CHAPTER 6

DESIGN AND PERFORMANCE EVALUATION OF AQUIFER COUPLED CAVITY FLOW HEAT EXCHANGER SYSTEM
6.1 INTRODUCTION

In this chapter, Aquifer Coupled Cavity Flow Heat Exchanger System (ACCFHES) for cooling as well as heating of a composite climatic greenhouse is theoretically designed. Theoretical computation of the area and power requirement of ACCFHES for a complete range of sol-air temperatures for different greenhouse areas is presented. Constructional details of the greenhouse and ACCFHES are presented. Area and power requirements of ACCFHES have also been compared with the existing EAHES. Finally, experimental performance evaluation of the designed system is presented for full winter as well as for summer months.

6.2 DESIGN METHODOLOGY OF ACCFHES

Design of ACCFHES was carried out for cooling purposes in summer conditions, however the same system was also used for heating purposes during the winter conditions. Variation of climatic parameters such as greenhouse air temperature, ambient air temperature and global solar radiation on a horizontal surface outside the greenhouse ($I_t$) for an extreme summer day is shown in Fig. 6.1. It was observed that greenhouse air temperature remained 7-8 °C higher as compared to ambient air temperature (42.5 °C) during the peak hours. Using these climatic parameters, sol-air temperature (as discussed in chapter 5, Eqn.5.14a) range as shown in Fig. 6.2 was computed for generalizing the design of ACCFHES. Quantity of heat required to be removed from the greenhouse in order to maintain the design room air temperature is governed by Eqn. 6.1 and already discussed in detail in chapter 5 section 5.4. Mass flow rate required to remove the given quantity of heat is given by Eqn 6.1a. It was assumed that all the heat removed from the greenhouse was transferred to the ACCFHES (Eqn. 6.1b). Minimum velocity of air (at different sol-air temperatures) through the pipe at different pipe diameters is shown in Fig. 6.3a. After computing the values of Reynolds number for air and water, air side and water side heat transfer coefficients were computed which resulted in the computation of the overall heat transfer coefficient $U_h$ of the ACCFHES (Eqn. 6.7). The minimum area required by ACCFHES was then computed using Eqn 6.8.

Considering the arrangement of water and air as counter flow, optimum Logarithmic Mean Temperature Difference ($LMTD$) of the ACCFHES was theoretically calculated using Eqn. 6.9. Variation of area of heat exchanger, power requirement and effectiveness of the system (Eqn. 6.13) at different values of $LMTD$ is shown in Fig. 6.3. It was observed from the figure that area and power requirements decreased with the increase in $LMTD$ and so did the effectiveness. However, above an $LMTD$ value of 12, the decrease in effectiveness was very small showing further decrease in the area and power. Therefore, an economically suitable
$LMTD$ value of 13 °C was selected by making a compromise between effectiveness & area of heat exchanger and effectiveness & power consumption. Finally, power requirement of ACCFHES was computed using Eqn. 6.12. A computer program in C++ was used for computing the area and power requirements of ACCFHES at different sol-air temperatures and for different greenhouse areas.

**Fig. 6.1** Variation of climatic parameters for different hours of an extreme summer day at 31°N latitude (11-05-05).

**Fig. 6.2** Variation of sol-air temperature for different sun-shine hours of an extreme summer day at 31°N latitude (11-05-05).
Fig. 6.3 Relationship of area, effectiveness and power for ACCFHES at different LMTD values.

Total quantity of heat required to be removed from the greenhouse air in order to maintain the design room air temperature \(T_r\) at steady state as given by Eqn 5.13 in chapter 5 can also be written as

\[
Q_p = A_g \left[ r I - U(T_r - T_d) \right] = - m_a c_a (T_d - T_r) \tag{6.1}
\]

The same heat is to be transferred to the ACCFHES

\[
Q_p = U_h A_h \times LMTD \tag{6.1b}
\]

Volume flow rate \(V_{fa}\) required to remove the total heat gain is

\[
V_{fa} = Q_p / [\rho_a c_a (T_r - T_d)] \tag{6.2}
\]

Where \(T_d\) is the delivery air temperature of the circulating air at the pipe outlet which is much lesser than \(T_r\). Minimum velocity of air \(v_a\) through the pipe (shown in Fig. 6.3a) can be found out as

\[
v_a = V_{fa} / a_a \tag{6.3}
\]

Where, \(a_a\) is the cross sectional area of the pipe with selected diameter \(d\) of the pipe.
Fig. 6.3a Variation of air velocity through pipe at different diameters for various sol-air temperatures.

