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An Analysis of Greenhouses Heat and Ventilation Requirements in Winter Arid Climate

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Abstract. This study investigates environmental conditions, heat and ventilation requirements of greenhouses in winter arid climate. Simulation models for estimating greenhouse heating and ventilation requirements with five greenhouse-glazing systems in arid climate conditions were presented. All estimates were for the central region of Saudi Arabia for crop production requiring 22°C day temperature, and 10/18°C night temperatures. The estimated ventilation and heating requirements were calculated from weather data on single fiberglass, single polyethylene, single glass, single glass & thermal blanket and double glass. Also, measurements from a 39- × 9-m Quonset-style greenhouse planted with tomatoes, covered with a sheet of fiberglass-reinforced plastic and equipped with a heating unit with a perforated poly-tube were presented and discussed. Heating requirement using single fiberglass was predicted to be slightly the highest among all covers. The annual heating requirements should be increased by 65% with 18°C set point temperature at night compared to a set point temperature of 10°C. It was estimated that 35-41% of annual heating is required during the month of January. The model predicted an annual energy saving of 8-34% for the single glass and blanket covering system, and 50-56% for the double glass system. A comparison of greenhouse heat and ventilation requirements was also conducted for sunny and cloudy days. Vertical and horizontal distributions of temperature and relative humidity were also discussed. Ventilation load peaked at midday hours, and reached zero during nighttimes. Heating load peaked in the morning before sunshine. Ventilation and heating systems were capable of maintaining the inside conditions at permissible limits for plants growth. However, heating system was not capable to maintain the desired temperature of 18°C at a significant number of nights. Averages of inside temperature and relative humidity at daytime were 21.5°C and 51.7%, respectively, as compared to 16.5°C and 33.6%, respectively, outside the greenhouse. Whereas, nighttime inside averages were 13.7°C and 75.6%, respectively, while the outside averages were 11.3°C and 43.6%, respectively.

Introduction

Greenhouses are required for crop production in Saudi Arabia during summer and winter periods. Greenhouses can provide a suitable environment that will result in improving crop growth and production. Thus, a greenhouse is equipped with some environmental modifications such as heating, ventilating and cooling systems. During cold outside conditions, heat is added to the greenhouse to maintain an adequate air temperature inside the greenhouse for crop production. The source of greenhouses heating in Saudi Arabia is generally driven by diesel fuel and boilers, central or localized (Al-Helal, 2008). In central system, one or more boilers are located in a single position, and the steam or hot water generated is piped to various greenhouse locations. Hot pipes are usually placed low and between the rows of a crop or beneath the benches of most potted crops.

One of the problems facing greenhouse industry in Saudi Arabia is the inadequacy of the heating system to maintain the environment at required temperature during cold winter nights (Al-Helal, 2008). This may be attributed to the insufficient capacity of heating system. This could result in dropping the inside air temperature below the desired air temperature. In some cases where heat is not added to the greenhouse, night temperature drops very rapidly to the outside air temperature. Most greenhouses in Saudi Arabia have a surplus solar heat supply during the day because of the availability of solar radiation. The amount of monthly solar radiation incident on a horizontal surface for Riyadh varied between 670 and 1000 W/m^2, the lowest value being in December and the highest observed value was during July, with the ratio of the actual to the maximum sunshine hours varied between 0.62 and 0.8 (Hummeida and Mohammad, 1993).

Greenhouses require ventilation during wintertime to remove excess heat and moisture, increase air mixing, and maintain adequate level of carbon dioxide. Winter ventilation requirement needs to be determined, since poor ventilation would lead to inappropriate conditions in the greenhouse, which adversely affects plant growth and production. Therefore, a good knowledge of ventilation requirement is essential for good greenhouse management. During winter, a greenhouse requires ventilation at only daytime because of its ability to collect solar radiation energy. An unventilated, unheated greenhouse will reach over 30^{o}C in a bright sub-freezing winter day. On cold winter nights, the greenhouse should be closed to reduce heat requirement. A more efficient designed greenhouse must not allow night temperature to decrease below 16^{o}C and day temperature to range from 22^{o}C to 28^{o}C (Short *et al.*, 1980). To maintain the greenhouse at the desired air temperature, the greenhouse requires heating during nighttime and ventilation during daytime.

