An analysis of the thermal environment of an evaporatively cooled storage structure

Sanjaya K Dash¹ and Pitam Chandra²

ABSTRACT

A mathematical model was developed to represent the thermal environment within an evaporatively cooled (EC) storage structure. The parameters included in the analysis were the structural parameters such as size and shape, structural materials, thickness of different components; environmental parameters such as ambient temperature, relative humidity, solar radiation and wind velocity; operational parameters such as rate of evaporation from the structural surfaces and rate of infiltration through the structure; and different produce properties. The latitude and longitude of the place were considered to determine the sunshine hours and solar irradiation on the surfaces of the structure. The heat conduction through the structural surfaces and produce was obtained by finite element analysis. The computer model was validated with an experimental storage structure of 1 m³ capacity. The maximum deviations between the predicted and observed temperatures and relative humidity for the test days were 1.1°C and 12.1%, respectively. The corresponding values for the mean deviation were 0.5°C and 4.4%. The results of the study can be directly utilized for analyzing the effects of different parameters on the thermal environment of EC structures and selection of suitable design parameters of such structures for storage of fresh produce under different climatic conditions.

Evaporative cooling principle has been used extensively in some tropical and sub-tropical countries for creating favorable atmosphere in an enclosure for storage of horticultural produce. Evaporatively cooled (EC) storage structures, due to their low investment, and almost no energy requirement have become quite popular for short term storage of horticultural produce in many places and they have been observed to increase the shelf life of fresh perishable commodities by 2-10 fold (Chandra et al., 1999). Several studies have been carried out to prove the beneficial effects of evaporative cooling for storage of fruits and vegetables (Roy and Khurdiya, 1986; Roy and Pal, 1991; Habibunnisa et al., 1988; Umbarkar et al., 1991; Hegde, 1996; Pal et al., 1997). Dash(1999) reviewed the storage of different types of fruits and vegetables under evaporative cooling conditions and observed that all the previous experiments on storage of different types of commodities in EC structures had their limitations in observing only the cooling effect as produced in the natural way. A limited information was available on the effects of different input parameters, such as diurnal and seasonal temperature variations, ventilation rate, rate of

¹ Dept. of Agricultural Processing & Food Engineering, Orissa University of Agriculture & Technology, Orissa, and ² Division of Agricultural Engineering, Indian Agricultural Research Institute, New Delhi-110 012, India
evaporation from the surface, size of the structure and construction materials, etc. on the thermal environment in the structures. Such information is necessary to quantify the modified atmosphere that can be obtained under a given set of input conditions. The need of a systematic study of the process was felt to provide a vivid idea on the outside environment-storage environment interactions, and act as a guide line for the development of EC structures under varied operational and environmental conditions. This paper is an attempt in that direction to develop a mathematical model for the thermal environment within an evaporatively cooled structure.

MATERIALS AND METHODS

Theoretical formulation

The different factors affecting the thermal environment of an EC structure are: (i) environmental parameters such as variations in ambient temperature and relative humidity, wind velocity, solar insolation; (ii) structural parameters as size and shape of the structure, construction materials, wall thickness; (iii) operational parameters as rate of evaporative cooling on the structural surfaces and ventilation/infiltration through the structure; and (iv) produce parameters such as type, load, initial temperature, respiration and transpiration rates and thermal properties. A schematic diagram of thermal energy and moisture exchange in an EC storage has been given in Fig. 1. A model for the thermal environment of an EC structure should include adequate consideration of all the above factors.

The assumptions made were:

- The air inside the structure is well mixed at all times and no temperature and moisture gradients exist.
- All construction materials and produce are homogenous.
- The length, breadth and height of the structure are much larger compared to wall thickness and heat transfer through the walls is essentially one-dimensional. The effects of corners and edges have no significance.
- The heat transfer through the produce is two-dimensional neglecting the thermal gradients in lateral direction.
- Thermal gradient in ground exists only in vertical direction.