Taking the properties at mean air temperature, Reynolds number for air $Re_a$ through the pipe thus can be found out using the following equation as given by Mcadams (1954)

$$Re_a = \frac{v_a \times d}{\nu_a}$$  \hspace{1cm} (6.4)

Prandtl number for air $Pr_a$ can also be calculated from the given properties at mean air temperature. Nusselt number $Nu_a$ is thus known from the following equation which leads to the computation of air side heat transfer coefficient $h_a$.

$$Nu_a = 0.023 \ (Re_a)^{0.8} \ (Pr_a)^{0.33} \quad \text{(for cooling)} \quad Nu_a = 0.023 \ (Re_a)^{0.8} \ (Pr_a)^{0.4} \quad \text{(for heating)}$$  \hspace{1cm} (6.5a, 6.5b)

$$h_a = Nu_a \times k_a / d$$  \hspace{1cm} (6.6)

Similarly, using the same criteria, heat transfer coefficient from water to air $h_w$ can also be calculated by taking the properties of water at mean temperature. Neglecting the thermal resistance of the material, overall heat transfer coefficient $U_h$ of the ACCFHES is

$$U_h = h_a \times h_w / (h_a + h_w)$$  \hspace{1cm} (6.7)

Total area of ACCFHES required to remove the given quantity of heat is

$$A_h = Q_p / U_h \times LMTD$$  \hspace{1cm} (6.8)
Maximum inlet temperature of greenhouse air $T_{hi}$ in pipe was considered as 50°C and inlet temperature of aquifer water $T_{ci}$ in trench was taken as 24°C. Hence, for different outlet conditions of air $T_{ho}$ and water $T_{co}$, LMTD values were computed for summer conditions and shown in Table 6.1. Computation of LMTD for earth-to-air heat exchanger system (EAHES) was also made in order to compare the area and power requirements of the two systems for the same heat removal $Q_p$. Comparison is based on the fact that in the case of EAHES, temperature of soil mass $T_c$ around the pipe remains constant and only the temperature of air inside the pipe decreases from $T_{hi}$ to $T_{ho}$ during the heat exchange process. Whereas, in the case of ACCFHES temperature of hot fluid decreases from $T_{hi}$ to $T_{ho}$ and the temperature of cold fluid increases from $T_{ci}$ to $T_{co}$ while moving in the counter flow configuration as shown in Fig. 6.3b. Thus for the same inlet and outlet temperature condition of hot fluid (greenhouse air) LMTD for EAHES and ACCFHES has been computed.

**Fig. 6.3b Configuration of hot and cold fluid flow for ACCFHES and EAHES.**

\[
LMTD = (\theta_i - \theta_o) / \ln \theta_i / \theta_o
\]

\[
\theta_i = T_{hi} - T_{co}
\]

\[
\theta_o = T_{ho} - T_{ci}
\]

where
Table 6.1 LMTD values for inlet and outlet conditions of air (hot fluid) and aquifer water (cold fluid) through pipe.

<table>
<thead>
<tr>
<th>$\Delta T_a$(°C)</th>
<th>50</th>
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<tbody>
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<td>$T_a$(°C)</td>
<td>26</td>
<td>26</td>
<td>30</td>
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<td>$T_c$(°C)</td>
<td>24</td>
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<td>$T_c$&quot;(°C)</td>
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<tr>
<td>LMTD</td>
<td>8.8</td>
<td>8.3</td>
<td>13.0</td>
<td>12.3</td>
<td>11.2</td>
<td>10.5</td>
<td>14.5</td>
<td>13.8</td>
<td>7.8</td>
<td>9.9</td>
<td>13.1</td>
<td>11.6</td>
</tr>
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Coefficient of friction $f$, which is a function of Reynolds number, is calculated using the Schiller (1992) Eqn.

$$f = 0.005 + 0.396 (Re_a)^{0.3} \quad \text{(for } 2 \times 10^4 < Re_a < 2 \times 10^6)$$

