CHAPTER 2

REVIEW OF GREENHOUSE THERMAL CONTROL
TECHNOLOGIES AND APPLICATIONS:
STATE-OF-THE ART
2.1 INTRODUCTION

Based on the working principles, greenhouses are classified into active and passive greenhouses as shown in Fig.2.1. Active solar greenhouses are equipped with heat collection systems that utilize a collecting system, which is separate from the greenhouse cell, and are independent heat storage systems. These greenhouses use fan and pumps with the help of mechanical energy to move the working fluid in the system. This can further be classified into heating and cooling systems as described by Santamouris (1994). Passive solar greenhouses are those, which do not require mechanical energy for moving fluids for their operation. Fluids and energy move by virtue of temperature gradients established by the absorption of radiation. They rely on natural convection and radiation for heat transfer, Duffie and Beckman (1991). The greenhouse acts as a collector, as the glazed area, walls and roofs are used for collecting, storing and distribution of solar energy in the greenhouses by natural processes of convection, radiation and conduction. These systems purely depend on architectural design that can be used to maximize solar gain in the winter and minimize them in summer. Passive systems can further be sub-divided on the basis of heating and cooling methods. For heating during the day, excess heat is transferred from the inside air in the greenhouse to the heat storage area and it is recovered at night in order to satisfy the heating needs of the greenhouse. The greenhouse air after transferring its heat to the thermal storage medium is not fed back to the greenhouse i.e. an open air cycle is used during the day. For cooling purposes the greenhouse air after transferring its heat to the thermal storage medium becomes comparatively cooler and is fed back to the greenhouse. Repeated recirculation of the greenhouse air through the heat storage medium causes cooling effect inside the greenhouse. Passive heating may be due to water storage, rock bed storage, phase change materials, north wall, mulching and movable insulation etc.

2.2 REVIEW OF EXISTING THERMAL CONTROL TECHNOLOGIES

The review is divided into thermal heating, thermal cooling and composite system sections and discusses representative important applications of thermal control technologies used world wide for agricultural greenhouses. In thermal heating technologies section, heating of greenhouses using water storage, rock bed storage, phase change material storage, earth-tube-heat-exchangers, movable insulation/thermal screens, ground air collector, north wall etc. have been discussed. Upto date information for water, rock and phase change material storage has been compiled and analysis performed to correlate the relevant parameters in order to develop some important empirical relations. These empirical relations may prove to be a good tool for estimating the storage volume or weight required for a given
greenhouse area for different storage media and cover materials. In thermal cooling section, cooling of greenhouses using ventilation (natural and forced), shading, evaporative cooling and earth-air-heat exchanger systems etc. have been discussed with special emphasis on earth-air-heat exchanger systems i.e. composite system. The advantages and limitations of each thermal control system are also discussed. Using the compiled information some important conclusions have been drawn based on the performance of the systems. Limitations of the existing heating, cooling and composite technologies have been discussed. Based on these limitations, formulation of the problem for the current study has been made and finally the objectives of the study have been listed.

Fig. 2.1 Classification of greenhouses
2.2.1 Greenhouse Heating Technologies

2.2.1.1 Water storage systems

Sensible heat storage involves a material that undergoes no change in phase over the temperature domain encountered in the storage process. The basic energy equation for an energy storage unit operating over a finite temperature difference is given in terms of heat stored per unit volume as shown by Sukhatme, 1990

\[ Q_s = m_w C_w (T_2 - T_1) \]

Thus the ability to store heat depends upon the product \( \rho_w \times C_w \) which the water has the highest value. The heat storage system can be placed inside the greenhouse in which case the heat exchange is directly between the system and the indoor air. Plastic bags or plastic pipes (Fig. 2.2a) filled with water which are laid on the pathways between the rows of plants or in water containers (Fig. 2.2b) along the north side of the greenhouse which act as solar collectors and heat storage mediums. The systems absorb and trap the incident solar radiation during the day. During the night, the stored heat is returned to the interior by natural convection and radiation. The heat storage medium can also be placed outside the greenhouse, in which case a heat transfer fluid must be used. The excess heat available in the greenhouse during the day can be transferred with a heat transfer fluid. Generally inside hot air from the greenhouse is used to transfer heat to the stored water (thermal mass) through a heat exchanger for latter use. The storage system can be placed on the surface that is also exposed to the incident solar radiation or it can be placed underground. At night the stored heat is transferred back to the lower-temperature air of the greenhouse. In this section, review of representative applications using different water storage techniques all over the world has been presented. Govin and Black (1980) used a vertical water storage area placed at north side of the greenhouse. The incident solar radiation entering from the south side of the greenhouse is directly absorbed by the storing medium, especially during the winter when the sun is at low solar attitudes. The storage medium also acts as an insulator of the north side. At night, the stored heat is returned to the greenhouse by natural convection and radiation. Vonarburg and Gallacher (1982) covered the interior space during the night with an additional polyethylene cover placed at a height of 1m along with water circulation through plastic pipes. Interior air temperatures of 3-4 °C higher than the minimum ambient air were observed.
Fig. 2.2 Passive solar greenhouse with water storage in (a) plastic bags (b) water containers.
However, the main problem in this type of system is that the plastic bags occupy valuable ground space inside the greenhouse, which cannot be used for cultivation. Carnegie et al. (1984) have made a simulation studies on a single glazed shallow solar pond (SSP) water heater integrated with double glazed greenhouse. The proposed size of SSP water heater provided about 77 per cent of total annual thermal energy requirements of the greenhouse. Similar study was also carried out by Mohamud (1995) towards the potential of a solar pond and used the same as a primary heating system. Connellan (1986) used warm water as heat source to heat the greenhouse through a pumped system. Water at temperature of 20-25 °C was passed through a simple polyethylene pipe network, buried 15 cm below the soil surface from December to June. He found that wastewater heating system was proved to be a good approach in terms of energy conservation. Transparent polyethylene bags (180 μm thick), filled with water and placed on path rows along the ground surface of the greenhouse, have been used by Kyritis (1987), Fotiades (1987) and Sallanbas (1987). The plastic bags are placed on a black polyethylene film (50 μm) to increase solar radiation absorptivity under which there might be a layer of insulating material such as 2-3 cm polystyrene panels in the extreme cold climatic regions have also been used by Grafiadellis (1987), Pacheco (1987), Esquira (1987) and Mourou and Verlodt (1987). The bags have a diameter ranging from 23 to 35 cm, containing about 60-70 l of water per meter of tube length. The water tube length varies from 2 to 6 m. These water tubes covered 20 - 40% of the ground surface, requiring 20-40 l/m² of greenhouse surface area. Water remained still and absorbed the incident solar radiation. It was observed that greenhouse temperature raised by 3-5 °C. To improve the water’s thermal storing capacity, Baillie (1987) and Farah (1987) circulated the water through the tubes with very low pressure. The interior temperatures were observed to be 2.5 - 4 °C higher than the minimum ambient temperature. The cost of constructing the collecting surface can be minimized by using simple black steel barrels as used by Carribent (1988). The system temperatures were observed to be 2-10 °C higher than the minimum ambient temperature.

A system described by Picciurro (1988) used 36 galvanized steel water drums of 160 litres each, placed at north side of a 100 m² experimental polycarbonate cover greenhouse. The southern roof is tilted at an angle of 64° and the northern roof is tilted at an angle of 26°. The southern roof is equipped with reflectors (50 cm high at a distance of 50 cm and at an angle of 26°) which completely absorb and reflect incident solar radiation during winter. These reflectors serve as sun screens during summer. The system can serve, both for cooling during the summer days and heating during the winter nights. During summer, the warm air
from the inside the greenhouse is blown and circulated through a cold water reservoir installed at north side and then returned into the greenhouse. The cold water reservoir cools down during the night by delivering heat to the surroundings. The storage tanks are covered with insulation made of white painted polycarbonate to protect against sun radiation. During winter, the system provides heating by circulating the cold interior air through the warm water reservoir. The water in the barrels has to be warmed during the day by direct solar radiation on the reservoir surface. Damrath & VonZabeltitz (1987) placed large air water heat exchangers on the ground of a 230 m² glass greenhouse. During the daytime, water at a temperature of 2-6 °C is pumped to the air-water heat exchangers from the cold water storage located outside the greenhouse. During this process, the greenhouse air delivers the excess heat to the water. As a result the greenhouse air is cooled and the old water storage is heated to 18-24 °C. The excess heat from the greenhouse is stored into two water tanks having a volume of 21 m³ each. The heated water in the greenhouse is cooled back to the initial temperature level by a water to water heat pump. Levev and Zamir (1987) used a spraying tower placed at the north side of a 1000 m² P.E. covered greenhouse using an air-to-water heat exchanger to extract heat from the air during the day. The water droplets are brought into direct contact with the warm air to the greenhouse through specially designed nozzles at the height of the ridge. The wall which separates the heat exchanger chamber from the greenhouse is open above the ridge in order to permit the entry of the warm air to the greenhouse. From the ground and up to the height of 0.8 m has another opening in order to make possible the re-entry of the cooled air into the greenhouse. The nozzles produce a fine mist which cools the surrounding air. The output is 2 litres per minute for each nozzle (using 1000 nozzles in total). A water pump maintains a water flow rate of 120 m³/hr. The sprayed water is collected in the lower part of the chamber and is then moved to the reservoir. During the night, the warm water is sprayed to the circulating air, releasing the stored heat back to the air. In order to achieve 25-26 °C during the day and 17 °C during the night, the maximum water temperature should be 21-22°C. The system can be used to lower the temperature of the inside air during the day, as well as to heat the air during the night. It was observed that a temperature difference of 11 °C was maintained between the indoor and outdoor air temperatures.

Amri-Alm (1997) studied the effect of solar water heater by fixing it on the interior of gable even span greenhouse. It was reported that the productivity of tomato was enhanced by 46.67% in the greenhouse due to heating of greenhouse by solar water heater. Teital et al.
(1999) conducted a comparative study of hot water pipe system (diameter 14, 16, 26 and 28mm) with that of hot air distributed via perforated polyethylene ducts (diameter 220mm) in multispan greenhouse 6m width and 22.5m long. Hot water was generated through boiler and hot air. Gupta and Tiwari (2002) developed a computer model based on the transient analysis and compared with that of experimental results. It was observed that thermal energy storage of water mass has a significant effect on the room air temperature. Important applications of water storage systems have been compiled in Table 2.1.

Table 2.1 Summary of the performance of water storage greenhouse systems.