Heat Balance of inside air

The inside air of the storage structure exchanges heat with the structure wall, floor, top surface, and stored produce by convection. The infiltration-exfiltration through the walls and top surface of the structure also influences the energy balance of the air. At any time, t, the heat balance of the enclosed air can be written as,

\[
\rho_a V_m C_p \left( \frac{\partial T_i}{\partial t} \right) = \sum_{m=1}^{n} h_{m, w} A_m (T_i - T_i^{(w)}) + \sum_{m=1}^{n} h_{m, p} A_m (T_i^{(p)} - T_i^{(w)}) + \rho_a V_R C_p (T_i^{(r)} - T_i^{(w)}) \quad \ldots (1)
\]
Fig. 1 Schematic diagram of the thermal energy and moisture exchange in an evaporatively cooled structure
The first term on the RHS 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 with the produce. The third term is the contribution from infiltration-exfiltration and ventilation, both of which are included in the term VR. Chandra (1979) observed that the thermal storage of the air in small confined structures (greenhouse) constituted a small portion of the overall total heat balance and may be neglected. For the present study also the thermal storage in the air was neglected. Employing finite difference approximation for the time derivative in equation (1).

At any time level, j, if the surface temperatures and parameters on the RHS of the above equation are known, it can be solved for inside temperature.

**Moisture balance of inside air**

The moisture balance of the inside air at any time can be written as equation (3).

The first and second terms on the RHS represent the contribution of condensation/evaporation for 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, which need to be determined. The last term on the RHS represents the moisture contribution to the air due to infiltration-exfiltration or ventilation. If the terms representing evaporation/condensation of moisture for different surfaces and produce and transpiration are included in a single term MC(t), then the equation (3) can be written as equation (4).

Using forward finite difference approximation for the time derivative term, the solution of equation (4) can be written as equation (5).

The relative humidity of the enclosed air and other psychrometric quantities were calculated as per Albright(1990).

\[
TI^{(t)} = \frac{\left( \rho_a V_m C_P / \Delta t \right) \Delta T}{TI^{(t-1)} + \sum_{m=1}^{n} h_{\phi_m} A_{\phi_m} T_{\phi_m}^{(t)} + \sum_{m=1}^{n} h_{\varphi_m} A_{\varphi_m} T_{\varphi_m}^{(t)} + \rho_a VR C_P T_{inf}^{(t)}}
\]

\[
\rho_a V_m \frac{\partial W_l}{\partial t} = \sum_{m=1}^{n} Dk_{\phi_m} A_{\phi_m} \left( W_{\phi_m}^{(t)} - W_l^{(t)} \right) + \sum_{m=1}^{n} Dk_{\varphi_m} A_{\varphi_m} \left( W_{\varphi_m}^{(t)} - W_l^{(t)} \right) + M_{tr}^{(t)} + \rho_a VR \left( W_{inf}^{(t)} - W_l^{(t)} \right)
\]

\[
\rho_a V_m \frac{\partial W_l}{\partial t} = MC^{(t)} + \rho_a VR \left( W_{air}^{(t)} - W_l^{(t)} \right)
\]
\[ W_T(j+1) = \frac{(\rho_a V_{in} / \Delta t)WT^{(t)} + MC^{(j)} + \rho_a VR(W_{inf} - WT^{(j)})}{(\rho_a V_{in} / \Delta t)} \] .. (5)

**Determination of temperature of various surfaces**

To have a solution of the heat and moisture balance equations and to determine temperatures of various surfaces of the structure, the principle of energy conservation along with initial and boundary conditions was applied. As the heat and moisture balance in an EC enclosure is time dependent, transient thermal analysis was applied for obtaining the solution.

