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W.P. No. 2009-11-04
November 2009

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AHMEDABAD-380 015
INDIA

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Abstract

A program was initiated in 1998 to develop technology to improve water and land productivity in Kutch, a vast semi-arid and hot region in north-west India. Greenhouse cultivation was identified as basic approach. A new experimental facility was designed consisting of a greenhouse coupled to ETHE in closed–loop with added provisions for shading, natural ventilation and supplementary evaporative cooling via the foggers.

ETHE was placed in a trench 20 m long, 6 m wide and 3 m deep and back-filled with excavated soil. The greenhouse, a single span saw-tooth (20 X 6 X 3.5 m) structure was erected directly above. ETHE provided 40 air changes per hour. There are three continuous (closable) vents - two laterals along base of long sides, one near top of taller wall. A retractable cover with 60 % shading was provided on top over the cladding. There are 39 overhead foggers placed overhead. The facility was installed in late 2001, at Kothara (φ 23° 14 N, λ 68° 45 E) and investigations carried out to determine (a) the extent to which new facility improves yields, extends cropping season, conserves water compared to open- field in the area, and (b) the extent to which environmental control is achieved.

By using control measures in sequence and in conjunction, it was possible to crop the greenhouse over a span of ten months (July to April), long enough to raise two crops. Hybrid tomato has been raised three times, with mean single crop yield of 62 t / ha, and crop water use 245 mm. Additional 50 mm water was used in supplementary cooling. Yield was nearly two times that of open-fields and water used (for irrigation and cooling) less than half. Natural ventilation along with top shading was effective till the end of February, limiting greenhouse temperature to 34°C. Subsequently, ETHE and foggers were operated. With adult tomato crop inside (4 plants / m^2), operating the ETHE (vents closed, top shaded) for six hours with evaporative supplement from foggers restricted greenhouse temperature to 37 – 38°C.

Water used by foggers, 100-108 liters over the day was one third to one fifth of what fan and pad would need to service a facility of this size. ETHE used 20-24 kWh over a day, about 25% more than estimated for fan and pad system. It was found economical to crop till the end of April or fist week of May and keep the house closed till the end of June. In heating mode - ETHE was able to heat the greenhouse easily from 9°C to 22-23°C in half hour in the cold winter nights and keep it at that till morning. The new facility appears promising for improving yields, making better use of water and extending the growing season in this hot semi-arid region. Work is ongoing, to find ways to reduce installation cost of the ETHE and to develop a more easily scalable design than the present one.

Key words: earth-tube-heat- exchanger; greenhouse; semi- arid areas

Introduction

Kutch region of north-west India spread over 45,000 sq km is semi-arid, characterized by wide occurrence of salt-affected soils and poor quality water. It is bordered in the west by Arabian Sea and in the north by a barren arid expanse. Rainfall is low (mean 300 mm, coefficient of variation 60%), ambient temperatures are high (>31°C in all months, spring and summer >35°C). Vast tracts remain un-cultivated. Livelihood from farming has always been unattractive and difficult due to low and unstable yields. It is generally acknowledged that open-field agriculture in such environment will always be risky, but there has been little research on possible better alternatives (Sharan 1997). Arid climate occurs in many parts of the world. In some areas significant improvement in productivity of land and water has been made by use of protected and covered cultivation. Mears (1990) pointed to such possibilities specifically for arid regions of India. He stated "while a greenhouse is generally regarded as necessary to provide a warm environment in cold climates, it has also been shown that with properly designed cooling system, it is possible to improve plant growing conditions under extensively hot conditions. Adaptation of modern cooling technologies to Indian conditions will undoubtedly lead to increased opportunities for production of high value plants and materials in areas where the environment is extremely harsh. Protected cultivation also has the potential benefit of substantially increasing plant productivity per unit water consumption, which is important in many areas where good quality water is severely limited." Greenhouse technology has come to India, but is limited to colder regions. Adequate research and development effort have not been directed to adapt it to arid hot areas. With that in view, a comprehensive research program was initiated in 1998 by the Centre for Management in Agriculture, Indian Institute of management, Ahmedabad. A new R&D centre was established inside Kutch at village Kothara (φ 23° 14 N, λ 68° 45 E) to develop greenhouse technology specially adapted to conditions that prevailed. Work reported in this paper is drawn from that initiative.