Eqn. 6.10

$f$ is then used for the calculation of pressure drop $\Delta P$ through the pipe using the Darcy Eqn. (1992)

$$\Delta P = \frac{4f \times L \times v_a^2 \times \rho_a}{2d}$$

Eqn. 6.11

Finally the pumping power ($P$) requirements are

$$P = \Delta P \times v_a$$

Eqn. 6.12

Effectiveness $E$ of the ACCFHES is also calculated using the well known relations for counter flow heat exchanger system.

$$E = 1 - \frac{e^{-NTU(1-R)}}{1 - R \left( e^{-NTU(1-R)} \right)}$$

Eqn. 6.13

where

$$R = \frac{C_{\text{min}}}{C_{\text{max}}} \quad C_{\text{min}} = C_h \quad \text{if } C_h < C_c$$

$$C_{\text{min}} = C_c \quad \text{if } C_c < C_h$$

$$C_h = m_a \times c_a$$

$$C_c = m_w \times c_w$$

$$NTU = U_h \times A_h / C_{\text{min}}$$

Eqn. 6.14

6.3 CONSTRUCTIONAL DETAILS OF GREENHOUSE AND ACCFHES

An even span, east-west orientation greenhouse of 6m length and 4m width was constructed at Rayat and Bahra Institute of Engineering and Bio-technology near Chandigarh (31° N latitude), Punjab, India and used for the study. The frame of the greenhouse was constructed using 6mm and 4mm diameter M S round bars. 6mm bars were used at the corners for giving greater strength. 14 holes of 0.50m depth at 1 m interval were dug and 2.5m long lengths of rods were inserted in these holes (Fig. 6.4). In order to improve the strength of
the foundation a round plate of M S flat (10 cm diameter) was also welded at the bottom of each rod before inserting in each hole. Mixture of cement-sand and concrete was then added in each hole upto the ground level. The soil was thoroughly rammed after the mixture became dry. 14 rods of 2.75m length (of each rod) were used over the inclined north and south roofs. These lengths were welded at the centre and at the ends making an angle of about 27° with horizontal. Greenhouse was covered with a single sheet of UV stabilized polyethylene (P E). The sheet was properly fixed with the rods using 50 mm (2 inch) wide adhesive tape from inside along the length of each rod. A door of 1x1.9m size kept on the west side for the entry was fabricated using 19mm angle iron. Two ventilators of 1 x 0.5m size were kept on east and west wall respectively for natural ventilation. A shallow cavity (trench) was dug around the perimeter of the greenhouse in which a 20 m long and 0.1016m (4 inch) diameter plastic pipe was horizontally placed (Fig. 6.5a). Dimensions of the trench (0.30m x 0.30m) were kept in such a way that the pipe remained fully immersed in water and could carry the minimum quantity of water required for removing or delivering the heat. Underground aquifer water from a deep tubewell near the greenhouse sight was allowed to pass through the trench (Fig. 6.5b). Top view of the greenhouse coupled with the ACCFHES in cooling mode is shown in Fig. 6.5c. To keep the pipe fully immersed in water, supports on the top of the pipe were provided after every 2.5m length. These supports were simple iron rods fixed across the channel at the water level so that the plastic pipe could not rise above the aquifer water level and remained fully immersed as shown in Fig. 6.5d (pictorial view).

The system used 1 hp (746W) motor and blower assembly that provided an air flow rate of about 1700 m$^3$/hr (Fig. 6.5e). Direction of water and air was kept as counter flow in order to maximize the effectiveness of the system. Cold or hot air from the greenhouse was sucked near the roof and passed through the pipe in a forced circulation mode. Greenhouse air moving through the pipe at a specified velocity lost or gained heat to or from the water through indirect contact. This air was uniformly distributed through a delivery pipe centrally placed inside the greenhouse at a height of 30cm for providing the maximum cooling effect near the vegetable plants. Repeated circulation of greenhouse hot air during summers significantly lowers the greenhouse temperature and vice versa.
Fig. 6.4 Constructional details of the greenhouse
Fig. 6.5a Layout of plastic pipe inside the trench dug around the greenhouse

Fig. 6.5b Aquifer water being supplied by deep tubewell near the greenhouse sight
Fig. 6.5c Top view of the greenhouse cooling process using ACCFHES