Understanding of the greenhouse thermal behavior can be accomplished by the use of simulation models (Bot, 1983; Wang and Boulard, 2000; Shukla *et al.*, 2006; Tiwari *et al.*, 2006; Abdel-Ghany and Kozai, 2006). Some models have been developed to predict greenhouse environmental conditions from meteorological conditions. Shukla *et al.* (2006) presented a thermal model for the heating of greenhouse by using different combinations of inner thermal curtain, an earth-air heat exchanger, and geothermal heating. The results showed that an earth-air heat exchanger might prove an alternative source for the heating of greenhouse when geothermal energy is not available. Marsh and Singh (1994) used a steady state energy balance to determine the amount of the heat energy required for a time step of 1 hour. Also, Power *et al.* (1989) developed a Degree-Day method for greenhouses to estimate annual heat requirements over a wide range of inside set point temperatures.

The most critical early decision, when starting or expanding an efficient greenhouse production system, is the selection of adequate heating and winter ventilation systems. Heating and ventilation management is one of the most important considerations for improving the future economic viability of a commercial greenhouse operation and control. Little data is available on greenhouses heating and ventilation requirements and operations during winter in Saudi Arabia. Therefore, the objectives of this paper were to:

- Design and determine winter heating load and ventilation requirements for a greenhouse in arid climate conditions under different covers for a given set of weather data.
- Investigate environmental conditions, and heat and ventilation operations of a fiberglass greenhouse in winter arid climate.

Material and Methods

Simulation models for estimating heating and ventilation requirements for a greenhouse in arid climate conditions were proposed. Also, measurements from a Quonset-style greenhouse equipped with a heating unit with a poly-tube were presented and discussed.

Simulation models

The steady-state energy balance for the greenhouse was applied (Hellickson and Walker, 1983; Albright, 1990). The model assumed that incoming solar radiation energy (Q_{sr}) and heater energy (Q_h) to be equal to the outgoing heat losses (Q_{loss}) and the heat removed by ventilation air (Q_v). Neglecting the change of energy stored in the greenhouse and other small fluxes such as , the energy balance equation for the greenhouse was written as:

$$Q_{sr} + Q_h = Q_{loss} + Q_v \qquad (1)$$

By assuming half of the incoming solar radiation to be transferred into latent heat (Hellickson and Walker, 1983), the variable Q_{sr} was expressed as:

$$Q_{sr} = I \, \tau \, A_f (1 - E\,F) \qquad (2)$$

where

I = amount of solar radiation energy received per unit area and per unit time on a horizontal surface outside the greenhouse (W/m^2).

τ = transmissivity of the greenhouse covering materials for solar radiation.

A_f = floor area of the greenhouse (m^2).

E = the ratio of evapotranspiration to solar radiation.

F = ratio of ground covered by plants to total ground area.

Heat can be lost by conduction through the covering material (Q_c), by infiltration through cracks in the covering (Q_{inf}), and by thermal radiation exchange between the surfaces inside the greenhouse and the atmosphere (Q_t). Thus:

$$Q_{loss} = Q_c + Q_{inf} + Q_t \quad (3)$$

The transmitted thermal radiation loss was included as a part of the U value for the overall heat transfer coefficient (Hellickson and Walker, 1983). Therefore, the variables Q_c and Q_t (W) in Eq. (3) were defined by the following relationship:

$$Q_{ct} = Q_c + Q_t = U\, A_c\, (T_i - T_o) \quad (4)$$

where
A_c = area of the greenhouse covers (m^2).
T_i = inside air temperature (°C).
T_o = outside air temperature (°C).
U = overall heat transfer coefficient ($W/m^2\,^oC$).

Heat loss due to air infiltration was calculated from the following equation:

$$Q_{inf} = V\,(N/3600)\,\rho\, C_p\,(T_i - T_o) \quad (5)$$

where
V = greenhouse volume (m^3).
N = number of natural air exchange between inside and outside greenhouse per hour (1/hr).
ρ = density of air (kg/m^3).
C_p = the specific heat of air (J/kg °C).

The heat is removed by the process of ventilation (Q_v) were expressed as (Hellickson and Walker, 1983):

$$Q_v = V_{air}\,\rho\, C_p\,(T_i - T_o) \quad (6)$$

where V_{air} was the volumetric ventilation rate (m^3/s), and Q_v in W.