<table>
<thead>
<tr>
<th>Greenhouse area (m²)</th>
<th>Cover material</th>
<th>Storage type</th>
<th>Volume stored (m³)</th>
<th>Cultivation</th>
<th>Results</th>
<th>Ref. Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>72</td>
<td>P.E</td>
<td>Ground tubes</td>
<td>1.5</td>
<td>Strawberries</td>
<td>2-4 °C higher</td>
<td>Montero</td>
</tr>
<tr>
<td>150</td>
<td>P.E</td>
<td>Ground tubes</td>
<td>5.0</td>
<td>Tomatoes</td>
<td>2-4 °C higher</td>
<td>Kyritsis</td>
</tr>
<tr>
<td>231</td>
<td>P.E</td>
<td>Ground tubes</td>
<td>5.4</td>
<td>Plants</td>
<td>2-4 °C higher</td>
<td>Baille</td>
</tr>
<tr>
<td>218</td>
<td>P.E</td>
<td>Ground tubes</td>
<td>4.4</td>
<td>Plants</td>
<td>3 °C higher</td>
<td>Von</td>
</tr>
<tr>
<td>260</td>
<td>P.E</td>
<td>Ground tubes</td>
<td>12</td>
<td>Melons</td>
<td>2.5 °C higher</td>
<td>Esquira</td>
</tr>
<tr>
<td>300</td>
<td>P.E</td>
<td>Ground tubes</td>
<td>15</td>
<td>Melons</td>
<td>2-4 °C higher</td>
<td>Pacheco</td>
</tr>
<tr>
<td>190</td>
<td>Glass</td>
<td>Water barrels</td>
<td>4</td>
<td>Plants</td>
<td>10 °C higher</td>
<td>Mercier</td>
</tr>
<tr>
<td>22</td>
<td>Filon</td>
<td>Water tanks</td>
<td>2.25</td>
<td>Plants</td>
<td>16-22 °C &gt; T_air</td>
<td>Mac</td>
</tr>
<tr>
<td>1000</td>
<td>P.E</td>
<td>Water tanks</td>
<td>40</td>
<td>Roses</td>
<td>11 °C higher</td>
<td>Levav</td>
</tr>
<tr>
<td>12</td>
<td>Glass</td>
<td>Water barrels</td>
<td>3.2</td>
<td>Tomatoes</td>
<td>4 °C higher</td>
<td>Sorensen</td>
</tr>
<tr>
<td>72</td>
<td>Double glass</td>
<td>Water tanks</td>
<td>1.7</td>
<td>Plants</td>
<td>3 °C higher</td>
<td>Fourcy</td>
</tr>
<tr>
<td>30</td>
<td>P. E</td>
<td>Water tanks</td>
<td>1</td>
<td>Plants</td>
<td>2-3 °C higher</td>
<td>Nash</td>
</tr>
<tr>
<td>500</td>
<td>P. E</td>
<td>Water tanks</td>
<td>60</td>
<td>Vegetables</td>
<td>5-6 °C higher</td>
<td>Grafiad</td>
</tr>
<tr>
<td>235</td>
<td>Fiberglass</td>
<td>Water barrels</td>
<td>31</td>
<td>Flowers</td>
<td>75 °C heating</td>
<td>Gowen</td>
</tr>
<tr>
<td>30</td>
<td>Double PVC</td>
<td>Water tanks</td>
<td>6</td>
<td>Tomatoes</td>
<td>2 °C higher</td>
<td>Yiannou</td>
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<tr>
<td>287</td>
<td>P.E.</td>
<td>Ground tubes</td>
<td>25.6</td>
<td>Melons</td>
<td>2-3 °C higher</td>
<td>Farah</td>
</tr>
<tr>
<td>60</td>
<td>Glass</td>
<td>Water barrels</td>
<td>14.2</td>
<td>Flowers</td>
<td>70 °C heating</td>
<td>Mercier</td>
</tr>
<tr>
<td>167</td>
<td>Filon</td>
<td>Water barrels</td>
<td>22</td>
<td>Vegetables</td>
<td>13-22 °C &gt; T_air</td>
<td>Flerking</td>
</tr>
<tr>
<td>500</td>
<td>P. E</td>
<td>Ground tubes</td>
<td>100</td>
<td>Flowers</td>
<td>2-4 °C higher</td>
<td>Grafiad</td>
</tr>
<tr>
<td>300</td>
<td>Polycarbonate</td>
<td>Water tanks</td>
<td>5.8</td>
<td>Cucumber</td>
<td>2-10 °C higher</td>
<td>Campiotti</td>
</tr>
</tbody>
</table>

From Table 2.1, representative average value of water storage used for most commonly used covering materials like glass and polyethylene sheet comes out to be 0.045 m³/m² and 0.0484 m³/m² of greenhouse floor area respectively which is very close to the 0.05 m³/m² as reported by Santamouris (1994). A smaller quantity of water required for glass as a cover material is probably due to higher temperatures available in glasshouses as compared to polyethylene covered houses which produce lower greenhouse effect as compared to glass houses. Similarly, representative value of volume of water storage in ground tubes and in water tank/barrels comes out to be 0.032m³/m² and 0.048m³/m² respectively. The smaller value of water requirement per unit area of greenhouse for ground tubes indicates the greater efficiency of heat storage utilization for ground tubes as compared...
to water tanks and water barrels. The storage volume which is needed to satisfy the specific heating needs of a greenhouse will also depend on the latitude of the installation. Overall, for polyethylene cover greenhouses using ground tubes an average value of about 0.049 m³/m² of ground surface area should provide a satisfactory coverage of the heating requirements for most of the locations. Solar greenhouses using water storage with ground tubes can result in inside air temperature 2-5 °C higher than the minimum outdoor air temperature and can satisfy 70-75% of the annual heating needs of the greenhouses. The information from Table 2.1 is used to develop a general relationship between greenhouse area and volume of water stored. Best line of curve fit (as shown in Fig. 2.3) to predict the water storage volume for given greenhouse area along with $R^2$ as 0.611 and coefficient of correlation as 0.781.

$$Y = 0.1324X - 9.6296$$

Where $X$ is greenhouse area and $Y$ is volume of water stored

Different water storage media like ground tubes, water tanks and water barrels have been separately shown in Fig. 2.4 just to have the idea of which storage medium is the best suited for water storage. It is observed that the best line of curve fit for greenhouse area versus ground tubes is best suited for water storage ($R^2 = 0.78$, coeff. of correlation = 0.92) followed by water tanks ($R^2 = 0.75$, coeff. of correlation = 0.87) and then water barrels ($R^2 = 0.178$, coeff. of correlation = 0.28). The reason for low correlation coefficient is that the collected data was recorded by different authors at different locations using different size greenhouses and considering different parameters. Moreover the number of data collected is also low.

![Fig. 2.3 Relationship between greenhouse area and water storage volume](image-url)
2.2.1.2 Rock bed thermal storage systems

The amount of heat storage ‘Qa’ in the rock bed through direct gain of solar energy is;

\[ Q_a = m_b C_r \Delta T \]  \hspace{1cm} (2.4)

Energy balance on the bed material and air (Fig. 2.5) is given by (Hamdan, 1996);

\[ \varepsilon \rho_f C_f \frac{\partial T_f}{\partial t} + \frac{4m_a C_f \partial T_f}{\pi D^2 \partial x} = h_v (T_s - T_f) \] \hspace{1cm} (2.5)

\[ h_v = 650 \text{ (G/d)}^{0.7} \] \hspace{1cm} (2.6)

\( \rho_f, \rho_s, T_f \) & \( T_s \) are densities and temperatures of the fluid and solid respectively.

For sensible heat storage with air as the energy transport mechanism, rock, pebble and gravel in a bin has the advantage of providing a large, cheap heat transfer surface. Its thermal capacity however, is only about half that of water and the bin volume will be about 3 times the volume of a water tank that is heated over the same temperature interval Rai (1997).

Though water is superior because of its lower material cost and lower volume required per unit of energy stored, a well designed packed rock bed has some characteristics that are
desirable for solar applications as rock acts as its own heat exchanger, which reduces total system cost. The heat transfer coefficient between the air and solid is high.

The conductivity of bed is low when air flow is not present. Air is generally used as the heat transport fluid at low temperatures. The large surface area of rocks and the tortuous air flow passage through the bed ensures good heat transfer to/from air by direct contact. However, heat flow from the pebble bed (when there is no air flow) by conduction is very low as rocks have only a small surface contact with surrounding rocks and the air present in the voids being stagnant is a poor conductor of heat. Therefore, not much insulation is required around the storage. Large pebble bed storages are conveniently placed under ground as shown in Fig. 2.6. The pressure drop between the upper and lower plenum (i.e. the space filled with matter) must be sufficient to ensure uniform distribution of air flow in the rock bed so that much of the thermal storage capacity of the rock bed may be used. A popular and economical heat storage material is a rock bed, which consists of 20-100 mm diameter gravel. The storage area is placed under or near the greenhouse at a depth varying between 40 and 50...
cm. The gravel can be enclosed in an insulated concrete storage enclosure. During the day, excess heat is transferred from inside the greenhouse to the underground store. A ventilator can be used to transport the greenhouse air to heat the storage area. At night, the process is reversed. The cool air from the greenhouse is moved through the rock storage volume, where heat is transferred from the gravel to the colder air and then returned to the greenhouse.

![Diagram of a greenhouse with rock-bed storage](image)

**Fig. 2.6 Greenhouse with rock-bed storage**

Some important applications using the rock bed heat storage system for the thermal control of greenhouses have been discussed here. Mazria & Baker (1981) designed an experimental greenhouse coupled with 13 tons of gravel. The system maintained a mean interior air temperature of 10-20 °C. Eggers (1983) used a rock bed storage placed underground. A 14 kW heat pump was also used as a back-up system. The system satisfied 20% of the annual heating needs. Fotiades (1987) describes a 300 m² double inflated P.E. cover greenhouse utilizing rock bed heat storage with a total volume of 40 m³. The air is circulated using a 1.7 kW fan, through insulated ducts, with the aid of direction giving shutters. The system can provide 76% of the annual heating needs of the greenhouse. A 432 m² glass covered greenhouse, described by Jelinkova (1987) is coupled to an underground concrete bed which is filled with gravel and concrete tubes are laid. A ventilator transported air from inside the greenhouse into the storage at a rate of 40 m³/hr to the loaded accumulator where it transfers its heat to the gravel. During the night the process is reversed. To regulate the air temperature and humidity, a wet pad is used. There is an option to mix the circulating air from the storage with the outdoor air. There is no available information on the performance of the system.
A different system was designed by Bredenbeck (1987) for a 1700 m² greenhouse which is covered with a triple layer poly-carbonate sheet and a thermal screen close to the top of the greenhouse. The storage consists of 5-15 cm gravel. The storage area was divided into 11 chambers, 3.25 m long and 40 m wide. The air is circulated through 0.6 m diameter concrete pipes. The total air flow of 60000 m³/hr was created by 12 fans which forced the air through the storage. The system satisfied 30% of the annual heating needs of the greenhouse.

Bouhdgar (1990) described a 240 m² P.E. greenhouse which was coupled to a 10.6 m³ rock bed, containing 50-100 mm gravel. The system could achieve an increase of 4-6 °C temperature and a decrease of 10-15% relative humidity. Bricault (1982) designed a 2850 m² P.E. covered greenhouse which utilized a rock bed storage area located at a depth of 0.4m and filled with 202 tons of 40 mm gravel. The system could satisfy 40% of the annual heating needs of the greenhouse. Bricks were also been used as the heat storage medium in an application for a 100 m² P.E. covered greenhouse described by Kavin and Kurtan (1987). Air was circulated at the rate of 5500m³/hr through the 48 tons of brick storage area. However, the system was able to retrieve only 53% of the stored energy for heating the greenhouse air.