**Initial conditions:** For using the analysis to predict thermal environment in the structure for a particular day, temperatures for various elements in the space domain at the beginning of the day are needed. In a transient heat transfer problem, the temperature field at any time, \( t \), depends upon the temperature field at the previous time step, \( t - \Delta t \), besides other factors. These temperatures for the structural components and the underlying ground should reflect the absence of any initial transients. Very thin cover surfaces would quickly reach thermal equilibrium with the surrounding conditions because of their low thermal masses. Therefore, the surrounding air temperature at the starting time could be used as their initial temperatures. But thicker walls may take a longer time to overcome the initial transients. Hence the initial temperatures were assigned as the surrounding air temperature at the starting time, and the program was run for several time steps (corresponding to 72 hours) to obtain more reasonable and realistic initial conditions for the elements in the structure. The temperature measurements in the experimental structure confirmed that under saturated conditions, the walls came to the steady-periodic equilibrium conditions within this time period. The surrounding air temperature at the time of loading was used as the initial temperature value for elements in produce, which was updated for each test day from the results and measurements of the previous day.

The ground would respond mainly to periodic variations of the environmental conditions within and outside the EC structure. Although the periodic variations of the environmental conditions have several frequencies, daily variations are important for studying the EC structure’s thermal environment. The daily variations of the environmental temperatures rarely affect the temperature beyond a depth of about 1 m in soil (Hillel, 1998). As the data on the EC structures were taken after more than 3 days of the installation of the structures, it was safe to assume that the ground below the structure had overcome all the transients due to the structure’s presence. For a test day, the steady state solution for temperature fields for the ground was obtained with the daily average surface conditions (air temperature, solar radiation, etc.). This steady state solution served as the source of initial temperature field for the ground for that day.

**Boundary conditions:** The effect of all
environmental thermal forces in the present case can be conveniently grouped under three categories: (i) specified temperature boundary condition, (ii) convection boundary condition, and (iii) normal flux boundary condition.

If the storage structure is kept on the ground, as in the present case, then heat transfer would extend to a considerable distance in the downward and lateral directions. Theoretically, the thermal influence extends to infinity. However, to keep the effort of numerical computation within reasonable limits, only a finite region in the ground should be selected for discretisation. It is logical to consider only that region in the ground beyond which thermal effects due to the structure are not significant, i.e., where the annual climatic fluctuations do not penetrate. Chandra (1979) and Shrivastava (1995) observed that beyond about 12 m depth the thermal influence of the structure above the ground is practically absent. In the present analysis also, the zone of thermal influence of the structure was restricted to 12 m depth in the ground. The specified temperature boundary condition was included in the model by the scheme suggested by Polivka and Wilson (1970).

Heat is transferred from a solid surface to the surrounding fluid by convection. The overall heat transfer is represented by the convective heat transfer coefficient, \( h \), and the boundary condition is represented as

\[
q_s = h(T_s - T_{\infty})
\]

Transpiration from the commodity, condensation/evaporation for the commodity and structural surfaces, and radiation fluxes are included in this category. Absorbed solar radiation fluxes for opaque surfaces of the storage structure also form a part of the normal flux boundary condition (Chandra et al., 1981). Determination of these quantities, constituting the normal flux boundary conditions is presented below.

**Solar radiation:** The solar radiation absorbed by a material at any time depends on the quantity of irradiation, material radiation properties and influence of surroundings. The solar radiation fluxes were calculated as per Garg and Prakash (1997), with the information on the hourly total solar radiation fluxes incident on a horizontal surface outside the structure under the field conditions. The total absorbed hourly radiation quantities as obtained above were converted to unit surface areas and represented by the exponential form of Fourier series. The Fourier series representation of these quantities permitted their estimation at any time. The sunrise and sunset times at any place were determined from the latitude and longitude of the place (Garg and Prakash, 1997).