When heater is used, the ventilation system should not work (or Q_v = 0). The amount of heat required for a unit area of ground surface at any given time was then determined by the following equation:

$$Q_h = [U\, A_c/A_f + \rho\, C_p\,(V\, N/3600)/A_f](T_i - T_o) - I\,\tau\,(1\text{-}0.5\, F) \quad (7)$$

If the calculated heat requirement, Q_h, is negative, then Q_h is set equal to zero. A negative heat requirement indicates the air temperature in the greenhouse is warmer than the set point temperature, and the greenhouse requires ventilation. During ventilation process, the natural air exchange between the inside and outside is negligible. Thus, Q_{inf} is set equal to zero. The ventilation rate (m^3 air/s per unit area of the greenhouse ground) was calculated by substituting Eqs. (2), (4) and (6) into Eq. (1) (letting Q_h and Q_{inf} equal to zero):

$$V_{air} = [I\,\tau\,(1\text{-}0.5\, F)/(\rho\, C_p\,(T_i - T_o)) - U\, A_c/(A_f\,\rho\, C_p)] \quad (8)$$

Equations 7 and 8 were used to estimate heating and ventilation requirements, respectively. The inputs of the models were hourly temperature and solar radiation data recorded at the solar village in Uuaina near Riyadh (latitude 24°53' N, longitude 46°26' E) in the middle of Saudi Arabia for the period 1996-2000. The models calculate the energy losses and gains including solar radiation, conduction through glazing and infiltration. If the total energy gain is less than the total energy losses, the model calculates the required heat to keep the set point temperature constant. If the total heat gain is greater than losses, the model calculates the heat needs to be removed by the process of ventilation to keep the set point temperature constant. The data was analyzed for only six months (from November to April). The data was analyzed on single fiberglass, single polyethylene, single glass, single glass and thermal blanket, and double glass. It was assumed that the thermal blanket is drawn off in the morning so that it is only used during nighttime. The calculated daily heat requirements were summed to obtain the yearly heat requirement. Table 1 lists the parameters values used for the simulation.

Experimental greenhouse

Experiments were carried out in an experimental Quonset type greenhouse with an effective floor area of 351 m^2 (Fig. 1). The north-south oriented greenhouse was located at the research station of King Abdulaziz City for Science and Technology at Al-Muzahmyah near Riyadh (latitude 24°28' N, longitude 46°14' E). A diesel-oil heating system with a rated thermal output of 50 kW was used to heat the greenhouse. The heater was located at the north side of the greenhouse and hanged with the ceiling. The heated air was injected into a perforated poly-tube for circulation and distribution inside the greenhouse. The temperature inside the greenhouse was controlled at 18/22°C (night/day) by means of one air sensor placed at a height of 1.5 m in the middle of the greenhouse. The greenhouse consisted of metal framing and fiberglass-reinforced plastic covering.

Table 1. Input variables used in energy balance simulation model

Variable	Value	Source
I	Hourly weather data	Weather data
T_o	Hourly weather data	Weather data
T_i	22°C (day), 10°C and 18°C (night)	Set-point temperature
τ	0.88 (glass), 0.89 (single polyethylene), 0.79 (single fiberglass) and 0.78 (double glass)	Hellickson and Walker (1983)
U	6.3 (glass), 6.8 (single polyethylene), 6.8 (single fiberglass); 3 (single glass & thermal blanket) and 3 (double glass)	Hellickson and Walker (1983)
A_f	351 m^2	Floor area of the experimental greenhouse
A_c	561 m^2	Cover area of the experimental greenhouse
F	0.78	Estimated value for the experimental greenhouse
E	0.5	Hellickson and Walker (1983)
N	1 air exchange per hour	Hellickson and Walker (1983)
ρ	1.1 kg/m^3	Incropera and DeWitt (1990)
C_p	1007 J/(kg °C)	Incropera and DeWitt (1990)