Deforche (1990) described a group of four greenhouse modules, totaling 1000 m², which were coupled with pebble bed storage. The system included an air collecting system at the ridge of each greenhouse (9.15 x 23.1m) with two air conditioning ducts placed above the screens. The upper part was painted black, while the lower part was insulated. The air distribution system consisted of two perforated ducts which are placed along the side walls at ground level. The pebble bed is located at an adjacent area, above ground. Each module was connected with a storage unit of 40m³. Vinyals (1990) describes a 500 m² greenhouse which is designed with an asymmetric roof having a large south facing area. This greenhouse used a pebble bed for heat storage. Ozturk (2003) used volcanic material with the sensible heat technique for heating the tunnel greenhouse of 120 m². The external heat collection unit consisted of 27 m² of south-facing solar air heaters mounted at a 55° tilt angle. The dimensions of the packed-bed heat storage unit were 6 x 2 x 0.6 m deep. The packed-bed heat storage unit was built under the soil at the centre of the tunnel greenhouse. The heat storage unit volume per square metre of ground surface of the tunnel greenhouse was 0.6 m³, while the storage volume per square metre of the heat collection unit was about 0.7 m³. The heat storage unit was filled with 6480 kg of volcanic material equivalent to 54 kg of heat storage material per square metre of the greenhouse ground surface. Energy and exergy analyses were applied in order to evaluate the system efficiency. The results showed that 18.9% of the total heating requirement of the tunnel greenhouse was obtained from the heat storage unit.
Chen and Liu (2004) conducted the numerical and experimental analysis of convection heat transfer in passive solar heating room with greenhouse and rock bed storage. It was informed that the thermal insulation of solar heating room has significant effects on temperature distribution and airflow in the heating chamber of this solar system.

Heat transfer and air flow in a rock bed, which is used as solar absorber and storage layer, are also studied. If porosity is kept within certain range, increasing the rock size causes an increase of the capability of thermal storage and heating effects; increasing the porosity of thermal storage materials results in an increase of the bed temperature but a decrease of the rock mass. The specific heat capacity and thermal conductivity have a remarkable effect on the average temperature of rock bed. Available data shows that these systems can satisfy 20-70% of the annual heating needs with inside temperature ranging from 4-10 °C higher than the minimum ambient air temperature. Some representative applications from the above mentioned information are compiled and arranged in Table 2.2.

Information collected and presented in Table 2.2 shows that the most commonly used rock bed materials are gravel and pebble which consists of 20-100 mm diameter & the most commonly used greenhouse cover material is polyethylene. The storage area is placed under or near the greenhouse at a depth varying between 40 and 50 cm. It is also observed that an average value of the weight of rock used is 340 kg per m² of the greenhouse floor area which can be used as a thumb rule for future applications of rock bed heat storage. It can also be concluded that polyethylene sheet as a cover material is a better option for the researchers as compared to glass. Gravel and pebble as a heat storage media are also preferred as compared to bricks. Empirical relation for relating the weight of rock required versus the greenhouse area is shown in Fig. 2.7 with a coefficient of correlation over 0.9. Where ‘X’ is greenhouse area and ‘Y’ is weight of rock in tons.

\[ Y = 0.064X + 34.526 \]
Phase change materials

Latent heat storage using phase change material (PCM) for greenhouse heating (Fig. 2.8), in general provides much higher energy storage density than systems using sensible heat storage. In a heat storage cycle, PCM can store large amounts of heat in the change of phase from solid to liquid (latent heat of fusion) at a constant temperature corresponding to the phase transition temperature. In heat dissipation cycle a circulating fluid air or water can
extract heat from the storage unit causing the phase change material to solidify Lane (1983). Kern and Aldrich (1979) indicated that a phase change energy storage system using calcium chloride hexa hydrate (CaCl₂ · 6H₂O) also called as chliarolithe worked satisfactorily as a thermal storage unit and that it would provide a desirable alternative to rock bed storage. Abhat (1983) studied low temperature PCMs in the temperature range 0-120 °C and investigated their melting and freezing behaviours. The most studied PCM include Glauber’s salt, which melts at 32.4 °C, a compound of sodium thiosulfate penta-hydrate, which melts at 56 °C and CaCl₂ · 6H₂O, which melts at 29.7 °C.

A system utilizing heat storage with 13.5 tons of CaCl₂·6H₂O, placed in 9000 underground bags of 1.5 kg each, was used to heat a 5000 m² glass cover greenhouse by Jaffrin and Cadier (1982). The thermal performance of the system was satisfactory, providing for 75% of the greenhouse heating needs. In a similar system described by Balducci (1985) 2800 kg of underground stored chliarolithe material was used in a glass cover greenhouse with a 200 m² ground surface.

![Fig. 2.8 Passive solar greenhouse with phase change material](image)

This system satisfied 22% of the annual thermal needs of the greenhouse. In another installation described by Boulard (1987) the system was used for a 176 m² polycarbonate double skin experimental greenhouse equipped with a forced ventilation system. CaCl₂·6H₂O was packed in specially designed PVC containers. The design allowed for air flow with a small pressure drop and high exchange surface ratio (0.4 m²/kg of chliarolithe). The system used 990 containers of 3 kg each, with a total storage capacity of 0.6 kWh/m². The containers were located inside a 7 m³ metal frame stand. In a greenhouse described by Groves (1984),
3000 kg of latent heat material was placed in two heat exchangers inside a 200 m² greenhouse. Brandstetter (1987) used 100 kg of calcium chloride hexa-hydrate in a glass-covered 20 m² small experimental greenhouse. Huang et al. (1982) described a 100 m² fiberglass greenhouse which utilized 46 bars of chiliarolithe. The length of each bar was 1.83 m. These bars were placed underground. Melting temperature and latent heat of the material used was 29 °C and 191 kJ/kg. Using the PCM, interior air temperature was maintained 2 °C higher than the minimum outdoor air temperature. Yiannou is (1990) used a combination of chiliarolithe and acetic acid (melting points are 29 °C and 15 °C, respectively) integrated into the north wall of a polyethylene-covered 4 m² greenhouse. The system utilized 32 kg of material. The combination of these materials allowed for the construction of a storage system which could control the maximum and minimum air temperature peaks in the greenhouse during the day. During the winter, inside air temperature was 2-3 °C higher than the temperature of an unheated greenhouse. A different latent heat material, composed of Sodium hydroxide (NaOH) solution and Cr₂N (melting point 15.6°C), was used at a 445 m² experimental glass greenhouse described by Paris (1981). The material was stored in 21 containers. The heat storage produced a minimum air temperature of 8 °C inside the greenhouse. Kimura and Kai (1984) showed that by adding NaCl, the stability of chiliarolithe can be improved if it contains slightly more water than the stoichiometric composition. The salt was found to be very stable following more than 1000 heating-cooling cycles. Machida et al. (1985) selected latent heat material composed of (0.45 Na₂SO₄ ·10 H₂O/0.45 Na₂CO₃ ·10 H₂O/0.1 NaCl) with a total weight of 2500 kg, which was used in a 352 m² experimental greenhouse. The phase temperature of the material is 24 °C and the heat released during the phase change is 167.5kJ/kg. During the monitoring of the system, the inside temperature was maintained 8 °C higher than the minimum outdoor air temperature. The mean temperature during the night was 9.5 °C.

Ghonium (1989) found the effect of PCM properties on the performance of solar air based heating systems. He investigated the effect of melting temperature and latent heat for different storage masses on solar system performance for different ratios of incident solar energy on heating load. The performance of solar heating systems utilizing industrial grade and pure paraffin were also investigated. A computer model was used to study the performance of an electrical storage heater that stores PCM (Paraffin wax) by Farid and Hussain (1990). It included the effect of natural convection in the melt phase. Results indicated that 30-50% of the heat transfer resistance was lying in the flowing air. Bansal and
Buddhi (1992) found the performance equations of a collector cum storage system using PCM (Stearic acid) for quasi-static-state conditions. Performance equations using Hottel-Whillier-Bliss type for flat plate collector cum storage system were obtained. Calculations were also performed for a wide range of parameters to investigate the applicability of the developed mathematical model. Sari and Kaygusuz (2001) also used a thermal energy storage system using stearic acid as phase change material. Lacroix (1993) developed a theoretical model to predict the transient behavior of a shell-and-tube storage unit with the PCM on the shell side and the heat transfer fluid (HTF) circulating inside the tubes. The multidimensional phase change problem was tackled using an enthalpy-based method. Results showed that the shell radius, the mass flow rate and the inlet temperature of the HTF must be chosen carefully in order to optimize the performance of the unit. Hamdan and Elwerr (1996) theoretically investigated a two-dimensional melting process of a solid PCM (n-octadecane). In this study the convection mode was considered to be the dominant mode of heat transfer with in the melted region except with in the region very close to the solid surface at the bottom where conduction mode was only taken into consideration. The analysis was also used to predict the melted fraction of the PCM and hence the amount of stored energy. Ismail and Goncalves (1999) studied the thermal performance of a phase change material based on two dimensional heat transfer problem around a tube. Zivkovic and Fujii (2001) conducted an analysis of isothermal PCM with in rectangular and cylindrical containers. Hamada et al. (2003) found the effect of additives on the heat transfer rates of PCM around heat transfer tubes. Sari and Kaygusuz (2002) used a eutectic mixture of lauric and stearic acid as PCM encapsulated in the annulus of two concentric pipes. Due to higher melting point of stearic acid and lauric acid and its eutectic mixture as compared to chlialolithe (CaCl₂·6H₂O) their utility is limited for greenhouse applications. Farid (2004) conducted a review on different compounds of phase change materials and described the efforts to develop new classes of materials with focus on PCM materials, encapsulation and applications. Thermo physical properties of important PCM compounds have been shown in Table 2.3 (a). He also endorsed the views of Lane (1980) and Abhat (1983) that chlialolithe (CaCl₂·6H₂O) still has a great potential for PCM storage. Representative applications of the above discussed information is compiled and arranged in Table 2.3(b). The best lines of curve fit to predict the weight of PCM (CaCl₂·6H₂O) storage required for given area of greenhouse (Fig. 2.9) is computed with coefficient of correlation as 0.99 and R² as 0.9808 is given as under;

\[
Y = 15.696X - 97.093
\]

where \(X\) is greenhouse floor area in m², \(Y\) is weight of PCM (CaCl₂·6H₂O) required in kg.
The derived relation in Eqn 2.8 shows an excellent relationship between the greenhouse area and weight of CaCl₂ · 6H₂O used. The developed empirical relation can be a tool to provide an approximate requirement of weight of CaCl₂ · 6H₂O for the selected greenhouse area. Solar greenhouses using latent heat storage (PCM) can result in inside air temperature 2-8 °C higher than the minimum outdoor air temperature. Based on the available information compiled from the literature it appears that the most common latent heat material used appears to be calcium chloride hexa-hydrate (CaCl₂ · 6H₂O), which melts at 29.7 °C. The representative value of (calcium chloride hexa-hydrate) the storage mass is approximately 9 kg per m² of the greenhouse surface area.