Literature Review

Broad suitability of a region for covered cultivation with simple measures like natural ventilation can be determined by a method developed by Kitts (1995) who used it for that purpose for various regions of Greece. Using the radiation levels and wind velocities of a given region, temperature rise in an unventilated greenhouse (with well watered crop) is first determined using equation (1).

$$\Delta T = \frac{0.017\,K + 2.64}{1 + 0.085\,u^{0.08}} \qquad \text{---------- (1)}$$

Where ΔT is temperature difference (°C), K global irradiance outside greenhouse (w / m^2), and u is wind velocity (m / s) at height of 4 m above ground. Table (1) shows the measured global solar irradiance at noon (12:00) and mean day time wind velocities measured at height close to 4 m at Kothara over all months. Using these in equation, temperature difference was computed and is shown in column (3). As seen, temperature inside closed greenhouse could be above ambient by 11°C in January. The difference increases to 13°C by March. It reduces to 11 only after summer is over. Closed greenhouses will be overheated practically in all seasons in Kothara area. The simplest procedure to reduce temperature, one that does not use energy or water, is natural ventilation. It is close to the coast of Arabian sea (15 km) and wind speeds are generally high , particularly during day time and in spring and summer. Another expression by Kitts, equation (2), gives the relationship between air change rate (renewals) and temperature difference under given radiation levels.

$$R = \frac{0.31\,K_{max}}{\Delta T} \qquad \text{---------- (2)}$$

Where R is renewal (air change rate) per hour, Kmax maximum global irradiance. Natural ventilation is capable of producing up to 40 air changes per hour in windy locations near coast. Assuming that a greenhouse has well designed natural ventilation providing 40 renewals per hour, temperature difference will reduce by nearly half in various months (column 5). It is now possible to indicate the minimum and maximum temperatures that would be expected to occur in greenhouse closed at night and naturally ventilated during the day. A closed greenhouse, without any measure of control, is usually at the same temperature as the ambient at night. During the day, with natural ventilation on, the temperature will be higher by the amount shown in column 5. Minimum and maximum temperatures expected are shown in column six. This is a useful information for planning control measures or for determining whether specific crops can be grown in naturally ventilated greenhouse in an area. For optimal yields the range of temperature for tomatoes is 12°C - 32°C. It is seen that more effective cooling than possible from natural ventilation will be required if tomato is to be grown over all months except December. Heating requirement would be much less, restricted to nights in December to February. Other condition for good growth is the daily mean radiation level outside greenhouse be above 200 W / m^2 which as seen is well met. This illustrates the special challenge such areas pose for use of covered cultivation. Although, as pointed out by Kittas *et al.* (1996), natural ventilation is popular in Mediterranean regions, in Kutch more effective methods need to be devised.

Santamouris *et al.* (1995) reported the experience of coupling the greenhouses to earth-tube-heat-exchangers for environmental control. Eighteen greenhouse installations drawn from different countries using ETHE were reviewed. Most used the ETHE to supplement heating. ETHE was reported to meet 28% to 60% of the heating requirement at different places. Actual use in cooling mode, if any, was not mentioned. But using simulated results for a facility in Athens (37.5° N) they stated that ETHE would be an equally attractive supplement for cooling. Air temperature of the greenhouse in summer was predicted and compared with measurements from their 1000 m^2 glass-covered greenhouse coupled to a set of four underground parallel pipes made of plastic. The air change rate was not indicated. Simulations showed that continuous ventilation of greenhouse with air from the buried pipes will keep the inside air temperature below 40°C. Unventilated greenhouse commonly goes up to 45°C, they stated. ETHE uses energy but no water.

Most common method of cooling greenhouses is the fan-pad system. Water is made to flow down thick cellulose pads installed vertically across a side of greenhouse. Stream of ambient air moves across the pads. Well designed systems of this type can cool the air to near wet bulb and provide effective cooling. Design procedures are standardized, components widely available. Calculations using the Indian Standard Code showed that in the hottest part of the year (June) in Kothara area, fan-pad system will consume approximately 5 - 7 mm of water per day, and will need pumping power depending on the size, about 2 kW , for a 120 m^2 house. Environmental control of greenhouse in Kutch region has special challenges. On one hand the cooling load is excessive; on the other water is in short supply and energy expensive. Yet , given the vastness of lands that produce very poorly in open-fields, there is a need to develop and try various methods of control and make a selection based on the strategy that water and energy use be low, and adverse effects on yields be low.

Table 1 Temperature rise in unventilated and naturally ventilated greenhouse under conditions of Kutch region

Month	Global solar irradiance at noon (w/ m^2)	Mean 4 - m wind velocity during day time (m/s)	Maximum temperature difference – unventilated house Δ T (^oC)	temperature difference with 40 air changes/ hr Δ T (^oC)	Expected greenhouse minimum and maximum temperatures (^oC)	Minimum daily mean global irradiance outside (w / m^2)
January	725	6.1	11	6	8 - 38	385
February	781	6.4	12	6	9 - 39	262
March	883	6.6	13	7	17 - 44	411
April	914	6.4	13	7	20 –44	515
May	952	8.7	13	7	21 - 43	495
June	962	8.5	13	7	20- 42	510
July	658	4.5	11	5	25 - 38	283
August	842	8	13	7	27 - 35	270
September	948	7	13	7	23 - 39	334
October	827	5.5	13	6	19 - 46	334
November	746	5.3	12	6	15 - 37	300
December	678	5.6	11	5	7 - 32	325

At night temperature inside and outside a closed greenhouse is usually equal
Maximum Day time temperature in naturally ventilated greenhouse will be higher by amount shown in column 5.