Fig. 6.5d Pictorial view of plastic pipe and aquifer water being filled in the trench
6.3.1 Mixing of Water with Circulating Air

It was also observed that the relative humidity inside the greenhouse also dropped to a very low value of less than 30% during the extreme summer conditions. Thus relative humidity was increased by mixing water at around 26 °C within the pipe along the circulating air just after the completion of the sensible cooling process (between state points 5 and 6 in Fig. 6.5c and 6.5f, pictorial view). The quantity of water required for evaporation was also calculated depending upon the desired relative humidity (70%) inside the greenhouse. It was found that only 10-12 liters/hr of water was required for the selected size greenhouse which was provided by the gravity head through a container having flow control valve placed at about 0.5 m height from the delivery pipe. A small hole of about 10mm size was drilled and an 8mm (inner diameter) flexible plastic pipe was inserted inside the hole for mixing water with air and for providing sufficient contact of water with the air before the delivery (Fig. 6.5f, pictorial view). High velocity air moving through the pipe broke these water droplets into smaller particles and mixed with the circulating greenhouse air thereby increasing its relative humidity.
Evaporation of water particles also took away the latent heat of vaporization from the circulating air which further lowered the temperature of the air inside the pipe to around wet bulb temperature and the overall cooling effect inside the greenhouse was significantly improved as compared to the outside air temperature conditions. Thus, the mixing of water with the circulating air improved the RH value as well as further lowered the temperature of the circulating air inside the greenhouse. It was observed that most of the sprayed water was evaporated and the small left over water that came out of the delivery pipe along with the cool air was allowed to flow in the central path inside the greenhouse. Aquifer water after passing through the trench was allowed to go into the field for irrigation purpose (Fig. 6.5g, pictorial view). It was however observed that due to continuous mixing of water vapors with the circulating air, relative humidity inside the greenhouse kept on increasing which lowered the evaporative cooling efficiency. Thus, an optimum percentage of the outside ambient air (20% by volume) at lower RH value was mixed with the re-circulating greenhouse air (state 2, Fig. 6.5c and 6.5f pictorial view) to prevent too much increase in RH. This optimum percentage of outside air was selected on the basis of maintaining the minimum number of air changes of the greenhouse air without affecting the cooling effect. Further increase in the percentage of outside air mixing with the greenhouse air lowered the volume flow rate of the greenhouse circulating air which lowered the rate of heat transfer.

One important observation was also made that the air temperature after passing through the blower was raised by about 3-4 °C in winter and 5-6 °C in summer. In order to nullify the heating effect of air in summer (state point 3 and 4, Fig. 6.5c), blower and motor assembly was placed on the suction side so that hot air from the greenhouse once cooled was directly fed to the greenhouse from the delivery side. However, in winters, the motor blower assembly was placed on the delivery side so that air after heating through the channel was further heated (state point 2 and 3, Fig. 6.6) by the blower vanes in order to improve the heating effect.
Fig. 6.5f Pictorial view of water and outside air mixing process along with pressure drop measurement. State points: 1-inside air suction, 2-outside air mixing, 5-before water mixing, 6-after water mixing, 7-delivery air, 0-pressure drop measurement.

Fig. 6.5g View of aquifer water being sent for irrigation in fields
**Fig. 6.5h** View of thermostat and temperature sensor inside the greenhouse

Aquifer water in the channel  
Circulating air in the pipe  
Open cavity (Trench)

![Diagram](image)

**Fig. 6.6** Top view of greenhouse heating process using ACCFHES

Aquifer water in the channel  
Circulating air in the pipe  
Open cavity (Trench)

Blower  
Hot air delivery  
Plantation  
Cold air suction

Water outlet to field  
Water  
Air gaining heat

**Fig. 6.6** Top view of greenhouse heating process using ACCFHES
6.4 RESULTS AND DISCUSSION

In this section, results of area and power requirements of ACCFHES for a complete range of sol-air temperature for different greenhouse areas have been presented. The results have also been compared with the EAHES for a 100 m$^2$ greenhouse area. Experimental performance of greenhouse coupled with ACCFHES in heating as well as in cooling mode is discussed in detail. Year round variation of climatic and plant parameters is also shown.