For considering thermal radiation exchange in the model, the analysis suggested by Albright (1990) was used. It was assumed that all surfaces participating in the radiation exchange could be idealised to form a radiation enclosure. Each surface of the enclosure was isothermal and gray, i.e., thermal radiation properties were independent of wavelength. The reflected and emitted radiation from the surfaces was diffusely distributed. Air did not participate in the thermal radiation exchange and the radiation leaving a surface was uniformly distributed over the surface. As the EC structure is expected to have only opaque
surfaces to prevent solar insolation from entering inside, only the case of opaque surfaces exposed to radiation heat transfer was considered.

**Condensation:** When the temperature of a surface in contact with moist air drops below the dew point temperature of the moist air, some amount of moisture from the air condenses on the cool surface. The rate of condensation was determined as per ASHRAE(1997) as,

\[(M_{co})_s = (A_{co})_s Dk_s (W_a - W_s) \ldots (7)\]

The evaporation coefficient, \(Dk\), on any surface is related to the convective heat transfer coefficient of the surface for small condensation rates by the Lewis relation,

\[Dk = \frac{h_s}{Cp_a} \ldots (8)\]

where,

\[Cp'_a = (1 + W_a)Cp_a \ldots (9)\]

Heat flux due to condensation was calculated as

\[q_{co} = \frac{(M_{co})_s h_{fg}}{A_{co}} \ldots (10)\]

where \(h_{fg}\) is the latent heat of evaporation of moisture on the surface of condensation.

**Transpiration:** The moisture loss from the stored commodity due to transpiration was included in the model by using the following equation(Sastry et al., 1978)

\[M_{tr} = TRC \cdot Wt(p_{w,p} - p_{w,in}) \ldots (11)\]

Heat flux due to transpiration was calculated as

\[q_{tr} = \frac{M_{tr} h_{fg}}{A_{S,p}} \ldots (12)\]

**Principle of energy conservation**

Temperature in solid regions, for which the initial and boundary conditions have been defined, can be determined by using the energy conservation principle along with Fourier's law of heat conduction (Holman, 1997). The partial differential equation that represents temperatures in an orthotropic material along with appropriate initial and boundary conditions is given by,

\[\nabla^2 \phi + \nabla' = pC_p \left( \frac{\partial \phi}{\partial \tau} \right) \ldots (13)\]

with the boundary conditions,

\[K_{xx} \left( \frac{\partial \phi}{\partial x} \right) + h(\phi - \phi_a) = 0 \text{ at } S_1 \ldots (14)\]

and

\[K_{xx} \left( \frac{\partial \phi}{\partial x} \right) + q = 0 \text{ at } S_2 \ldots (15)\]

Here, \(\phi\) is the boundary temperature (unknown), \(S_1\) and \(S_2\) are the surfaces/boundaries experiencing heat convection and heat flux, respectively.

An analytical solution of equation (13) is not feasible in the present case because some of the boundary conditions, i.e., thermal radiation, condensation, transpiration, etc., are non-linear functions of temperature. Hence the finite element method was used, which could also be conveniently extended for irregular shaped enclosures, material heterogeneity and complex geometries.

\[ [C] \frac{\partial \{\phi\}}{\partial t} + [K]\{\phi\} + \{F\} = 0 \quad \ldots (16) \]

where, \([C]\), \([K]\) and \([F]\) are called the capacitance matrix, global conductivity matrix and the global load vector, respectively. The details of the derivation of these equations by employing the Galerkin’s approach has been described in Dash (1999).

Using the finite difference solution in the time domain, the following recursive equation is obtained.

\[ ([K] + \frac{2}{\Delta t}[C])\{\phi\}^* = \frac{2}{\Delta t}[C]\{\phi\}_0 - [F]^* \quad \ldots (17) \]

Using this explicit presentation for the temperature, a set of simultaneous differential equations is obtained. These equations involve time derivatives of temperature, which can be represented by a suitable finite difference approximation. By doing so, a set of simultaneous differential equations is converted into a set of simultaneous algebraic equations. The solution of this set of algebraic equations yields the desired temperature field, i.e., the temperature of the elements in terms of temperature of the nodes of the element.