The use of CaCl₂ · 6H₂O can satisfy 30-75% of the annual heating needs. The energy storage density is over 10 times larger than this value. Therefore, the CaCl₂ · 6H₂O system will require only 1/10 of the storage volume needed by the rock-bed storage system. Based on the current prices of CaCl₂ · 6H₂O and gravel, the CaCl₂ · 6H₂O system will cost about four times more than gravel system to store the same amount of energy. However, the rock-bed storage system requires about 10 times larger container and associated labor and material costs. On the other hand, the utilization of space gained by the reduction in storage space may well justify the use of CaCl₂ · 6H₂O storage system. The type of cover material also influences the thermal performance of the greenhouse. Plastic greenhouses have higher heating requirements, since they exhibit higher thermal losses during the night.

Table 2.3 (a) Thermo physical properties of some important PCMs (Farid, 2004).

<table>
<thead>
<tr>
<th>Compound</th>
<th>Freezing/Melting temp. Range (°C)</th>
<th>Heat of fusion (kJ/g)</th>
<th>Thermal conductivity (W/mK)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Paraffin compounds</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paraffin 5913</td>
<td>22-24</td>
<td>189 00</td>
<td>0.21 (solid phase)</td>
</tr>
<tr>
<td>Octadecane</td>
<td>28.00</td>
<td>244 00</td>
<td>0.15 (solid phase)</td>
</tr>
<tr>
<td>Paraffin 6106</td>
<td>42-44</td>
<td>189 00</td>
<td>0.21 (solid phase)</td>
</tr>
<tr>
<td><strong>Organic compounds</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Caprilc acid</td>
<td>16.50</td>
<td>148 50</td>
<td>0.148 (20.0 °C)</td>
</tr>
<tr>
<td>Polyglycol E 600</td>
<td>22.00</td>
<td>127 20</td>
<td>0.189 (38.6 °C)</td>
</tr>
<tr>
<td>Capric acid</td>
<td>32.00</td>
<td>152 70</td>
<td>0.153 (38.6 °C)</td>
</tr>
<tr>
<td>Lauric acid</td>
<td>42-44</td>
<td>178 00</td>
<td>0.147 (50.0 °C)</td>
</tr>
<tr>
<td>Palmitic acid</td>
<td>63.00</td>
<td>187 00</td>
<td>0.165 (70.0 °C)</td>
</tr>
<tr>
<td>Stearic acid</td>
<td>70.00</td>
<td>203 00</td>
<td>0.172 (70.0 °C)</td>
</tr>
<tr>
<td><strong>Inorganic compounds</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KF 4H₂O</td>
<td>18.50</td>
<td>231 00</td>
<td>-</td>
</tr>
</tbody>
</table>
### Table 2.3(b) Summary of greenhouse performance using different phase change materials.

<table>
<thead>
<tr>
<th>Greenhouse area (m²)</th>
<th>Cover material</th>
<th>Cultivation</th>
<th>Storage medium of PCM</th>
<th>Quantity of PCM (kg)</th>
<th>Remarks</th>
<th>Ref. Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>445 Glass Plants</td>
<td>NaOH + Cr₂N</td>
<td>-</td>
<td>Gain of 500 l oil</td>
<td>-</td>
<td>-</td>
<td>Paris</td>
</tr>
<tr>
<td>176 Poly-carbonate</td>
<td>Tomatoes</td>
<td>CaCl₂ 6H₂O</td>
<td>3000</td>
<td>30% cover</td>
<td>Brandstetter</td>
<td>Boulard</td>
</tr>
<tr>
<td>20 Glass Plants</td>
<td>CaCl₂ 6H₂O</td>
<td>100</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Groves</td>
</tr>
<tr>
<td>200 Glass Roses</td>
<td>CaCl₂ 6H₂O</td>
<td>3000</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Groves</td>
</tr>
<tr>
<td>5000 Glass Roses</td>
<td>CaCl₂ 6H₂O</td>
<td>13500</td>
<td>75% cover</td>
<td>-</td>
<td>-</td>
<td>Jaffrin</td>
</tr>
<tr>
<td>500 Glass Roses</td>
<td>CaCl₂ 6H₂O</td>
<td>-</td>
<td>51% cover</td>
<td>-</td>
<td>-</td>
<td>Jaffrin</td>
</tr>
<tr>
<td>100 Fiberglass Plants</td>
<td>CaCl₂ 6H₂O</td>
<td>-</td>
<td>2 °C ↑</td>
<td>-</td>
<td>-</td>
<td>Huang</td>
</tr>
<tr>
<td>4 PE Plants</td>
<td>CaCl₂ 6H₂O + Acetic acid</td>
<td>32</td>
<td>2-3°C ↑</td>
<td>-</td>
<td>-</td>
<td>Yoshioka</td>
</tr>
<tr>
<td>200 Glass Flowers</td>
<td>CaCl₂ 6H₂O</td>
<td>2800</td>
<td>22% cover</td>
<td>-</td>
<td>-</td>
<td>Balducci</td>
</tr>
<tr>
<td>352 Glass Tomatoes</td>
<td>0.45 Na₂SO₄ 10H₂O/45Na₂CO₃ 10H₂O/1NaCl</td>
<td>2500</td>
<td>8 °C ↑</td>
<td>-</td>
<td>-</td>
<td>Machida</td>
</tr>
</tbody>
</table>
2.2.1.4 Ground air collector

Ground air collector is based on the principle of solar flat plate collector as shown in Fig. 2.10a and b. The difference between ground air collector and flat plate collector is that the former is installed in the sub surface of ground where as the latter is a portable device. Solar radiation transmitted through the glazing of ground air collector is absorbed by the blackened sand bed. The absorbed radiation heats up the sand bed and conducts the absorbed heat into the conduit pipe embedded in it. When air is circulated in the pipe, it is heated up and the hot air enters into the greenhouse at the outlet of pipe. The inlet end of the pipe sucks the cool air of the greenhouse and outlet end admits the hot air to the greenhouse enclosure for thermal heating during winter months. Barok and Aldrick (1984) developed a flat plated solar collector to heat the greenhouse irrigation water. It was made of sand mix concrete absorber plate with a vinyl hose embedded in serpentine shape. In this system, the temperature of outlet water was increased to 8 °C compared to inlet water temperature.
Fig. 2.10 (a) Front view of ground air collector

Fig. 2.10 (b) Isometric view of ground air collector
Kurata and Takakura (1991) investigated the possibility of solar energy storage in a soil layer under a greenhouse for heating it in winter. Bargach et al. (2000) conducted the experiment on an installation of solar flat plate collector used for heating a tunnel greenhouse. The water temperature at inlet and outlet end were 20 °C and 40 °C respectively during the month of January. Jain and Tiwari (2003) developed a mathematical model to study the thermal behavior of a greenhouse while heating with a ground air collector (GAC). A computer program based on MatLab software has been used to predict the plant and room temperatures as a function of various design parameters of the ground air collector. Experiments conducted during winter months for an even span greenhouse of effective floor area of 24 m² with a GAC and having a brick north wall. The model was validated experimentally in the climate of Delhi for the winter season. A parametric study involves the area of the GAC, mass flow rate and heat capacity. The predicted plant and room temperatures show fair agreement with the experimental values.

2.2.1.5 North wall

If the north wall of the greenhouse is composed of thick thermal mass, made of brick or cement blocks filled with concrete, then the transmitted solar radiation through the glazed north wall can be checked and be retained in the greenhouse for use in photosynthesis and for increasing temperature (Fig. 2.11). The concept of opaque north wall is commonly employed for east-west oriented greenhouse in northern hemisphere. Because in east-west oriented greenhouse, maximum solar radiation falls on the south wall during winter months and leaves greenhouse through north wall due to low altitude angle of the sun. North wall is therefore insulated and painted black internally for thermal storage. During day time the incident solar radiation impinges on the wall and significantly raises its thermal storage. This stored energy is released during winter night for thermal heating inside the greenhouse. Santamouris et al. (1994) tested the performance of north wall and reported that the temperature inside the greenhouse were 10 °C higher than ambient temperature. Singh and Tiwari (2000) reported that there is a significant effect of thermal storage from the north wall on the plant and room air temperature. Thermal load leveling (reducing fluctuations between the maximum and minimum temperatures) decreases with increasing its isothermal mass in the case of heating and vice-versa.
2.2.1.6 Movable insulation/thermal screens

Movable insulations are usually night curtains or thermal screens, which are drawn inside or outside the greenhouse cover during night time in winter months to reduce heat losses to ambient resulting in the conservation of energy in the greenhouse. These movable insulations are uncovered during daytime in order to allow solar radiation to enter into the greenhouse for thermal heating. Huang (1976) conducted a theoretical analysis of internal and external covers for greenhouse heat conservation. The analysis indicated that heat savings (30%) by the use of an internal shade as well as external shade will be same on clear or cloudy nights, with the main effect resulting from lower convective losses. Measurements by Dawson and Winspear (1976) showed that at a typical wind speed of 2 m/s, the reduction in heat loss achieved with thermal screens range from 35% using black polyethylene to 58% with aluminized plastics film. It was also reported that thermal screens influence heat transferred by convection and radiation and the transfer of latent heat. Simpkins et al. (1976) experimentally evaluated a number of curtain materials and installation techniques for their heat conservation capacity. The authors estimated that half of the energy needed to heat a double layer; inflated, multispan polyethylene greenhouse could be saved by using a highly reflective internal curtain. The authors also suggested that the side of the curtain with maximum reflectivity should face outside for internal curtains, and inside for external curtains. Rebuck (1977) observed savings up to 60% with a commercially available night curtain material viz. Foylon XA-2425, an aluminum foil hybrid fabric. The aluminized side faced inside. Albright et al. (1978) tested a highly insulated night curtain with both sides
reflective. Their greenhouse had 40 tons of crushed rock under benches for storage of solar energy. During night the night curtain enclosed the heated rocks and the plants grown on the benches with less than a meter clearance above plant height. During two weeks of testing it was observed that the heating requirements reduced by 90%. Chandra and Albright (1980) developed an analytical procedure, using energy balance principles to estimate the energy conserving potential of night curtains used in greenhouses. Bailey (1981) used aluminized polyethylene sheet in a glass house at night to reduce the loss of heat. The reduction of heat was between 35 and 60%. Garzoli and Blackwell (1981) studied the effect of movable insulation that could check the exchange of long infrared radiation, emitted by the roofing material with sky during cold night.

