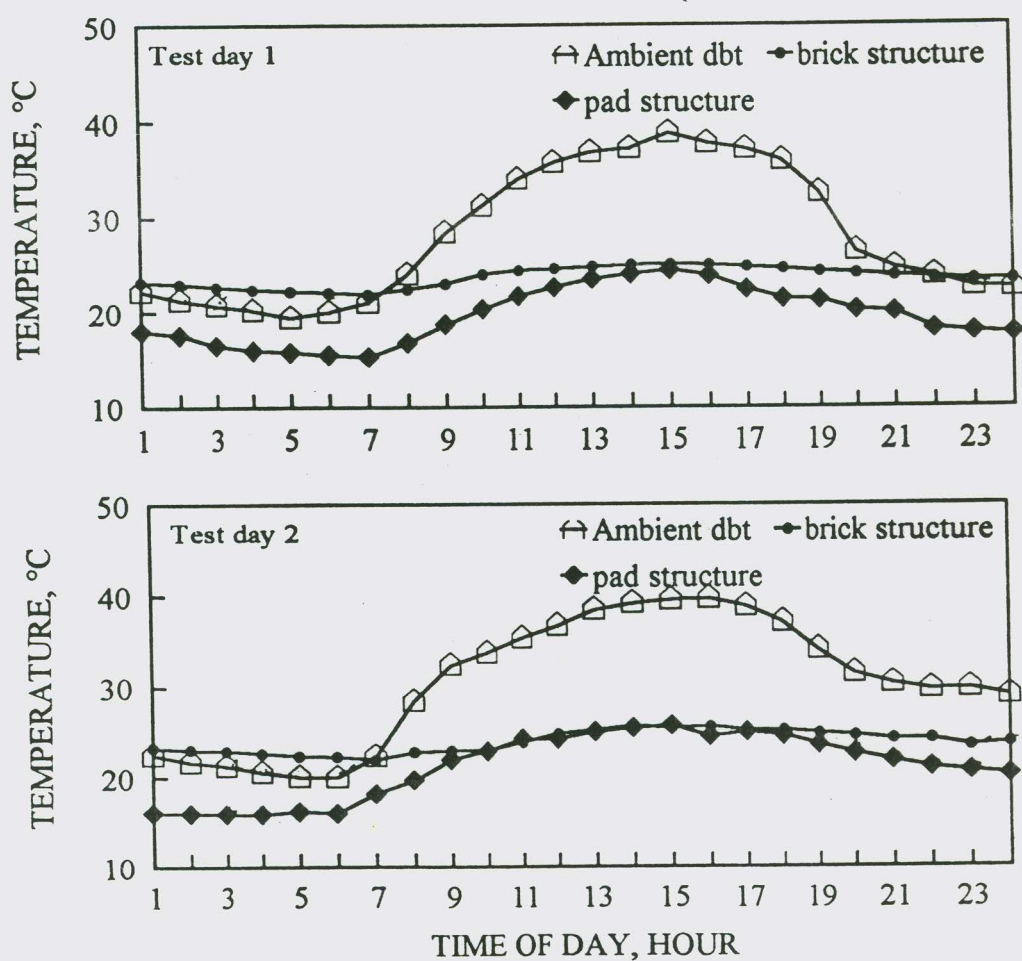


Figure-9 : Comparison between the observed air temperatures within the EC structures made of brick and porous pad on two test days.

potato was loaded in the structures, the RH ranged between 80-100% throughout the day. The pad structures maintained the higher RH because the air entering the pad structures was almost saturated. The RH in the brick structure was lower because of the comparatively higher inside air temperatures. However, the range of RH obtained in both types of structures is favourable to reduce transpiration and increase the shelf life of perishables.

It was observed that the marketable life of potato tubers treated with 0.25% CIPC was 16 weeks in EC chamber whereas the room temperature stored tubers lost their marketability after 12 weeks because of shriveling and sprouting. The tubers stored in cool chamber showed higher specific gravity, more dry matter, higher tuber firmness lower accumulation of reducing and total sugars and was most suitable for processing into shreds. It indicates that the EC storage can be effectively utilised for extending the shelf life of perishable commodities under high temperature and low RH conditions.

3.4 Advantages of the Improved EC structure

As the rate of decay of the stored commodity is directly proportional to the storage temperature, this improved EC structure would increase the shelf life of the commodity by maintaining a lower temperature and higher RH than ambient and other competitive rustic storage practices. Besides, as these types of structures are light weight, they can be conveniently shifted from one place to another and can be used as temporary storage structures for short term storage or for transportation in trucks/rail cars. They can also be installed within a short time at any place to meet immediate demands.

The evaporatively cooled (EC) storage structures can be utilized in places where the fresh perishable commodities are readily spoiled by high temperature and low RH. It is not a competitor of the refrigerated storages and the quality of produce stored in EC chamber may not be compared with that in refrigerated storages. In EC structures, one cannot maintain the most optimum temperature for storage of any particular commodity; rather, it is tried to take the maximum advantage of natural environment by manipulating the ambient air and bringing down

the temperature to a considerably low level. Further, to prevent fungal growth and sprouting, as occurs in some commodities, suitable anti-fungal and anti-sprouting chemicals have to be applied.

4. CONCLUSION

The lack of cold storage facilities to accommodate ever increasing supply of fruits and vegetables has compelled the producers to adopt alternative storage practices; practices that in effect would ideally be less expensive than the cost of renting space in a cold store and more efficient than rustic storage procedures. Therefore, evaporatively cooled (EC) storage structures, which can maintain lower temperature coupled with high humidity, provide enough promise for short-term storage of horticultural produce. The design of an EC storage structure suggested in the present paper has the capability to maintain low temperature coupled with higher humidity than the ambient and some other traditional EC storage practices, which can increase the shelf life of horticultural produce. The shelf life of potato could be increased by about 1 month as compared to room temperature storage under summer conditions. The advantages could be still better for more perishable commodities. Besides, this type of structure can be erected at any place in a short time to meet immediate requirements, more particularly for short-term on-farm storage of commodities, and can be used in transport trolleys.

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