**Finite element representation of the EC structures**

As the thermal fluxes on the side walls and the top surface of the EC structure would be quite high, large temperature gradients are expected in the walls and top surface. Hence, the number of elements in the side walls of the structure having the wall thickness 0.35m was varied between 1 to 35 and it was observed that fluctuations were reduced to acceptable limits by taking 24 elements (25 nodes) in the walls, 9 elements (10 nodes) on the top cover and 13 elements (14 nodes) in the floor and ground. The number of elements in the side walls of thin walled structures could be reduced further depending on the wall thickness, but in the present study, the number of elements in side walls was kept at 24 uniformly for all thicknesses for convenience in adopting the program for different structures. This would require only the structural configurations to be changed in the data files without any modifications in the main program. The heat flow through walls was considered to be one-dimensional as the thick-ness of the walls was much smaller as compared to other dimensions. The perimeters of the one dimensional elements in the ground were assumed to be insulated. The constant temperature at the depth of 12m in the ground was assumed to be 20°C (Shrivastava, 1995). After the steady periodic conditions are attained, the produce would be exposed to small thermal fluxes. Hence, for simplicity in analysis, the produce was considered to consist of 8 two-dimensional elements and respiration heat generation by the produce was included in the model as a source of heat gene-ration in the elements under consideration.

**Development of computer program**

A computer program was developed in Fortran-77 using the above analysis to predict the thermal environment in an EC structure (Dash, 1999). To obtain the thermal environment within the EC structure, 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. The computer program directly gives the air temperature and relative humidity inside the EC storage structure as output.

**Experimental validation of the model**

An experimental top loading type storage structure of 1 m³ capacity was constructed (Fig.2) to test the validity of the model. 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 in between filled with riverbed sand, as per Roy and Khurdiya (1986) and 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. Thus, the floor of the structure was 12.5 cm above the ground level 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 hessian cloth to keep the cover wet at all times and simultaneously to avoid direct entry of water into the structure. Due to the better water holding capacity of the hessian cloth, the frequency of wetting was reduced. The brick in the walls were joined with 1:15 cement mortar. This is a very lean mixture, which was used to allow sufficient porosity. In regular brick works, a mixture of 1:4 or 1:5 is commonly used. Drip laterals were used for continuous wetting of the sand layer in the walls and the outer surfaces of walls were wetted twice daily by sprinkling water as suggested by Roy and Khurdiya (1986). The structure was oriented in

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![Schematic representation of the evaporatively cooled structure used for validation of the model](image)

**Fig.2** Schematic representation of the evaporatively cooled structure used for validation of the model

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67
east-west direction. A temporary shed was constructed over the experimental structure and was adjusted such that there was no direct solar radiation on the top surface. The site was selected so as to allow sufficient natural draft of ambient air around the structure.

The environmental conditions (temperature, RH, solar radiation, wind velocity) were measured at the experimental location. The azimuth and tilt angles for the structural surfaces were measured for inclusion in the model. Suitable radiation shape factors were also taken 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 following equations for forced convection heat transfer coefficient (ASHRAE, 1997) were used for the outside surfaces of the structure.

\[
\begin{align*}
    h & = 5.62 + 3.9 \ V, \quad V < 5 \text{ m/s} \quad \ldots \quad (18) \\
    & = 7.2 \ (V)^{0.8}, \quad 5 \text{ m/s} < V < 30 \text{ m/s} \quad \ldots \quad (19)
\end{align*}
\]

The natural convection on the inner surfaces were also calculated as per ASHRAE (1997) and Holman (1997). The physical and thermal properties of the materials used for construction were taken as per Albright (1990), ASHRAE (1997) and Domkundwar (1997) and the thermo-physical properties of air were taken as per ASHRAE (1997). Linear equations for the relationships of these properties with temperature were obtained by regression analysis for use in the computer model. The evaporation coefficient of 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 several factors such as density, specific heat, thermal conductivity, heat of respiration, transpiration, etc. It will also depend on a great extent on the amount of load. However, as the EC structures for short term storage would generally accommodate a variety of commodities, it may not be specifically designed for any particular produce. Hence it was decided that the model be validated under no load conditions. However, the computer model was later validated with commodity in storage (Dash, 1999).