In a very important experimental study by Grange and Hurd (1983), the microclimate and yield of an early tomato crop were studied in a glasshouse fitted with a thermal screen by which could be pulled over the crop each night to save energy. The screen was made of aluminized polyester material, slightly permeable to air, and it gave an estimated saving of 31% of the "unscreened" energy costs. The parked screen caused a radiation loss of 3–5% during the day. At night, the humidity under the screen was slightly higher than in the unscreened control, depending on outside temperature, but there was little difference in leaf-air temperatures between the plants of the two treatments. One important effect of the screen was the lower heat input, which reduced the convective distribution of heat. A vertical thermal gradient developed such that young plants were 2°C colder than those in an unscreened house set to the same temperature, based on temperature-control sensors in an aspirated screen 1.5 m from the ground. Under the screen, fruiting was slightly delayed compared with the unscreened crop, possibly due to the temperature differences referred to above. Final yields were slightly higher from the screened house, but the trial was not replicated, and because of the temperature differences, the crops were not strictly comparable.

Fig. 2.12 (i) shows a thermal screen system. In this case, one screen is covering the roof surface facing south as well as roof surface facing north. It covers from span to span. The shading percent is 65%. If thermal screen is dense, the ventilation is poor. A shading thermal screen only on the south side gives an effective protection against direct radiation as well as good ventilation as shown in Fig. 2.12 (ii). An acrylic plate on the north side instead of a single layer of glass means a reduction of the energy consumption of about 33 percent. A two-port system as shown in Fig. 2.12 (iii) gives an effective protection against radiation. In addition to this advantage, it is possible to make use of the sky radiation cooling on the north.
roof surface. Effective ventilation is also possible in such arrangement. Another two port system as shown in Fig. 2.12(iv) is used for winter condition. In this case, energy consumption is reduced and light radiation is reflected from screen facing north at low altitude.

![Fig. 2.12 Experimental greenhouse with thermal screen](image)

Zhang et al. (1996) examined the effect of covering materials on energy consumption and greenhouse microclimate. Single glass (GL) and three types of double polyethylene (PE) claddings were compared. The double polyethylene cladding consisting of an anti-fog thermal film for the inner layer and a standard PE film for the outer layer was the most energy efficient. It was observed that the use of thermal screens in the PE houses during the night reduced heat loss rates by 23–24%. The use of a thermal screen in a double PE houses caused only a slight increase in greenhouse humidity. Cohen and Fuchs, (1999) studied radiometric properties of reflective shade nets and thermal screens as screen materials are being used extensively in agriculture for conserving energy by reducing night radiant heat loss, and for reducing solar heat load by day. Barrel et al. (1999) tested the performance of
integrated thermal improvements of thermal improvements of thermal curtains as well as thermal blankets and reported that these movable insulations were proved to be very efficient to provide the required temperature levels for healthy growth of tomatoes and peppers during winter period. Plaza et al. (1999) also reported that the energy in the greenhouse could be saved up to about 20% by the use of thermal insulation. Ghosal and Tiwari (2004) developed a thermal model for heating of a greenhouse by using inner thermal curtain and natural flow of geothermal warm water through the P. E. tubes laid on its floor and was experimentally validated. From the results, it was observed that the temperature of air surrounding the plant mass (plants under thermal blanket) was maintained in the range of 14-23 °C during winter night and early morning which is about 8-12 °C above ambient during night time.

The review shows that movable insulation/thermal screens can save 30 -65% of the heating requirements of the greenhouse and are capable of keeping the inside air temperature higher by about 4-5 °C.

2.2.2 Greenhouse Cooling Technologies

2.2.2.1 Natural ventilation

Natural ventilation is based on the difference in pressure, which the outside wind or the greenhouse temperature creates, between the greenhouse and the outside environment. If the greenhouse is equipped with ventilation openings, both near the ground and at the roof, then this type of ventilation replaces the internal hot air by external cooler one during the hot sunny days with weak wind. The external cool air enters the greenhouse through the lower side openings while the hot internal air exits through the roof openings due to density difference between air masses of different temperature causing the lowering of temperature in the greenhouse. Tiwari, 1998 described the natural ventilation in the form of an equation with the provision of two openings having an effective area of $A_v$ made on the south and north sides of the roof. The rate of heat loss by natural convection due to buoyancy force is given by Eqn 2.9.

$$Q_{loss} = C_d A_v \sqrt{2 \frac{\Delta P}{\rho_a \Delta T}}$$  \hspace{1cm} 2.9

where

- $C_d =$ Coefficient of diffusion,
- $P =$ Partial pressure (N/m$^2$) at temperature $T$
- $A_v =$ Area of vent (m$^2$)
- $\rho_a =$ Density of air (kg/m$^3$)
- $\Delta P =$ $P(T_i) - \gamma P(T_a)$
Bot (1983) observed that ventilation due to temperature effects is of importance only at low wind speeds (normally < 2m/s). Bruce (1978, 1982) developed a theory in which a neutral plane is defined at a height that the thermally induced pressure difference on both sides of the opening is zero. This theory was experimentally verified by Down et al. (1990) using half scale models. They concluded that when the neutral plane is above the side openings of the building the theory can predict the ventilation rate satisfactorily. Based on a similitude analysis Timmons and Baughman (1981) defined the conditions for the use of scale models without introducing distortion. An alternative method of studying natural ventilation by thermal effects was presented by Linden and Simpson (1985) and Lane-Serff (1989). They simulated the phenomenon in the laboratory in scale models of some public buildings using water as the working fluid and added a salt solution to produce density differences. Oca (1999) also developed a laboratory method for the physical simulation of natural ventilation by thermal effects in greenhouses. A solution of salty water and black dye was injected to produce density differences that simulated the buoyancy flux due to the heating of the greenhouse air.

Teitel and Tanny (1999) theoretically and experimentally studied the transient response of the greenhouse air temperature and humidity, to the opening of roof windows. A theoretical model, based on non-dimensional mass and energy conservation equations was developed and similarity solutions were obtained. The model was calibrated against the results of experiments conducted in a full-scale greenhouse and the model parameters were identified. The study shows that opening the roof windows results in a decrease with time of the air temperature and humidity ratio and an approach to a steady-state. The effect of various physical parameters such as height of window opening, wind speed and solar radiation on the ventilation process, was studied by the model. The results show that the effect of the ventilation (i.e. the reduction in the temperature and humidity ratio within the greenhouse) increases with the height of the window opening and the wind speed, and decreases with the solar radiation. Bartzanas et al. (2004) numerically investigated the effect of ventilation configuration of a tunnel greenhouse with crop on airflow and temperature patterns using a commercial computational fluid dynamics (CFD) code. The numerical model was firstly validated against experimental data collected in a tunnel greenhouse identical with the one used in simulations. The airflow patterns were measured and collected using a three-dimensional sonic anemometer and the greenhouse ventilation rate was deduced using a tracer gas technique. A good qualitative and quantitative agreement was found between the numerical results and the experimental measurements. After its validation, the CFD model
was used to study the consequences of four different ventilator configurations on the natural ventilation system. The ventilation configuration affects the ventilation rate of the greenhouse and the airflow and air temperature distributions as well. For the different configurations, computed ventilation rates varied from 10 to 58 air changes per hour for an outside wind speed of 3 m s\(^{-1}\) and for a wind direction perpendicular to the openings. Likewise, the simulations highlight that while the mean air temperature at the middle of the tunnels varied from 28.2 to 29.8°C, for an outside air temperature of 28°C, there are regions inside tunnels 6°C warmer than outside air. Average air velocity in the crop cover varied according to the arrangement of the vents from 0.2 to 0.7 m s\(^{-1}\). The consequences of the marked climate heterogeneity on plant activity through the variation of crop aerodynamic resistance as well as the influence of the vent configurations on the efficiencies of ventilation on flow rate and air temperature differences between inside and outside, are also discussed.

Parra et al. (2004) studied the greenhouses to characterize the natural ventilation. An 882 m\(^2\), five span, polyethylene film covered greenhouse was fitted with either a rolling or a flap ventilator attached to one side of each ridge and rolling ventilators in two 38 m sidewalls. Ventilation rates for different configurations of the ventilators were measured using the dynamic tracer-gas method (decay rate method), with nitrous oxide (N\(_2\)O) as the tracer gas. With roof ventilators, the highest ventilation rates per unit ventilator area were obtained when flap ventilators faced the wind (100%), followed by flap ventilators facing away from the wind (67%). The lowest rates of roof ventilation were obtained with the rolling ventilators (28%); in this case the ventilation rate was independent of wind direction. The ventilation rates per unit area of rolling ventilator were highest for sidewall ventilation (42%), followed by roof and sidewall ventilation (37%). With the flap ventilators there was a non-linear increase in ventilation with increasing ventilator angle. The global wind pressure coefficient was found to be ventilation system dependent. Theoretical predictions of natural ventilation agreed well with the measured values for roof ventilation with root mean square and mean deviations of less than 1.2 m\(^3\)/s and ±2%, respectively. However, agreement was less good for sidewall and roof with sidewall ventilation. Theory showed that the stack effect made a significant contribution to sidewall and roof with sidewall ventilation. A deficiency in the method of estimating the stack effect was identified that result in its failure for ventilators in horizontal roofs. Measurements showed that an insect screen with a porosity of 0.39 under the rolling ventilator in the roof, gave a 35% reduction in the ventilation rate. Using this result together with published data, it was shown that the ratio of the ventilation rate with a
screen to the value obtained with the same ventilator without a screen could be represented by the quantity $\varepsilon(2-\varepsilon)$ where $\varepsilon$ is the screen porosity.

Shilo et al. (2004) studied Air-flow patterns and heat fluxes in roof-ventilated multi-span greenhouse with insect-proof screens. Experiments were performed in a semi-commercial, roof-ventilated, four-span greenhouse with insect-proof screens over its openings, to determine the air-flow patterns, heat fluxes and ventilation rates. The ventilation rate in leeward ventilation increased with wind velocity. A comparison between ventilation rates measured by the tracer gas and energy-balance methods showed good correlation between the two. An indication of the influence of outside wind direction on the ventilation rates and air-flow patterns was observed. The direction of air flow within the greenhouse at plant level was nearly opposite to that of the external wind. Both the mean and turbulent latent heat fluxes through the roof openings were much larger than the sensible heat fluxes. Both the sensible and latent turbulent heat fluxes had high values when the roof openings were opened, and then decayed with time. Their directions at the level of the openings were from the greenhouse towards the outside and at plant level they generally followed the direction of the ambient wind.

On the whole, the static ventilation systems are generally less efficient and are not satisfactory in sunny days without wind as described by Verlodt et al. (1984) and Silva and Rosa (1985). Total ventilator area equivalent to 15-30% of floor area is recommended by White (1975). Above 30% the effect of additional ventilation area on the temperature difference is very small.