6.4.1 Area Requirement of ACCFHES

Effect of variation of sol-air temperature on the area requirements of ACCFHES for different greenhouse areas at selected velocity and diameter (15m/s, 0.1016 m) is shown in Fig. 6.7. Area of heat exchanger required from the lowest (36.8 °C) to the highest (79.8 °C) sol-air temperature for a 24m$^2$ greenhouse area varied between 2.72 to 11.72m$^2$. Similarly, area of heat exchanger required for 50, 100, 200, 500 and 1000m$^2$ greenhouse area varied between 5.44 to 23.44 m$^2$, 10.88 to 46.88m$^2$, 21.76 to 93.76m$^2$, 54.4 to 234.4m$^2$ and 108.8 to 468.8 m$^2$ from the lowest to the highest sol-air temperature. It was observed that the area of ACCFHES requirement increased with the increase in the sol-air temperature for the same greenhouse area. It was due to the increase in the ambient air temperature and higher solar radiation which increased the heat input to the greenhouse. Hence, in order to lower the greenhouse room air temperature, greater area of ACCFHES was required. Area of ACCFHES requirement also increased with the size of the greenhouse. This variation was almost linear as shown by the linear equation generated by the best line of curve fit for 100 m$^2$ greenhouse area which shows an R$^2$ value of 0.99.

6.4.2 Power Requirement of ACCFHES

Power requirement of ACCFHES for 24m$^2$ to 100m$^2$ greenhouse area and from 200 to 1000m$^2$ greenhouse area from the lowest to the highest sol-air temperature is shown in Fig. 6.8a and Fig.6.8b respectively. Fig. 6.8a shows that the power requirement varied from 0.006 to 0.678 kW for 24 m$^2$ greenhouse area, 0.028 to 1.85 kW for 50m$^2$ greenhouse area, 0.111 to 5.45 kW for 100 m$^2$ greenhouse area, 0.445 to 21.8 kW for 200 m$^2$ greenhouse area, 2.78 to 136.9 kW for 500 m$^2$ greenhouse area and 11.12 to 545.4 kW for 1000 m$^2$ greenhouse area respectively from the lowest to the highest sol-air temperature value. It was observed that the power requirement of ACCFHES increased with the increase in the sol-air temperature at same greenhouse area. It was because of the higher heat gain by the greenhouse at higher ambient air temperature coupled with the higher solar radiation which needed greater air flow rate to lower the inside air temperature through the same diameter pipe.
It was also observed that the increase in the power requirement was not linear with the increase in the sol-air temperature. It is clear from the best line of exponential curve fit generated for 100 m² greenhouse area which gives an $R^2$ value of 0.9631 as shown in Fig. 6.8a. Hence, at higher sol-air temperatures, power requirement by the system suddenly increased as shown in Figs 6.8a and b. It was due to the fact that the pressure drop in the pipe.
increased as a square of the air velocity which was responsible for higher power requirements at higher sol-air temperatures. Hence, these figures can be used to find the power requirement of ACCFHES for any time and location depending upon the climatic conditions of the area.

![Graph showing the effect of sol-air temperature on the power requirements of ACCFHES for different greenhouse areas.](image)

**Fig. 6.8b Effect of sol-air temperature on the power requirements of ACCFHES for different greenhouse areas.**

### 6.4.3 Comparison of ACCFHES and EAHES

In this section, area and power requirements of the designed ACCFHES and the existing system EAHES have been compared for 100 m² greenhouse area at different sol-air temperatures. The comparison is based on the same inlet and design temperature condition of greenhouse.

#### 6.4.3.1 Area requirement

A comparative analysis of area requirement between ACCFHES and EAHES for the same inlet and design temperature condition of greenhouse air is shown in Fig. 6.9. It was observed that for all the sol-air temperatures, area requirement of ACCFHES was about 22 percent lesser than that of EAHES. At a sol-air temperature of 40 °C, area requirement of ACCFHES and EAHES was 11.08m² and 13.47m² respectively. Similarly at 50, 60 and 70°C, the area requirement of ACCFHES was again about 22 percent lower than EAHES. At the peak sol-air temperature of 80 °C area required by ACCFHES was 47.05m² as compared to 57.82 m² for EAHES. The lesser area of ACCFHES was due to the counter flow arrangement of aquifer water and air. Whereas in the case of EAHES, temperature of soil mass around the
pipe was constant and only the greenhouse air in the pipe moved that made it less effective as compared to ACCFHES.