**RESULTS AND DISCUSSION**

The variations of the air temperature inside the structure as observed experimentally along with the ambient dry bulb and wet bulb temperatures for two test days are presented in Fig. 3. It was observed that the maximum temperature inside the chamber remained 14-15°C below the maximum ambient dry bulb temperature. Similar observations were made by Roy and Khurdiya (1986), Roy and Pal (1991), Umbarkar et al. (1991) and other workers for small capacity EC chambers.

When the evaporation from all side walls and the top surface were considered to be occurr-
Fig. 3 Variation of temperature inside the evaporatively cooled structure on two test days.

ing at 100% of the potential evaporation, the predictions from the mathematical model gave much lower temperature value than those observed (Fig. 4A). Therefore, it appeared that the evaporation from the side walls might be occurring at a much lower rate than the full potential evaporation. Though, sufficient care was taken to completely wet the brick walls twice a day, it was observed that the surfaces dried up quickly and the wall surface temperatures approached the ambient dry bulb temperature within a short period of time. Thus, it was reasonable to assume that there was negligible diffusion of moisture through the brick section from the wet sand layer and, consequently, the evaporation of moisture from the outside surfaces of the brick walls was also negligible. With the passage of time the rate of moisture diffusion in the bricks is expected to be reduced due to deposition of salts in the pore spaces, thereby restricting evaporation from the wall surfaces.
In the model the evaporation from side walls was varied between 0 to 100% of the potential evaporation, that would have occurred if the outer surfaces remained completely saturated all the times. It was observed that if the actual evaporation from the side walls was kept at only 5% of the potential evaporation, the predicted values of temperature closely represented the observed temperatures. This small amount of diffusion of moisture and subsequent evaporation on the surfaces were possibly taking place at the brick joints and cracks. With this parameterization, the predicted and observed values for temperature in the structure for two test days have been plotted in Fig. 4B. For April 1, 1999 the maximum deviation between the predicted and observed temperatures was 1.1°C and the mean deviat-

![Graph](image)

Fig. 4 Comparison between predicted and observed air temperatures in brick structure (A) with 100% of the potential evaporation on side walls, (B) with 5% of the potential evaporation on side walls
ion was 0.5°C. For April 2, 1999, the maximum and mean deviations were 0.9°C and 0.4°C respectively. The chi-square ($\chi^2$) values for the comparison were 0.28 and 0.22 for the two test days. The $\chi^2$ values for 23 degrees of freedom at 1% and 5% level of significance are 41.64 and 35.17, respectively (Chandel, 1998), indicating that the model adequately represented the temperature inside the EC structure.

For April 2, 1999, the corresponding values were 8.7% and 4.4%, respectively. The chi-square ($\chi^2$) values for the data were 8.38 and 8.03 for the two test days, which were below the acceptable limit indicating that the predictions were reasonably close to the observations at any instant of time. The close 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.

**CONCLUSION**

The paper discusses about the development of a computer based mathematical model to deter-

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**Fig. 5** Comparison between the predicted and observed relative humidity values in the empty EC structure on two test days.
determine the thermal environment within evaporatively cooled storage structures, which are commonly used for storage of horticultural produce in some tropical and sub-tropical countries. The model considered the different structural, environmental, operational, and produce parameters that are expected to affect the thermal environment within the structure. The heat conduction through the structural surfaces was computed by finite element analysis. It was observed that the model adequately represented the thermal environment within an EC structure. The model with its wide ranging applicability and capabilities would aid in deciding on the suitable design parameters of evaporatively cooled storage structures for different locations.