2.2.2.2 Forced ventilation

Infiltration refers to admittance of outside air through door and / or ventilator openings & cracks and interstices around the door and ventilators, into the planning space. Convective heat transfer (loss) due to ventilation is attributed to the air exchange rate, temperature difference between inside and outside the greenhouse and heat capacity of air as shown by Tiwari, 1998 in Eqn 2.10.

$$Q_v = 0.33 N V_g (T_R - T_a)$$ 2.10

Forced ventilation systems like fan, exhaust fan and blower etc. can supply high exchange rates whenever needed. These are simple and robust and allow maintaining inside temperature to level slightly higher than the outside temperature by increasing the number of air changes. Carpenter and Bark (1967) showed that air circulation fans reduced the vertical temperature gradients and eliminated the high temperature build up in the ridge area. Similar
work was also reported by Goodhind (1965). Walker and Duncan (1974) studied the
effectiveness of recommended greenhouse air circulation systems on tomato crop. They
studied the effect of different air circulation systems viz. vertical convection, horizontal
convection and sidewall ventilation using different fan positioning and air velocities.
However, they include large heterogeneity in the temperature fields (strong longitudinal
temperature gradients between the fan and the outlet) and their efficiency decreases rapidly
with the distance from the fan. Forced convection heat transfer mechanisms occurring inside
the greenhouse were studied by Papadakis et al. (1992), Faptista et al (1999), Wang and

Fuchs et al. (1997) studied the effects of ventilation on the energy balance of a
greenhouse with bare soil. Measurements of the radiation and energy balances in a
polyethylene greenhouse covering a bare, dry sandy soil were used to determine the heat
dissipation efficiency of four ventilation methods. It was observed that the 62% of incident
solar radiation transmitted by the roof provided the heat load on the system. Greenhouse was
tested with four ventilation treatments comprised passive ventilation obtained by rolling up
opposite end walls, activating two fans mounted in one gable and opening the opposite wall,
the same configuration but with a single fan, and completely closing the greenhouse. Opening
opposite walls generated sufficient draught to exchange air at a rate of 44 volumes per hour.
Operating one and two fans produced exchanges of 8 and 13 volumes per hour, respectively,
much under the specified rating of the equipment, because of pressure losses across insect-
proof nets on the vents. Closing the greenhouse limited the air exchange to three volumes per
hour. For the climatic conditions of the experiment, external wind speed and internal
buoyancy forces affected passive ventilation, but had no significant effects on fan ventilation.
It was reported that despite the dryness of the top layer of soil, the latent heat flux remained a
large term in the energy balance. High ventilation rates diminished soil heat flux, increased
sensible heat flux and slightly reduced latent heat flux.

2.2.2.3 Shading

The entry of direct solar radiation through the cover into the greenhouse is primary
source of maximum heat gain. The entry of unwanted radiation can be controlled by the use
of shading. Stretching a shade cloth over the roof of greenhouse is the effective way of
cutting excessive incoming radiation to the greenhouse as maximum solar radiation falls in
the roof of any structure during summer period. Another method of shading is the use of
water film on the greenhouse roof as tried by Morris et al. (1958) and Sodha (1986, Fig.
2.13). Thickness of water film was kept as 0.5mm on the roof slope of 20°. It was observed
that a drop of inside temperature of about 4-5°C was observed. Application of shading compounds to the greenhouse cover can reduce the infrared portion of solar spectrum which is responsible for enhancing the thermal energy in the greenhouse, ASHRAE (1978).

The shading compounds most commonly used are in forms of lime. Caustic compounds for removing shading are used to clean the cover when light transmittance becomes essential for the plant in the greenhouse. Many researchers in the past have also used thermal curtains during night for conserving greenhouse heat. However, these sheets can also be used as shading purposes for reducing the incident solar radiations. Bailey (1981) studied the shading effect and reported that an aluminum plated mesh reduced the inside greenhouse air temperature by 6 °C in comparison to the greenhouse without shading at an ambient temperature of 33 °C. Various methods of selectively filtering the incoming solar radiation have been tried as reported by Garzoli (1989). These involve running a film of water of dye solution over the surface of the greenhouse. Ideally most of the radiation in the photo synthetically active range is passed through the film into the greenhouse and the remainder (about 50% of the solar radiation) is absorbed as heat by the film and carried away.

Feuermann et al. (1998) developed a computer simulation model and studied the relationship between the parameters of the liquid radiation filter greenhouse and its thermal

Fig. 2.13 Roof shading of greenhouse

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performance under different climatic conditions. Shamim and McDonald (1995) carried out an experimental investigation to determine the feasibility of using liquid foam as an insulating media between the walls of a greenhouse in a hot-arid climate. The results showed that the foam is effective in attenuating the thermal radiations. A 25mm layer was found to transmit only 50% of incident solar radiation to greenhouse resulting in lowering the temperature in the greenhouse as compared to the greenhouse without foam.

2.2.2.4 Fan and pad evaporative cooling

Fan and pad evaporative cooling consists of a fan on one side and a pad on the other side. The principle of evaporative cooling is applied by running a water stream over the pad and consequent withdrawal of air through it by fans on the opposite side. Evaporative cooling involves no change in the heat content of the air/water vapor mixture. Rather, as water evaporates it takes heat from the air thus reducing its temperature i.e. conversion of sensible heat into latent heat of evaporated water but the total heat (enthalpy) of air remains the same. Further the humidity is raised due to the addition of water vapor in the air as discussed by Morris (1956) who determined the greenhouse cooling potential by evaporative cooling through a simple equation. Landsberg et al. (1979) did the major work on evaporative cooling for glasshouses in high energy environments. He estimated the average air temperature inside the glasshouse, subject to any specified radiant energy load, outside temperature and humidity. Hot outside air was passed through loosely hanged wet mats or pads. Analysis presented indicates that a freely transpiring crop in the glasshouse single stage evaporative cooling can reduce inside air temperature by 8-12 °C even under very high ambient temperatures and radiation intensities. The analysis also provides information on the humidity conditions likely to develop with specified Bowen ratios (β) i.e. ratio of sensible heat to latent heat (4:0.33).

Landsburg 1979, has also presented a detailed treatment of the greenhouse evaporative cooling process. The expression for temperature in the greenhouse is given by:

\[ T_0 = \frac{2 Q_n A_e + 2 h A_e T_0 + T_1}{h A_e + 2 v_a \rho C_a} \]

\[ T_0 = \frac{2 Q_n A_e + 2 h A_e T_0 + T_1 (2 v_a \rho C_a - h A_e)}{h A_e + 2 v_a \rho C_a} \]  \hspace{1cm} \text{(2.11)}

and

\[ Q_a = \frac{Q_s \times \beta}{\beta + 1 (1 - \alpha) \tau} \]

\[ Q_a = \frac{Q_s}{\beta + 1 (1 - \alpha) \tau} \]  \hspace{1cm} \text{(2.12)}

where

- \( Q_n \): net solar radiation absorbed in the greenhouse, W/m²
- \( Q_s \): total solar radiation incident on a horizontal surface, W/m² °C
Chandra et al. (1989) used a pad and fan system of evaporative cooling in a plastic covered greenhouse of 6 × 4m floor area as shown in Fig. 2.14.

![Fan and pad evaporative cooling system for greenhouse cooling](image)

**Fig. 2.14 Fan and pad evaporative cooling system for greenhouse cooling**

The author used Landsberg’s model to predict exhaust air temperature of greenhouse. The value of Bowen ratio was assumed as 2. The COP for the cooling system was also calculated between 40 and 60. Jamal (1994) studied that the greenhouse temperature can be lowered by 6-8 °C with pad-fan evaporative cooling system. Kittas et al. (2001) investigated the temperature and humidity gradients during summer in a rose production greenhouse equipped with a ventilated cooling-pad system and a half shaded plastic roof. The cooling performance was achieved upto 80% and the temperature of the greenhouse was lowered by 10 °C than the outside. Jain and Tiwari (2002) developed a mathematical model for experimental validation of thermal behavior in a small quonset type greenhouse of 5.03m length and 4.13 m width which used a fan pad evaporative cooling system. A metallic water tank used was of diameter 48 cm.
0.55 m and height 0.9m and painted black. The parametric studies involve the area of the cooling pad, mass flow rate and length of greenhouse. It was observed that greenhouse air temperature was raised by about 2-5 °C in winter. Cohen (1983) conducted an experimental comparison of evaporative cooling in a naturally ventilated glasshouse due to wetting the outer roof and inner crop soil surfaces. It was observed that when inside soil was kept dry the reduction of inside air temperature was obtained to be 9 °C in response to the roof wetting treatment. When the inside soil was kept wet the temperature drop reduced to only 1-2 °C. Willits and Peet (2000) conducted an experiment with intermittent application of water to an externally mounted greenhouse shade cloth. The results revealed that the rise of greenhouse air temperature was reduced by 41% under wet cloth as compared to 18% under dry cloth. Kittas et al. (2003) studied temperature gradients in a partially shaded large greenhouse equipped with evaporative cooling pads. He described that the main drawback of greenhouse evaporative cooling systems based on cooling pads and extracting fans is the thermal gradient developed along the direction of the airflow which can markedly affect the plant growth. To predict the temperature gradients along a greenhouse, a simple climate model is proposed which incorporates the effect of ventilation rate, roof shading and crop transpiration. In order to calibrate the proposed model, measurements were performed in a commercial greenhouse equipped with fans and pads and shaded in the second half. Experimental data show that the cooling system was able to keep the greenhouse air temperature at rather low levels. However, due to the significant length of the greenhouse (60 m), large temperature gradients, (up to 8°C) were observed from pads to fans. The model was calibrated by fitting temperatures in the middle and at the end of the greenhouse. The model was validated on experimental data different from those used for the calibration and then it was used to study: (i) the influence of different ventilation rates combined with shading on air temperature profiles along the greenhouse length; and (ii) the influence of the outside air temperature and humidity on the performance of the cooling system. High ventilation rates and shading contribute to reduce thermal gradients. Despite its simplicity, the model is sufficiently accurate to improve the design and the management of the cooling pad systems. By using roof evaporative cooling the heat flux through roof of greenhouse in summer period can be decreased substantially if water is evaporated on the surface of the roof as roof receives maximum amount of solar radiation (about 50% of total radiation) in summer, Sodha et al. (1986). Morris et al (1958) found that the transmissivity of solar radiation was reduced by 6% and internal air temperature was also lowered by the use of water film on the greenhouse roof.
2.2.2.5 Misting/fogging

Misting/fogging is generally used for creating high relative humidity, along with cooling. The foggers are fitted so as to provide complete misting inside the greenhouse. Systems based on high pressure nozzles studied by Press (1984), Giacomelli et al. (1985, 1989), Willits (1993) used 0.1-0.3 mm orifice nozzles to generate high pressure. Montero et al. (1990) used twin fluid nozzles which provided a combination of air and water under appropriate pressure and flow rates. The draw back of the system is that the compressor required high power which greatly increases the cost of the system and its operation. Montero and Anton (1994) used an air water fogging system and observed that the inside greenhouse temperature was 3 °C lower than that the other greenhouse. Arbel et al. (1999) used an evaporative cooling system for greenhouses based on spraying water in very fine droplets in the fog size of 2-60 μm. This system was compared with the pad and fan system. It was observed that the performance of the fog system was better than the fan and pad system as temperature increase was < 5° C and relative humidity variations < 20% with in the greenhouse. The proposed cooling system could provide desired range of temperature and relative humidity in the greenhouse uniformly during most months of the year.