Objectives

A special experimental facility was installed at Development and Outreach Station, Kothara (Kutch) towards the end of 2001. It consists of a 120 m^2 plastic clad greenhouse with provisions for natural ventilation, mechanical ventilation via ETHE, shading. It did not have a full fledged fan-pad system but provision was made for supplementary evaporative cooling via foggers. Work reported in this paper was carried out with following objectives.

1. To determine the extent to which environmental control is achieved with the use of various measures in sequence or combination – shading, natural ventilation, mechanical ventilation from ETHE, foggers.
2. To carry out cropping trials to determine the extent to which greenhouse with these controls can improve yields, reduce water requirement and extend cropping season.

Experimental Facility

Most components of the facility could be designed by established procedures. The ETHE however required several parameters for which new investigations had to be carried out. These related to soil temperature regime and performance of ETHEs in cooling and heating modes in the region. These are briefly described here.

A four meter long probe loaded with sensors was installed with lower three meter section below and top one meter above ground to monitor soil temperature regime at Ahmedabad. The probe described in detail by Sharan and Jadhav, 2002 was made of a 50 mm diameter PVC tube on which five sensors (RTD - PT 100) were mounted, one just 2 cm below ground surface, second third and fourth at -1 m, -2 m, -3 m , the fifth at +1 m. The one on top was shielded from direct sun. A year long monitoring showed that diurnal fluctuations ceased beyond about one meter depth. Fluctuation in the annual wave did persist but diminished in amplitude with depth. Measured characteristics of annual wave at the surface (peak on day 105 , amplitude 10 °C , mean 26 °C) enabled development of equation (3) describing annual wave in Ahmedabad region.

$$T(t,z) = 26 + 10\, e^{-\alpha z} \cos \left[\frac{2\pi}{365}(t-105) - \alpha z \right] \quad \ldots\ldots\ldots\ldots \quad (3)$$

Where T is temperature (°C) , t day of year beginning January 1, z depth below surface (m), k thermal diffusivity of soil , ω angular frequency of annual wave (2 π / 365), $a = \sqrt{\frac{\omega}{2k}}$, wave number. As generally known and apparent from the equation, that the higher frequencies (diurnal for instance) will decay faster than lower frequencies (annual). Soil temperature in the area near the place of measurement would be expected to become virtually constant (26°C) beyond 6 m. Choice of depth at which to place ETHE pipes depends on cost of trenching which goes adverse with depth and stability of temperature which improves. Equation (3) can be used to determine stability at any desired depth. In applications intended here - greenhouse and animal dwellings - ETHE would be on and off for a few hours alternately.

It was decided to choose 3 m strata to place the pipe. A single pass ETHE was built next for study of actual cooling and heating performance. The unit described in detail by Sharan and Jadhav, 2003 was made of a 10 cm diameter 50 m long mild steel tube buried 3 m deep (Figure 1). It was similar to that used by Baxter, 1992, 1994. Three sensors (thermister AD

590) were installed inside tube at inlet , middle (25 m) and outlet (50 m). Fan was direct drive industrial type 0.38 kW, blower with radial blades, air velocity in the tube 11 m/s , flow rate of 0.0863 m^3/s or 5.17 m^3/min. ETHE was operated over three consecutive days of each month, except January when tests were done at night. Test results of May, 2000 and January, 2000 are discussed briefly**.** Figure 2 shows test result averaged over three days of May. Tests began at 10 am and closed at 5 pm. Mean temperature of air entering the tube was 37°C, varying from 31°C to 41°C. After four hours, the temperature of air inside tube at 25 m was 30 °C and at outlet, 27°C. After seven hours it was 30.5°C in the middle and 27°C at outlet. The tube affected a mean difference of 10°C , of which a major part 7°C , occurred in the first 25 m. Figure 3 shows the results from heating mode tests averaged over three nights of January. Tests began at 6 pm and ended at 6 am next morning. Mean temperature of air entering the tube was 11°C varying from 20°C at the start of test to a low of 8°C early morning. After eight hours of operation, air temperature inside tube was 17.4°C midway and 21.7°C at outlet. After twelve hours of operation, the respective temperatures inside were 17°C and 21.6°C. Thus the tube affected a mean difference of 10.6°C in heating mode of which a slightly higher part occurred in the first half.