**Symbols and abbreviations**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>A</td>
<td>area of the surface/element, m²</td>
</tr>
<tr>
<td>B</td>
<td>radiosity, W/m²</td>
</tr>
<tr>
<td>[C]</td>
<td>global capacitance matrix</td>
</tr>
<tr>
<td>Cp</td>
<td>specific heat, J/kg⁰K</td>
</tr>
<tr>
<td>Dk</td>
<td>evaporation coefficient, kg/m²s</td>
</tr>
<tr>
<td>[F]</td>
<td>global load vector</td>
</tr>
<tr>
<td>[K]</td>
<td>global conductivity matrix</td>
</tr>
<tr>
<td>L</td>
<td>length of element, m</td>
</tr>
<tr>
<td>M</td>
<td>rate of moisture transfer, kg/s</td>
</tr>
<tr>
<td>MC</td>
<td>moisture contribution from transpiration and evaporation/condensation, kg/s</td>
</tr>
<tr>
<td>N</td>
<td>finite element shape function</td>
</tr>
<tr>
<td>p</td>
<td>pressure, kPa</td>
</tr>
<tr>
<td>q</td>
<td>rate of heat transfer or heat flux, W/m²</td>
</tr>
<tr>
<td>T</td>
<td>temperature, °C</td>
</tr>
<tr>
<td>t</td>
<td>time, s</td>
</tr>
<tr>
<td>TI</td>
<td>inside air temperature of the structure, °C</td>
</tr>
<tr>
<td>TRC</td>
<td>transpiration coefficient, kg/kg.s.kPa</td>
</tr>
<tr>
<td>V</td>
<td>volume, m³</td>
</tr>
<tr>
<td>VR</td>
<td>ventilation and/or infiltration rate, m³/s</td>
</tr>
<tr>
<td>W</td>
<td>humidity ratio, kg/kg of dry air</td>
</tr>
<tr>
<td>WI</td>
<td>humidity ratio of enclosed air</td>
</tr>
<tr>
<td>Wt</td>
<td>weight of the commodity, kg</td>
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**Greek**

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<tr>
<td>ρ</td>
<td>mass density, kg/m³</td>
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<tr>
<td>l</td>
<td>heat capacity</td>
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<tr>
<td>Δ</td>
<td>change or increment</td>
</tr>
<tr>
<td>ψ</td>
<td>latitude of place (north positive, south negative), degrees</td>
</tr>
<tr>
<td>φ</td>
<td>an unknown scalar quantity</td>
</tr>
<tr>
<td>Φ</td>
<td>nodal values of temperature</td>
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**Superscripts**

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<tr>
<td>(e)</td>
<td>related to element</td>
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<tr>
<td>(j), (j-1)</td>
<td>jth and (j-1)th time step</td>
</tr>
<tr>
<td>(t)</td>
<td>at tth time step</td>
</tr>
<tr>
<td>·</td>
<td>overall system matrix</td>
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**Subscripts**

<table>
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<th>Subscript</th>
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<tbody>
<tr>
<td>a</td>
<td>air / atmosphere used in shape function calculations</td>
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<tr>
<td>co</td>
<td>condensation</td>
</tr>
<tr>
<td>in</td>
<td>inside environment</td>
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<tr>
<td>inf</td>
<td>infiltrated air</td>
</tr>
<tr>
<td>m</td>
<td>represents a particular surface</td>
</tr>
<tr>
<td>p</td>
<td>stored produce</td>
</tr>
<tr>
<td>s</td>
<td>any surface of the structure</td>
</tr>
<tr>
<td>tr</td>
<td>transpiration</td>
</tr>
<tr>
<td>w</td>
<td>moist air</td>
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<tr>
<td>∞</td>
<td>ambient, at the boundary</td>
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REFERENCES