2.2.3 Composite System

Use of ground potential for air conditioning has gained an increasing acceptance during the last few years. Earth temperature below its surface at a depth of only a few meters remains stagnant (26 °C) throughout the year. This huge underground mass of the earth can be used as heat storage (for heating/cooling applications of greenhouses). Earth-to-air heat exchanger system (EAHES) basically consists of the underground pipes and the air flow system which forces the air through the pipes. Pipes usually run along the length of the greenhouse, with entrance and exit points of the circulating air at opposing sides. The warm air gives up its heat content to the pipe, by condensation, and is then dissipated to the soil by conduction. Cooler air is then returned back inside the greenhouse. In heating mode, cold air from inside the greenhouse is circulated through the pipes. Heat is transferred from the soil to the air stream and then back to the greenhouse. In cooling mode, hot air from the greenhouse is transferred to the soil mass and cooler air is returned to the greenhouse. This repeated circulation of cold/hot greenhouse air causes the heating/cooling effect inside the greenhouse. The same system can also be used for periods when both cooling during the day and heating during the night is desirable.
### 2.2.3.1 Earth-to-air heat exchanger systems for greenhouse heating (Fig. 2.15)

A representative number of solar greenhouses using underground pipes for heating have been reviewed and discussed here. Plastic pipes with a total length of 100 m buried at a depth of 80 cm were used in a 3000 m² glass cover greenhouse by Jaffrin (1982). Portales (1982) used two rows of plastic buried pipes at a depth of 80 cm and 210 cm. Two rows of plastic pipes were also used at a 1736 m² glass greenhouse by Kozai (1985), buried at a depth of 50 and 90 cm respectively. The diameter of the pipes was 10 cm with a total length of 5872 m. Mavrogiannopoulos and Kyritsis (1985) used aluminum pipes with a diameter of 20 cm and a length of 15 m each buried at a depth of 2 m in a 150 m² polyethylene polyhouse. Coffin (1985) used 10 cm pipes at a depth of 30 and 60 cm in a 200 m² greenhouse. The system was able to keep the inside air temperature by 10 °C higher. (Santamourious, 1994) described the greenhouse attached with EAHES and showing thermal analysis for the temperature distribution and heat transfer as shown in Fig. 2.16.

![Diagram: Earth-air heat exchanger system for greenhouses](image)

**Fig.2.15 Earth-air heat exchanger system for greenhouses**

Imamkulov (1986) experimented with a single row of 4 cm diameter plastic pipes buried at a depth of 40 cm. Air circulated at the rate of 21.6 m³/h. The temperature inside the greenhouse was maintained at 4 °C higher than the minimum ambient temperature. Bernier (1987) also used plastic pipes at a 100 m² greenhouse. In total, 16 pipes were buried at a depth of 45 cm and 75 cm. The length of each pipe was 12 m and its diameter was 10.2 cm. The air was...
supplied at a rate of 3240 m³/hr. The system satisfied 35% heating requirements of the greenhouse. Bascetincelik (1987) used 835 m² polyethylene covered greenhouse in which 10 cm plastic pipes were buried at a depth of 0.5 m from the ground surface. The air flow rates were maintained with axial propeller fans at 10000 m³/hr. An average interior air temperature of 5 °C higher than the outside air temperature was maintained during January and February. The operating ventilators caused a decrease of relative humidity inside the greenhouse to 65%. Santamouris (1987) used 25 cm diameter plastic pipes coupled with a 2500 m² poly carbonate greenhouse. The pipes were used at a depth of 1.2m and 1.8m. Yoshioka (1989) investigated using a small greenhouse with nine plastic pipes of 11.4 cm diameter and 7.8 m long buried underground at a depth of 50 cm. Temperature of the air inside the greenhouse was maintained 4 °C higher than the minimum ambient temperature.

Fig. 2.16 Greenhouse attached with EAHES

\[ T_{f_0} = T_o + (T_r - T_o) e^{-hL/m_fC_f} \]  \hspace{1cm} 2.13

and useful energy gain is given by

\[ Q_u = m_fC_f(T_{f_0} - T_r) \]  \hspace{1cm} 2.14
Boulard et al. (1989) used 176 m² polycarbonate cover experimental greenhouse in which 19 plastic pipes buried into two rows at a depth of 40 and 83 cm, with a distance of 80 cm between them and an air flow rate of 7400 m³/hr was maintained through the greenhouse. Bombelli (1989) used concrete pipes of 15 cm diameter 21 m pipe length buried at a depth of 40 cm in a 200m² polyethylene cover greenhouse. The distribution of air inside the greenhouse could be performed using a centrifuge fan that circulated air through a perforated polyethylene duct. During the winter months, night air inside the greenhouse equipped with underground pipes, can reach temperatures ranging between 3-5 °C higher than a conventional greenhouse. Herve (1990) experimented in a 1470 m² greenhouse and used rough cast pipe at a depth of 45 cm. This depth of the underground storage was found to be insufficient for the necessary transfer of heat to the soil. Johnson (1990) used plastic pipes coupled with 1000 m² glass greenhouse. The performance of the system is not known. In another application Mihalakakou (1994b) used double P E sheet cover material greenhouse of 58 m² greenhouse, in which plastic pipes were used at a depth of 2m and 2.1 m. the system was able to cover the 62% heating needs of the greenhouse. Gauthier et al. (1997) conducted a numerical study for the thermal behavior of soil heat exchanger storage system aimed at reducing the energy consumption of greenhouses. The system used 26 non-perforated, corrugated plastic drainage pipes, 10.2 cm in diameter. Two rows of 13 pipes, 10.5 m long are buried at 450 and 750mm depths.

The representative applications of the above mentioned information is compiled and arranged in Table 2.4. The variation of velocity of air used by different researchers for different greenhouse areas is also compiled in Table 2.5. It can be clearly shown that for different values of greenhouse areas used by different researchers, using different diameter pipes and keeping different flow rates the velocity of air through the pipes comes out to be between 3.80 and 7.27 m/s i.e. the average value of the velocity used is calculated as 5.90 m/s. The underground pipes are buried at depths varying between 50 and 200 cm and spacing between them is approx. 40 cm. The heat exchangers are constructed using plastic, aluminum or concrete pipes, having 10-20 cm diameter. From the above mentioned information it can be concluded that the most common pipe material is plastic with an average air velocity through the pipe is kept around 6 m/s, the most common pipe diameter is 10.2 cm which can cover around 35 - 75% heating needs of the greenhouse.
Table 2.4 Summary of performance of agricultural greenhouses using earth-to-air heat exchanger system.

<table>
<thead>
<tr>
<th>Ref. Name</th>
<th>Area (m²)</th>
<th>Cover material</th>
<th>Pipe material</th>
<th>System specifications</th>
<th>Flow rate (m³/hr)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N  d (cm)  L (m)  D₁  D₂ (cm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jaffrin</td>
<td>3000</td>
<td>Glass</td>
<td>Plastic</td>
<td>2</td>
<td>10.2 100 80  -</td>
<td>-</td>
</tr>
<tr>
<td>Farrah</td>
<td>300</td>
<td>Double PE</td>
<td>Plastic</td>
<td>2</td>
<td>40  -</td>
<td>-</td>
</tr>
<tr>
<td>Coffin</td>
<td>72</td>
<td>-</td>
<td>Plastic</td>
<td>1.0 10.2  -  30 60</td>
<td>10 °C↑</td>
<td></td>
</tr>
<tr>
<td>Kozai</td>
<td>1736</td>
<td>Glass</td>
<td>Plastic</td>
<td>10.2 10.2 5872 50 90</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Garcia</td>
<td>125</td>
<td>P E</td>
<td>Aluminm</td>
<td>20.4 15 200</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Groves</td>
<td>100</td>
<td>-</td>
<td>Plastic</td>
<td>40</td>
<td>21.6</td>
<td>-</td>
</tr>
<tr>
<td>Bascat</td>
<td>835</td>
<td>P E</td>
<td>Plastic</td>
<td>24 10.2  -  50 10,000</td>
<td>5 °C↑</td>
<td></td>
</tr>
<tr>
<td>Bernier</td>
<td>100</td>
<td>Glass</td>
<td>Plastic</td>
<td>16 10.2 12 16 45 75</td>
<td>3240</td>
<td>35% heating</td>
</tr>
<tr>
<td>Bernier</td>
<td>100</td>
<td>Glass</td>
<td>Plastic</td>
<td>9 11.4 7.8 50</td>
<td>-</td>
<td>4 °C↑</td>
</tr>
<tr>
<td>Von C</td>
<td>297</td>
<td>P E</td>
<td>Plastic</td>
<td>-  -  -  -</td>
<td>4 °C↑</td>
<td></td>
</tr>
<tr>
<td>Vonarg</td>
<td>500</td>
<td>P C</td>
<td>Plastic</td>
<td>19 10.2  -  40 80 7400</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Cariben</td>
<td>200</td>
<td>P E</td>
<td>Concrete</td>
<td>- 15.7 21 40</td>
<td>3.5 °C↑</td>
<td></td>
</tr>
<tr>
<td>Santamouris</td>
<td>1000</td>
<td>Glass</td>
<td>Plastic</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Herve</td>
<td>1470</td>
<td>P E</td>
<td>Rough cast</td>
<td>- 10.2  -  45</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Santamouris</td>
<td>2500</td>
<td>P C</td>
<td>Plastic</td>
<td>25.5 120 108</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Degrand</td>
<td>78.6</td>
<td>Double PE</td>
<td>Plastic</td>
<td>13 10.2 10.5 45 75 3420</td>
<td>5-7 °C↑</td>
<td></td>
</tr>
<tr>
<td>Portales</td>
<td>58</td>
<td>Double PE</td>
<td>Plastic</td>
<td>200 210</td>
<td>-</td>
<td>62% heating</td>
</tr>
</tbody>
</table>

N-number of pipes, d -diameter of pipe, L -length of pipe, D₁ - depth of first row, D₂-depth of second row.