Greenhouse inside temperature is normally maintained in the range of 18°C to 30°C. Night temperatures in winter in coastal areas of Kutch range from 7°C – 9°C. Day temperatures from March onwards vary from 35°C to 40°C. Heating mode performance of the experimental ETHE indicated that it would be able to provide hot air to heat the greenhouse to satisfactory level. Cooling mode performance indicated that ETHE would meet cooling needs only partially and may need to be supplemented by evaporative cooling.

New Cropping Facility

It was installed late in 2001. Detailed description can be seen in Sharan *et al*. 2003, Sharan and Jethva 2008. Figure (4) shows schematic diagrams of the facility and Figure (5) the actual photo of the ETHE before backfill. Greenhouse is a single span , saw-tooth structure (20 m X 6 m X 3.5 m) with floor area of 120 m^2 and volume 360 m^3. It is clad with 200 micron UV stabilized clear PE film. There are three closable vents , each 20 m X 0.5 m, two at the base of the side walls, third at the top of higher side wall. Those at the base are continuous; one on top is segmented to support closable louvers. Vents are screened with commercially available stainless steel wire mesh - 15 strands per inch in each direction and whole size less than a 1 mm. Unscreened vent area was 25 % of the floor area. A retractable shade net was put on top. Shade net was installed above the house over the cladding. Shade nets are knitted fabric of UV stabilized HDPE plastic. Net used was green-black with manufacturer-rated shading of 50 %. There are 39 foggers (each with discharge 0.007 $m^3 hr^{-1}$) installed overhead inside.

ETHE is buried 3m deep directly below and coupled to greenhouse in closed-loop. Initially it had a smaller flow rate, later upgraded to 4 m^3 /s or 0.033 m^3 per m^2 floor area per second, providing 40 air changes per hour. Existing standards for greenhouse ventilation stipulate that air change rate be at least 60 per hour. But the duct sizes were becoming unwieldy and expensive to fabricate. Therefore only 40 changes per hour were provided. It is made of eight pipes that merge into common headers at both ends. Pipes are of mild steel with wall thickness of 3 mm, arranged in two tiers. First tier is at 3 m, second at 2 m depth. Pipes are 23 m long and 20 cm diameter, placed 1.5 m apart laterally. Inside air from greenhouse is drawn, cycled through buried pipes and returned to the house. A centrifugal blower powered by 4 kW, 1440 rpm motor moves the air. Sharan and Madhavan, 2003 made a model of heat transfer between air flowing through buried pipe and surrounding soil for use as a tool of analysis and design. The model is for a single pass. In single pass a 20 m long pipe of the size and type used in ETHE would cool air enter at 40 °C to 36 °C to 37 °C .

Results and Discussion

Unventilated, empty greenhouse without shade stays at nearly the same temperature as the ambient through the night. It begins to heat up above the ambient after sunrise. June is usually the hottest month in Kothara. Table (2) shows temperature rise in closed, partially and fully ventilated house on three consecutive days in June when conditions were very similar. A closed house went up to 58 ^{o}C, 22 ^{o}C above the maximum in greenhouse. With two lateral vents open the difference reduced to 7, and with all three vents open further to 4. Higher temperature rise, than predicted by equation (1) was expected as the house was empty, soil bare without plants. High wind velocities in June induce high renewal rates in empty condition.

Cooling measures included (a) top shade (b) top shade and natural ventilation (c) top shade , forced ventilation via ETHE (d) top shade , ETHE on , supplementary evaporative cooling via foggers. Measures (a) and (b) do not use energy; (c) uses energy, no water and (d) uses energy and some water. Investigations aimed at determining the sequence in which the measures could be used with economy of energy and water. With crop inside, temperature in unventilated house do not rise as much. A series of observations on a set of successive days in June 2005 indicated the effectiveness of these measures. Radiation levels, wind velocity and ambient temperatures were very close together in that week. Sky was clear. Results are summarized in Table 3.

Table 2 Temperature rise in empty greenhouse with and without ventilation – Kothara June 2002			
Day	Greenhouse state	Day time ambient temperature (^oC)	Day time greenhouse temperature (^oC)
June 14, 2002	Empty, no shade, closed	31- 36 (mean 35)	36 -58 (mean 51)
June 15, 2002	Empty, no shade, two lateral side vents open, top vent closed	31- 37 (mean 35)	33 -44 (mean 39)
June 16, 2002	Empty, no shade, all vents open	33- 38 (mean 35)	34 -42 (mean 39)
Greenhouse temperature measured 1m above floor at three locations via logger, day time from 8:00 to 18:00			

Table 3: Effectiveness of various control measures - greenhouse had adult tomato crop inside - Observation made on successive days in June 2005 at Kothara				
Control Measure during day (10:00 to 17:00 hrs)	Mean ambient Temperature (°C)	Mean greenhouse Temperature (°C)	Mean relative humidity (%)	Energy and water use
Shade on vents closed	35	44	56	None
Shade on vents open	35	39	55	None
Shade on vents open ETHE on	36	40	55	24 kWh
Shade on vents open ETHE on foggers on 30 minute interval 2 minute burst	35	38	67	24 kWh 108 liters