![Graph showing area requirement of ACCFHES and EAHES for different sol-air temperatures (100m² greenhouse).]

**Fig. 6.9** Comparison of area requirement of ACCFHES and EAHES for different sol-air temperatures (100m² greenhouse).

### 6.4.3.2 Power requirement

A comparative analysis of power requirement between ACCFHES and EAHES for the same inlet and design temperature condition of greenhouse air is shown in Fig. 6.10. It was observed that for all the sol-air temperatures, power requirement of ACCFHES was about 20 percent lower than that of EAHES. At a sol-air temperature of 40 °C, power requirement of ACCFHES and EAHES was 85W and 111W respectively. Similarly at 50, 60 and 70°C, the power requirement of ACCFHES was lower than EAHES. At the peak sol-air temperature of 80 °C power required by ACCFHES was 4430W as compared to 5421W for EAHES. It was due to the lesser area of ACCFHES as compared to EAHES (i.e. lesser length) which caused a lower pressure drop for the same pipe diameter.
6.4.4 Experimental Performance of ACCFHES in Heating Mode

Experimental performance of the designed system was tested for its heating potential during the winter months of year 2004-05. The night heating (6pm to 8am) performance of the system from November to mid February is shown in Fig. 6.11. The figure shows the hourly average of greenhouse inside air temperature, outside air temperature, delivery air temperature from pipe outlet, inside and outside relative humidity for different weeks of each month starting from the first week of November. It is clear that the average inside air temperature remained higher by about 7-9 °C for different weeks of each month as compared to the outside air conditions. In the month of November, average night outside air temperature decreased from 18.6 to 11.8 °C. The inside greenhouse air temperature also dropped from 23.5 to 19.8 °C showing an increase of about 8 °C above ambient air conditions. In the month of December, average night outside air temperature further decreased from 11.2 to 6.5 °C. The inside greenhouse air temperature also dropped from 19.3 to 13.4 °C still showing an increase of about 7-8 °C above ambient air conditions. In the month of January, average night outside air temperature further decreased from 6.0 to 4.4 °C up to mid January and then increased to 8.5 °C in the last week. The inside greenhouse air temperature also dropped from 13.3 to 10.8 °C up to mid January and then increased to 16.1 °C showing an increase of about 8 °C above ambient air conditions. In the month of February ambient air temperature further increased up to 11.4°C in the second week and greenhouse air
temperature also increased up to 20.3 °C thus again showing an increase of about 9 °C above ambient. The slight decrease in the difference between greenhouse and ambient air temperature from mid December to mid January was due to the gradual decrease in the delivery air temperature and increase in greenhouse losses because of outside foggy conditions. It may also be due to slight cooling of the moving water in the trench due to convective heat transfer to air from the moving water surface from the open trench. It was observed that the delivery air temperature of heated air gradually decreased from 25.5 to 23.4 °C from November to mid January and again gradually increased to 25.2 °C in the mid February. The slight variation in the average delivery air temperature didn’t affect the performance of the system much and the system was able to maintain the greenhouse air temperature by about 9-7°C above ambient during winter months.

It is important to note that delivery air temperature was about 2°C higher than the inlet water temperature, which was due to the passing of air through the fast rotating blower vanes that raised the air temperature by about 4°C before delivery. Outside average relative humidity during night remained around 90%. Due to sensible heating of inside air at constant moisture content, the relative humidity is maintained 10-12% lower than the outside conditions for these winter months as also shown in Fig. 6.11.

![Graph showing temperature and relative humidity over months]

**Fig. 6.11 Performance of ACCFHES in heating mode during winter months**
Experimental Performance of ACCFHES in Cooling Mode

Performance of the designed system was tested in sensible cooling mode (8am to 6pm) during the months of mid March and April (without mixing of water with circulating air) and in combined sensible and evaporative cooling mode in May and June (with mixing of water to circulating air).