Table 2.5 Relationship between greenhouse area and velocity of air used

<table>
<thead>
<tr>
<th>Area of greenhouse (m²)</th>
<th>Material of pipe used</th>
<th>Flow rate used (m³/hr)</th>
<th>Number of pipes used N</th>
<th>Dia. used d (cm)</th>
<th>Calculated velocity V (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>Plastic</td>
<td>21.6</td>
<td>1</td>
<td>4.00</td>
<td>4.77</td>
</tr>
<tr>
<td>100</td>
<td>Plastic</td>
<td>3240</td>
<td>16</td>
<td>10.2</td>
<td>6.88</td>
</tr>
<tr>
<td>835</td>
<td>Plastic</td>
<td>10,000</td>
<td>24</td>
<td>10.2</td>
<td>6.80</td>
</tr>
<tr>
<td>500</td>
<td>Plastic</td>
<td>7400</td>
<td>19</td>
<td>10.2</td>
<td>7.27</td>
</tr>
<tr>
<td>78.6</td>
<td>Plastic</td>
<td>3420</td>
<td>13</td>
<td>10.2</td>
<td>3.80</td>
</tr>
</tbody>
</table>
2.2.3.2 Earth-to-air heat exchanger systems for greenhouse cooling

The potential of earth-tube-heat-exchanger-system for cooling purposes has also been established during the last decade. Some interesting studies for cooling of buildings have been done by Agas et al. (1991), Santamouris et al. (1995) and Agririou (1996). Cooling studies of agricultural greenhouses by earth-air heat exchanger system have been performed by Levit et al. (1989) who simulated a greenhouse microclimate by earth-air heat exchangers. Schiller (1992) developed a transient numerical model for predicting the performance of earth-air heat exchangers. However, its cooling performance in greenhouse has been extensively studied by Santamouris et al. (1995). From the parametric analysis performed for a typical 1000 m² glass greenhouse with four plastic pipes, it was observed that the indoor air temperature is reduced with increasing pipe length, decreasing pipe diameter, increasing depth up to 4 m and decreasing the air velocity.

2.3 LIMITATIONS OF EXISTING THERMAL CONTROL TECHNOLOGIES

2.3.1 Heating Technologies

Total cost of a thermal storage system depends upon the cost of thermal heat storage material, containment cost of the storage material, cost of heat exchanger for charging & discharging and the storage and operating cost.

1. Water as a thermal heat storage medium costs very little but the problem of using water for thermal control of greenhouses involves high containment cost. About 20-30% of the greenhouse valuable ground surface also becomes unavailable due to containment, which cannot be used for cultivation. Water can also be stored in a reservoir that can be used for transferring the excessive heat from the greenhouse by using some heat exchanger surface, which increases the cost of the system significantly. The corrosion and leakage of the water container is also one of the problem areas.

2. Rock pile as a thermal heat storage medium also costs very little, but the major problem of using rock bed storage systems is the huge quantity of rock pile required for the storage of thermal energy because of low thermal capacity of the rock as compared to water, and the bin volume will be about three times the volume of the water tank that is heated for the same temperature interval. Although this system does not require any heat exchanger surface as the rock pile itself acts as a heat exchanger, thus reducing the total system cost. However, the pumping cost of air through the rock pile increases many folds due to the high-pressure drop created by the resistance of the rocks. Also simultaneous charging and discharging of the rock material is not possible.
3. Use of phase change materials (PCMs) for greenhouse heating is still under experimental stage since last two decades. The cost of most suitable and commonly used PCM (calcium hexa-hydrate) is very high. It also does not show complete reversibility during repeated phase changes. The melt material does not properly crystallize at its thermodynamic freezing point. Some nucleating agents and cold fingers have to be used with storage material, which makes the system complicated. This type of storage system also requires containment for the storage materials and a metallic heat-exchanging surface that substantially increases the cost of the system. Also, due to incongruent melting a chemical modification is required. Moreover, the PCM deteriorates due to repeated phase changes and has to be replaced quite often. This increases the operating cost of the system and makes it commercially nonviable for medium value crops.

4. North wall is useful only where the solar radiation flux entering through the south side of the greenhouse is high during winter. It absorbs the solar radiation during day time and radiates back the absorbed heat during night. It has a marginal effect on the night time greenhouse temperature increase.

5. Movable insulation and thermal screens are used to conserve the absorbed heat by the greenhouse floor during the daytime by becoming a barrier between the greenhouse and sky. It helps to cut down the effect of night sky radiation during night. However its effect on the greenhouse air temperature is also marginal.

2.3.2 Cooling Technologies

1. Natural ventilation systems are generally less efficient and are not satisfactory in sunny days without wind in tropical climates where day time ambient temperatures rise above 30°C and greenhouse temperatures exceed 38°C. It is useful only during the spring and autumn periods of the year that too in mild climatic areas along with weak wind. It can only marginally lower the greenhouse air temperature (2-3°C) which is not sufficient to meet the crop temperature requirements during critical periods of flowering and fruit setting etc.

2. Although forced ventilation increases the number of air changes through the greenhouse yet is useful only in the mild hot weather conditions and becomes ineffective during extreme summer conditions when ambient temperatures rise beyond 35 °C.

3. Shading and use of reflector sheets help to restrict the entry of solar radiation inside the greenhouse but not much drop in the inside air temperatures can be achieved in tropical climatic conditions due to higher solar intensities.
4. Fan and pad cooling systems are also being extensively used for greenhouse cooling; still there are some unavoidable difficulties like formation of temperature gradient within the greenhouse length. This system works on negative pressure so there is always a problem of outside hot air mixing with the inside cool air through infiltration which reduces the efficiency of the system quite significantly. High levels of humidity (moisture) inside the greenhouse also promote the growth of microorganisms thus making the crop more susceptible to the diseases. Moreover, this method of cooling becomes ineffective during the rainy season when outside humidity levels are higher.

5. Evaporative cooling using foggers are also one of the currently used cooling techniques for the small and medium size greenhouses. However, this method uses expensive foggers or nozzles along with a plastic pipe network, which chokes due to insoluble and soluble salts present in the water thereby reducing the working efficiency of the system or using such nozzles require pre-treatment of water in order to prevent clogging which increases the operational cost of the system. High levels of humidity (moisture) inside the greenhouse also promote the growth of microorganisms thus making the crop more susceptible to the diseases. Moreover, this method of cooling becomes ineffective during the rainy season when outside humidity levels are higher.

2.3.3 Composite System

Earth-to-air heat exchanger system (EAHES) is currently the most popular operating system for greenhouse heating as well as cooling for composite climates. Studies show that earth temperature beyond 3-4 m depth becomes constant (23°C) throughout the year. If pipe network is laid at this depth then greenhouse heating in winter and cooling in summer can be achieved by utilizing the constant temperature of earth. However, the major disadvantage of using earth tube heat exchanger system is the cost of digging the soil and laying the pipes upto 3-4 meters depth. Horizontal laying and fitting of pipe network at this depth is not easy. Condition of the pipes, and leakage from the joints once laid cannot be checked. Corrosion of metallic pipes and deterioration of plastic pipes under soil pressure also makes this system less trustworthy for long duration projects. Moreover, temperature of the soil around the vicinity of the pipe rises after certain period of time thus lowering its efficiency. In one of the latest studies by Chandra and Puri (2000) conducted on heating and cooling potential of earth-to-air-heat-exchanger system at Roorkee, India for three consecutive years revealed that when PVC pipes of 15 cm diameter and 30 m length were laid at a depth of 3m for creating the thermal comfort for a room of size 2.5 × 1.95 × 3.9 m a cooling of 3-4°C could be
achieved in early summer and only 2-3 °C in extreme summer conditions. Similarly, maximum heating of about 2.5°C could be achieved in extreme winter conditions, which is not sufficient at all for the type of extreme climate in summer and winter. So it can be concluded that the working efficiency of the existing system is low which creates only a marginal effect inside the building. If the same system is put to use for creating a thermal comfort inside the greenhouse, it would not be sufficient at all as greenhouse also receives direct sunlight during day time in summer and is exposed to night sky radiation during winter nights. So there is a need to develop a more efficient thermal control system for composite climatic greenhouses.

2.4 FORMULATION OF THE PROBLEM

Out of the existing thermal control technologies, no single system can be used for composite climatic conditions except EAHES. As mentioned above this system has installation and operational limitations, there is an urgent need to develop a more efficient single composite system which can meet the needs of the extreme winter and summer climatic conditions for creating thermal comfort inside the greenhouse.

Therefore, in this study, a thermal control system for greenhouses has been presented which can be effectively used for heating in winter and cooling in summer. The system uses deep underground water from irrigation tubewell at the ground surface at almost constant temperature of around 24°C (year round). The system is named as Aquifer Coupled Cavity Flow Heat Exchanger System (ACCFHES) as it involves the flow of greenhouse air through a pipe placed horizontally in a shallow cavity (trench) dug on the ground surface through which underground water is allowed to flow in opposite direction just keeping the pipe fully immersed in the water. This underground aquifer water is then allowed to go to the crops for irrigation purposes. The movement of air and water in the opposite direction in the trench for heat transfer purposes makes it a counter flow heat exchanger configuration. Thus the system can be used for cooling the greenhouse during extreme summer days, when hot air from greenhouse at around 50 °C comes in contact with the under ground water (at around 25-26 °C) in the trench and lowers the inside temperature significantly. Similarly, the same system can be used for heating the greenhouse during winter nights, when cold air from greenhouse at around 4°C comes in contact with the under ground water (at around 25-26 °C) in the trench and raises the inside temperature significantly. The cost of lifting the underground water upto the surface and digging of trenches is nil as already existing tubewell and the trenches meant for irrigation can be used for the purpose. In big farms tubewell generally
keeps on operating depending upon the availability of electricity in the fields. The only cost is the cost of blower for moving the air through the pipe. As per the literature review, no such system has been tried anywhere and it would be the first working system of its kind used for year-round thermal control of greenhouses.

2.5 ADVANTAGES OF AQUIFER COUPLED CAVITY FLOW HEAT EXCHANGER SYSTEM (ACCFHES)

1. The proposed system can be used for both cooling in summer and heating in winter.

2. The system would be trouble free, easy to operate, long lasting and cheaper in cost. Its operation and maintenance does not require any high tech knowledge and can substantially lower the greenhouse air temperatures during summer and can raise its temperature during winter nights without using any other auxiliary system.

3. No digging of soil upto 3-4 m deep is required as in the case of EAHES thus saving the labour and maintenance cost.

4. No extra space for laying the pipes is required as already available tubewells and water cavities (trenches) used for irrigation purposes by the farmer would be used as a part of ACCFHES.

5. Due to counter flow arrangement, effectiveness of the proposed ACCFHES would be more as compared to the existing EAHES; therefore, area of pipes required for transferring the same quantity of heat as compared to the EAHES would be lesser which would reduce the cost of pipe material along with the cost of pumping air through the pipes.

6. The proposed ACCFHES system would be comparatively easier to operate and to maintain as compared to existing EAHES as no pipe network would be laid underground.

2.6 OBJECTIVES OF THE STUDY

1. To conduct state-of-the-art review of existing heating and cooling technologies and applications for thermal control of greenhouses.

2. To develop a mathematical model for solar radiation availability on a composite climatic greenhouse for the selection of its shape and orientation.

3. To develop a thermal model for the greenhouse coupled with aquifer coupled cavity flow heat exchanger system along with simulation studies.
4. To design an aquifer coupled cavity flow heat exchanger system for thermal control of composite climatic greenhouses and to evaluate its performance for heating (during winter) as well as for cooling (during summer) purposes.

5. To conduct field evaluation of the designed aquifer coupled cavity flow heat exchanger system in order to see its effect on the growth and yield of selected off-season vegetable crops.

6. To conduct a techno-economic analysis of aquifer coupled cavity flow heat exchanger system.