As seen with crop inside (adult tomato 4 plants / m^2) top-shaded, temperature inside closed greenhouse in June was on an average 9°C higher than the ambient (35°C). The mean humidity level during day time was 56%. Turning on natural ventilation along with top Shade, measure (b), reduced the difference between inside and outside temperature to 4°C. As indicated earlier opening all three vents was most effective. Actual measurement of ventilation rate during natural ventilation was not possible in the facility. But if one uses equation (2) with noon time radiation level (900 W / m^2) reduced to half to account for shade net effect , the renewal rates for a difference of 4°C would wok out to 35 per hour. This is plausible as wind velocities during noon are high, 8 m /s. Forced ventilation from ETHE with top shade on (measure c) also restricted the difference to 4 ^oC. Forced ventilation using recycled air from ETHE and fogging supplement kept the greenhouse at 38°C.

Greenhouse is closed from early evening to early morning in all months. Top shade is also retracted. Shade is put back on and vents opened during day for a span of time. With these measures from 10:00 to 17:00 in January , hourly values of mean greenhouse inside temperature were typically - 26°C (10:00) , 30°C, 31°C, 32°C, 33°C, 33°C, 33°C, 32°C. Similar measure in February had typical day temperatures - 23°C (10:00), 28°C, 31°C, 33°C, 34°C, 34°C, 34°C, 32°C, 31°C. Initially this measure was used for 4 hours (around noon) and later 6 hours. But it appears useful to keep it uniform for seven hours from 10:00 to 17:00 in the month of January and February. This prevented the inside greenhouse from going above 34°C.

Control measure (d) consists of top shade on, forced ventilation via ETHE and fogging burst at 30 minute interval. This measure, from 10:00 to 17:00 kept mean greenhouse temperature during the day at 37°C – 38°C**.** Figure (4) shows the details of the temperature and humidity during the day with measure (d) on. This measure is adopted in March, April and part of May when the mid-day temperatures typically reach 36°C to 37°C. With this water used is about 100- 108 liters. This is one third to one fifth of what would have been needed had fan and pad been employed. Five to six hours of ETHE operations used 20 – 24 kWh of electricity. The fan and pad system would use approximately 70% to 7% of that, 15 -18 kWh. Initially for two seasons, greenhouse was operated fully in the month of May and partly in June. But fruit sizes became small, electricity and water use increased. It was therefore decided to end cropping in April or early May.

Heating was required for only a short period from mid - December to mid -February, when night temperature begins to drop below 18°C. Sharan et al. 2003, reported that heating was effectively done with ETHE which was able to heat the greenhouse from 9°C to 22-23°C in half hour in the cold winter nights, Sharan et al. 2003. Temperature inside could be maintained above 18°C either by an on/off schedule or continuous run of ETHE.

Hybrid tomato has been grown three times. Mean yield in three years was 62 t / ha and water use for crops 245 mm. By limiting cropping to April, water used for foggers is equivalent of 50 mm. Water used in open-field in this area would be twice as much. In immediate neighborhood in this district the yields are much lower, but in humid areas on the province where commercial growers are, the best yield in open-fields reported 30 t / ha. For reasons of space no details are given, but mention is made of another application of ETHE. Three systems of single pass type were installed for animal houses.

Conclusion

Kutch region of north-west India is characterized by high temperatures, low rainfall, salt-affected soils and poor quality of water. Controlled environment agriculture appears to be a promising means to make these vast lands more productive. A special facility consisting of greenhouse with four measures of environmental control – shade net, natural ventilation , mechanical ventilation via earth-tube-heat-exchanger and supplementary evaporative cooling via foggers - was developed and cropping carried out over several seasons. Use of these controls in sequence and in conjunction permitted cropping over a ten month span, improved yields and reduced crop water requirement. In case of hybrid tomato which was raised three times, water required for irrigation was nearly half of that in the open field and the yield nearly two times.

Cropping could be done from July to April. It became too hot to continue through May and June. The schedule of environmental control was as follows - in colder months, opening the vents for six hours (10:00 to 17:00 hour) was adequate. Beginning February, top too was shaded during day. This kept the inside temperature below 34°C. From early March, ETHE needs to be operated along with fogging from 10 am to 6 pm. This prevented the inside temperature from rising above 37°C -38°C.

Fabrication of massive ETHEs is expensive. It would be desirable to find ways to reduce cost, which may be possible by use of plastic pipes. The present ETHE has a bundle of eight pipes arranged in two tiers. Such a configuration does not permit easy scale-up. It would be useful to develop new configurations that would permit making larger but compact ETHEs.