It is known that the greenhouse air temperature generally increases by 6-7 °C above outside air condition without any cooling arrangement. It is clear from the Fig. 6.12 that integrating the greenhouse with ACCFHES, the average greenhouse air temperature dropped by about 7-8 °C which was about 1-2 °C below ambient for different weeks of each month as compared to the outside air conditions. During the 3rd and 4th week of March, outside day air temperature increased from 31.1 to 32.2 °C. The inside greenhouse air temperature remained between 30.4 to 31.5°C which was 1-2 °C below outside air conditions and was well within the desirable range of plant growth. In the month of April, when the average day time outside air temperature increased from 34.2 to 37.8 °C, the inside greenhouse air temperature was maintained between 33.7 to 38.6 °C which was very close to outside air conditions i.e. 6-7 °C lower as compared to no cooling condition. However, during these months average relative humidity was observed to be between 25-28% only, which was very low and quite close to the outside conditions (A4, Fig. 6.12).

In order to further improve the cooling effect and relative humidity inside the greenhouse during the hottest months of May and June, a simple evaporative cooling process was added after the completion of the sensible cooling process (state points 5 and 6, Fig. 6.5c) before the delivery of cool circulating air. In this process, a measured quantity of water was mixed along with the circulating air in the pipe, starting from the 4th week of April. It was observed that with water mixing, greenhouse average room air temperature dropped from 38.6 to 34.9 °C i.e. 7 °C below outside. It was due to the removal of latent heat of vaporization from the circulating air. This difference was maintained throughout the months of May and June as evident from points M1 to J4 in Fig. 6.12. It was also observed that the average relative humidity appreciably increased from 28.3 % to 58.5 % following the mixing of water. It was also observed that the maximum average relative humidity inside the greenhouse did not increase beyond 70% even with the addition of water in the circulating air. It was due to the mixing of the outside dry air (20% by volume, state point 2, Fig. 6.5c) with the circulating air before entering the blower.
6.4.6 Comparison of Other Climatic Parameters

In this section, comparison of other climatological parameters (inside the greenhouse as well as outside) recorded once in each week for one day (at 1 hr interval) for full winter and summer season of year 2004-2005 starting from 2nd week of November to 1st week of July is presented and discussed.

6.4.6.1 Plant temperature

Average plant temperature inside the greenhouse during the heating period was observed to be 4-5 ºC above the outside conditions as shown in Fig. 6.13. Average inside plant temperature was observed as 23.2 ºC during 2nd week of November (N2), and lowered to 16.6 ºC upto 4th week of January, (J4) as compared to 18.9 ºC and 11.6 ºC during the same weeks for outside conditions. This increase was due to the night heating of the greenhouse with ACCFHES. During no thermal cooling period (F2 to M4) variation of both inside and outside average plant temperature was almost same and it gradually increased from 23 to 28 ºC upto (M4). When greenhouse cooling was started from the first week of April (A1) inside average plant temperature started decreasing as compared to outside conditions. The average plant temperature was then observed 4-5 ºC below the outside conditions from 2nd week of April (A2) upto last week of June (J5). Again due to the onset of rainy season in the first week of July (Jul) both inside and outside plant temperatures decreased.
Fig. 6.13 Weekly comparison of inside and outside average plant temperature during experimentation period at 31°N latitude.

6.4.6.2 Soil temperature

Average soil temperature at 5cm depth is shown in Fig. 6.14. It was observed that it remained 3-4 °C higher as compared to outside soil temperature during the heating period (November to February). This increase was due to the constant heating of greenhouse during night time. It varied from 21 °C to 13 °C which is quite a comfortable range for the roots to grow. During this period outside air temperature remained between 18 to 10 °C. During the month of March when no thermal control was used, inside and outside average soil temperature remained almost same i.e. around 26 °C. With the start of evaporative cooling process in May and June, average soil temperature inside the greenhouse was observed about 2 °C lower than that of the outside conditions. It was due to the lower air temperature inside the greenhouse and due to the shadow of the greater plant canopy (because of more plant area as compared to outside) which did not allow much beam radiation to penetrate inside the soil.
6.4.6.3 Relative humidity

Relative humidity (RH) is also an important parameter for the proper plant growth. It was observed that during the winter season (N2 to F2), average RH remained between 81 to 92% for outside conditions whereas, average RH inside the greenhouse was observed between 75-83% as shown in Fig. 6.15. This 10-12% decrease in RH was due to the sensible heating of inside air at constant moisture. In the 1st week of April, average RH for outside conditions dropped below 40% due to the increase in the dry bulb temperature and further dropped to 35% during the rest of the month for both inside and outside conditions. It was only when evaporative cooling process was started (by mixing water) in the 1st week of May, inside average RH increased significantly and was observed between 55 to 58 % for the rest of the experimental period as compared to outside RH which was observed between 33-30% during May and June. With the start of the rainy season, outside average RH also increased above 70% in the first week of July along with the inside RH as shown in Fig.6.15 so the experiment was terminated.