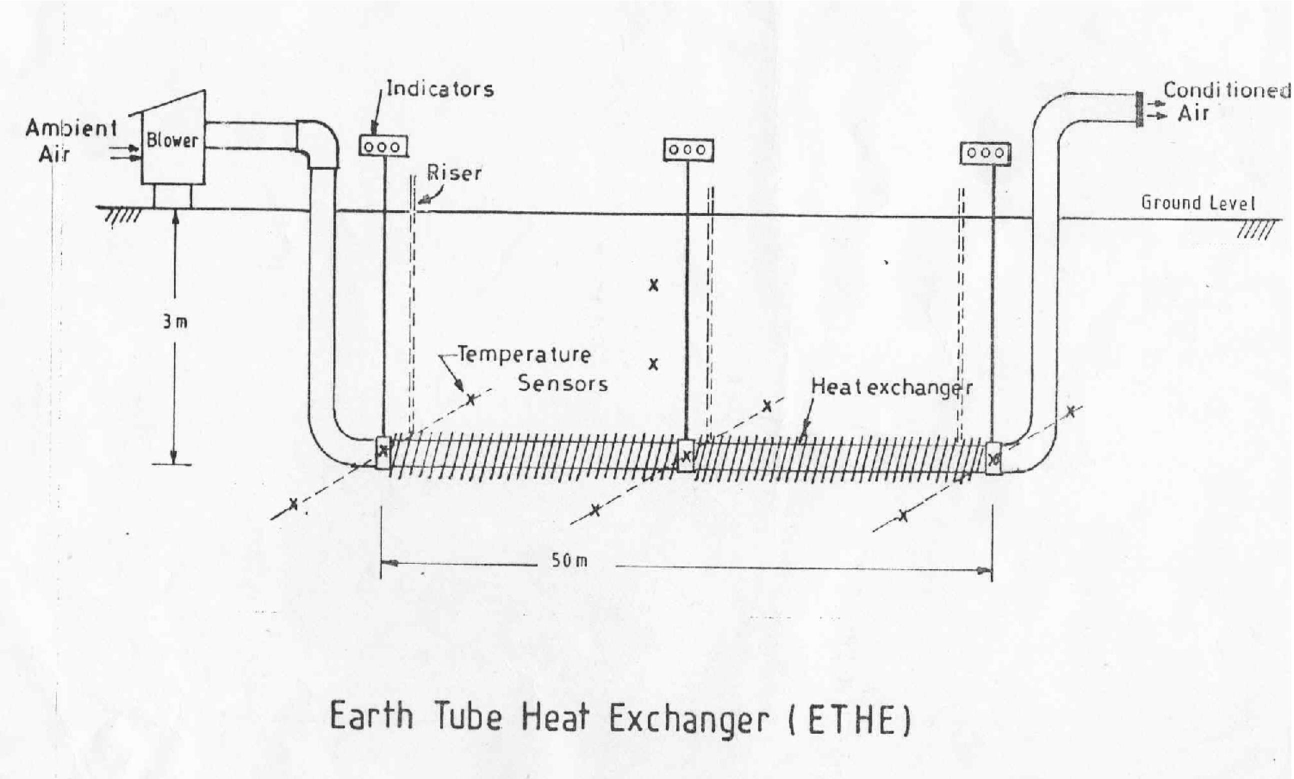

Fig 1:

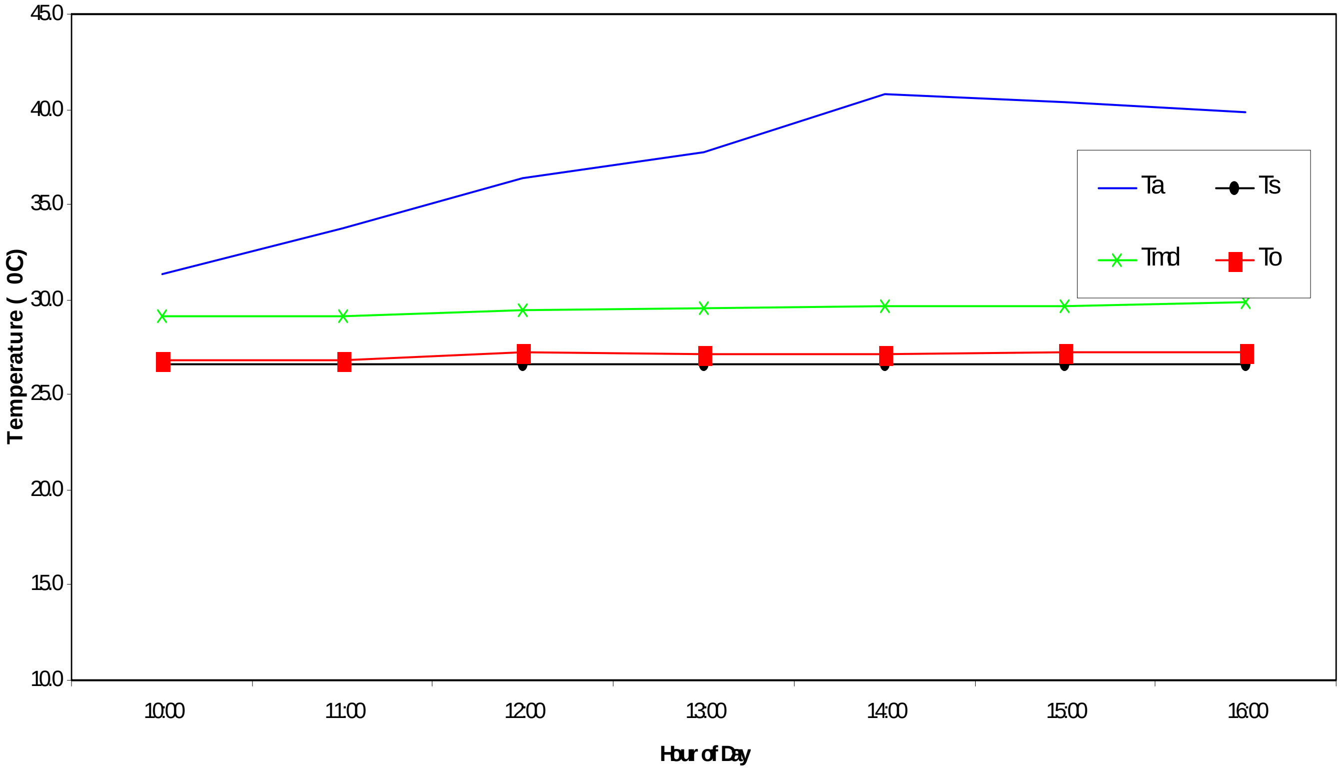

Fig 2 : Air temperature inside ETHE and soil temperature (May)