Fig. 6.14 Weekly comparison of inside and outside average soil temperature during experimentation period at 31°N latitude.
6.4.6.4 Light intensity

Light intensity (LI) is also one of the important parameters for optimum plant growth (photosynthesis). It was observed that the average LI inside the greenhouse remained lower as compared to outside LI for the whole experimental period. Inside average LI was observed as 25.8 klux as compared to 38.1 klux for outside conditions during the 2nd week of November (N2) as shown in Fig. 6.16. Average LI started decreasing with the onset of winter season and reached up to 23.5 klux during D1 as compared to 36.1 klux for outside conditions. A sudden drop in LI for both inside (11.5 klux) and outside (14.5 klux) conditions was recorded during D3, which was due to foggy conditions prevailing during daytime and continued up to J3. The difference between the inside and outside LI was not much (12-15%), which was due to very low beam radiation falling on the greenhouse. Mostly diffuse radiation was recorded during this period. During the 1st week of February (F1) when the sky cleared, improvement in the LI was observed. It was 25.1 klux inside the greenhouse as compared to 40.5 klux for outside conditions. During the rest of the period, LI was observed to be about 70% of the outside with a maximum average of 49.6 klux as compared to 73.2 klux during J4.
6.4.6.5 Solar radiation

The inside and outside solar radiation (SR) also varied along the same pattern of LI as discussed in section 6.4.6.4. It was observed that the average SR was 246.5 W/m² for outside conditions as compared to 135.4 W/m² for inside conditions during the second week of November as shown in Fig. 6.17. Average outside SR remained between 185-120 W/m² during the foggy period of December and January whereas, inside the greenhouse it was between 120-70 W/m² during the same period. From the 1st week of Feb (F1), average outside SR was observed between 278 W/m² to 373 W/m² till the end of March whereas; inside the greenhouse average SR increased from 162 W/m² from F1 to 243 W/m² upto last week of March (M4). From the 1st week of April (A1) upto the last week of June (J5), average outside SR increased from 385 to 457 W/m² as compared to 248 and 298 W/m² inside the greenhouse during the same period.

Fig. 6.16 Weekly comparison of inside and outside average light intensity during experimentation period at 31°N latitude.
6.5 CONCLUSIONS

From the above mentioned results following conclusions can be drawn:

1. Area requirement of ACCFHES is about 22% lower as compared to EAHES.
2. Area requirement of ACCFHES for maximum sol-air temperature of 80°C is 11.72 m² for 24 m² greenhouse area at 31°N latitude.
3. Power requirement of ACCFHES is about 20% lower as compared to EAHES.
4. Power requirement for ACCFHES for maximum sol-air temperature is 678 watts for 24 m² greenhouse area at 31°N latitude.
5. The designed ACCFHES is capable of maintaining the greenhouse average room air temperature by 7-9°C above ambient in winter months.
6. The designed ACCFHES is capable of maintaining the greenhouse average room air temperature by 6-7°C below ambient during summer months.
7. Average plant temperature inside the greenhouse during the heating period remained 4-5°C above the outside conditions and about 4-5°C below the outside during cooling period.
8. It was observed that the average soil temperature at 5 cm depth remained 3-4°C higher as compared to outside during the heating period and about 2-3°C during cooling period.

Fig. 6.17 Weekly comparison of average inside and outside solar radiation during experimentation period at 31°N latitude.
9. Average relative humidity (RH) for outside conditions remained between 81 to 92% whereas, average RH inside the greenhouse was observed between 75-83% during the heating period. Similarly, average RH for outside conditions dropped below 30% for outside conditions in summer months. Whereas inside average RH was between 55 to 60 % during the same period.

10. The average light intensity inside the greenhouse remained about 70 % of the outside conditions both in winter and summer months. Similarly, average solar radiation inside the greenhouse also remained about 70% of the outside conditions during the winter and summer months.