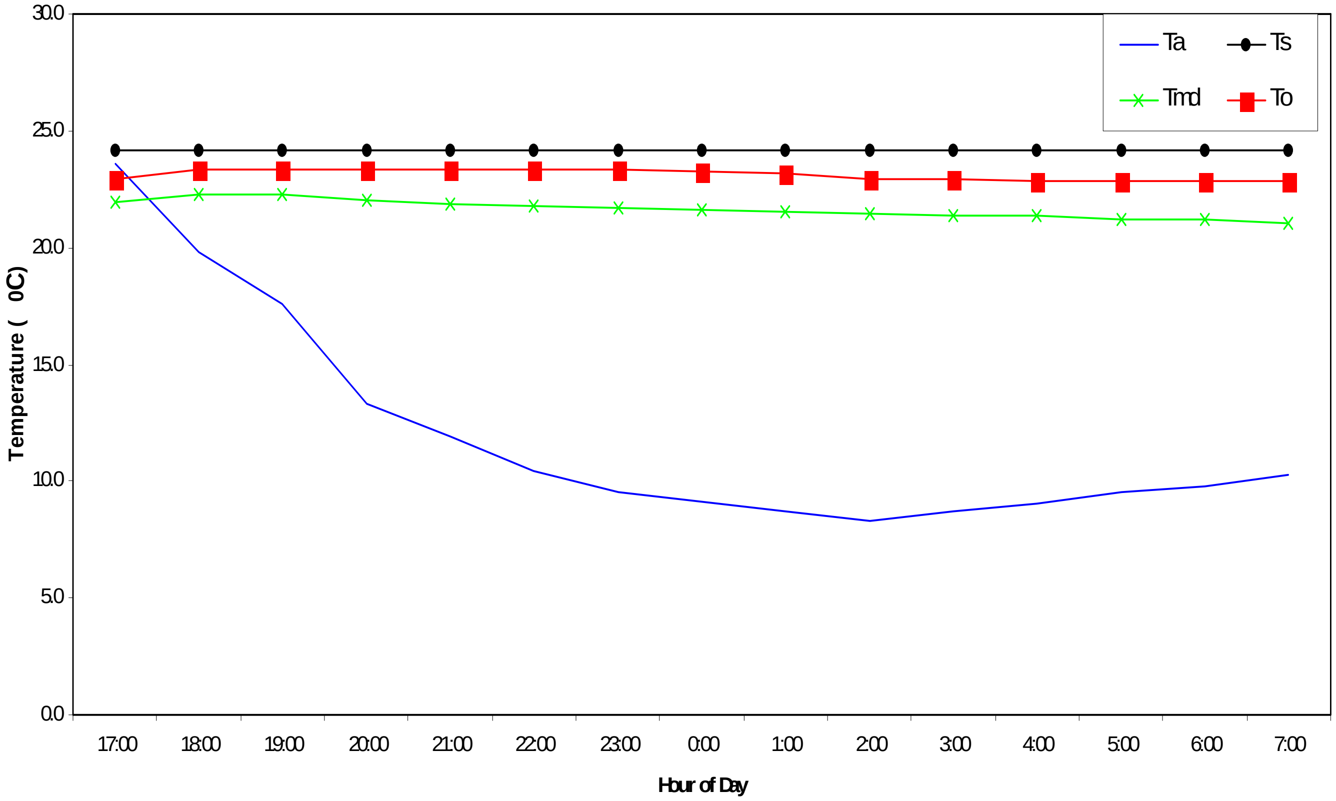

Fig 3 : Air temperature inside ETHE and soil temperature (January)

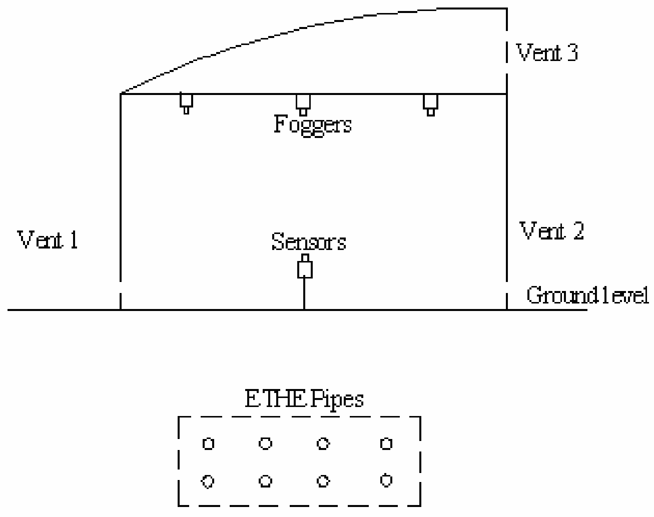

Fig.4 . Arid Area green house schematic

Fig 5. Earth tube heat exchanger before backfill

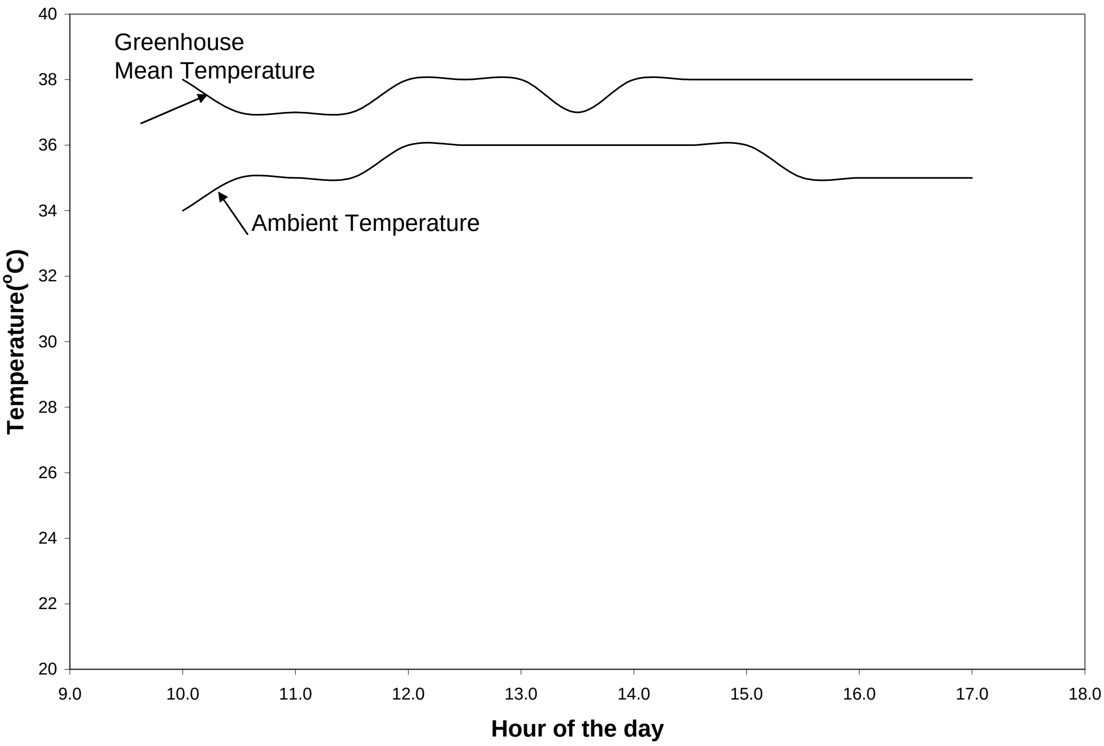

Fig 6. Mean temperature of greenhouse air and ambient With ETHE ventilation and fogging

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