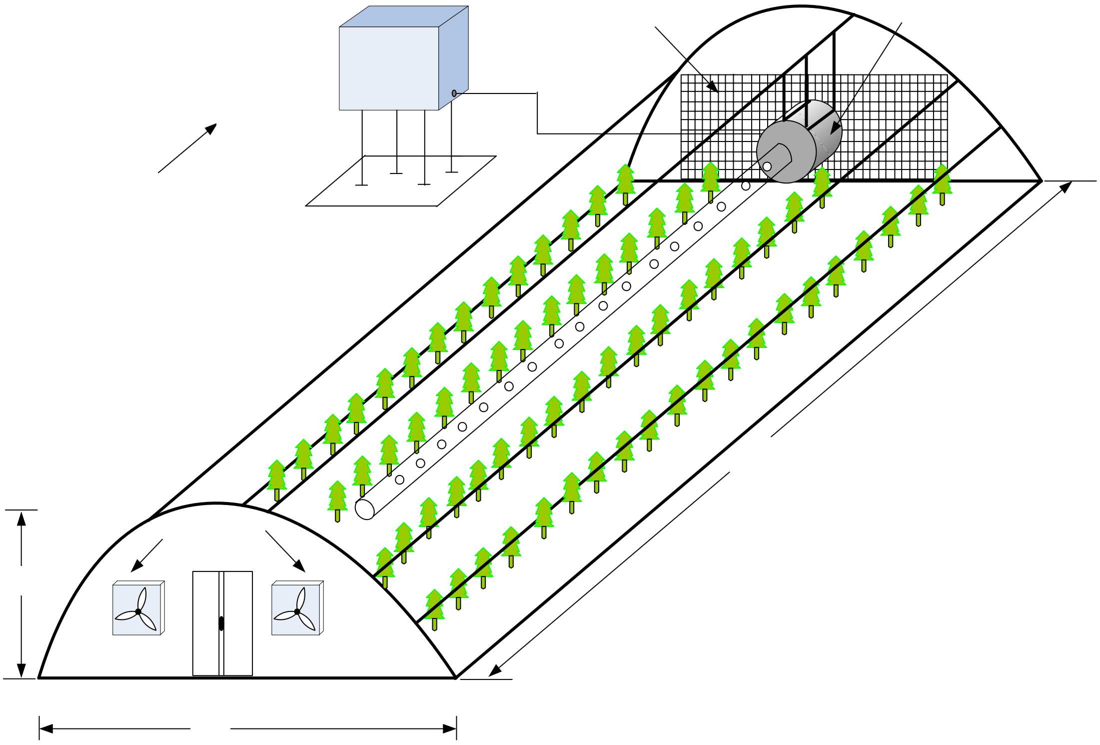

Fig. 1. Schematic plane of the experimental greenhouse.

Ventilation was achieved by two exhaust fans located on the south-end of the greenhouse, and incoming air was forced through 12 m^2 (2 m × 6 m) of 10 cm thick pads set on the north-end of the greenhouse, and used only during summer months. The rated ventilation rate of each fan was 36,000 m^3/hr. Fans controller allowed the fans to operate whenever the greenhouse temperature exceeded 22°C. Tomato seeds were planted in a nursery and grown for three weeks. Then, seedlings were transferred inside the greenhouse with a density of 1.8 plant/m^2. Plantation cycle started on 5 November 2002 and concluded on the end of April 2003. Water and fertilizers were supplied by a drip irrigation system. Data was analyzed for the period from 1 January 2003 to 31 January 2003.

Diesel tank

N

Measurements

The arrangement of sensors in the greenhouse is shown in Fig. 2. The following climatic parameters were measured:

(i) Air temperature inside the greenhouse at six locations. Data taken at the six locations were averaged to determine inside air temperature.
(ii) Inside relative humidity at four locations.
(iii) Outside climatic conditions including air temperature, relative humidity, incoming solar radiation incident on a horizontal surface and wind speed.
(iv) Air speed inside the greenhouse at two locations.

Electrical energy consumption by the ventilating fans was also measured. Diesel fuel consumed during the heating process was measured manually from the fuel level in the tank readings that were taken daily at 7:00 AM. The difference between readings for two consecutive days was assumed to have been consumed. Temperature and relative humidity outside and inside the greenhouse were measured with portable, shielded and naturally ventilated sensors (Vector instruments, Denbighshire, N. Wales, United Kingdom). The solar radiation outside the greenhouse was measured using a solar radiation sensor (Kipp & Zonen). All data were acquired in an instantaneous manner by a data logger and an IBM compatible computer to collect data every five seconds and averaged over 1-minute periods.

Results and Discussions

Simulation data

Monthly day and night temperatures, and solar radiation for Uuaina for six months (November to April) averaged over the period 1996-2000 are illustrated in Table 2. The monthly averages of day temperatures ranged from 15.1 to 26.6°C, and from 12.5 to 23.9°C at nighttimes. The lowest average of ambient temperatures occurred during the month of January, while the highest occurred in April. The highest monthly average of solar radiation was 492 W/m^2 during the month of April, while the lowest was 359 W/m^2 in January. Figure 3 shows the frequency distribution of different ambient temperature ranges for the four winter seasons. The highest frequency was for the range (15 to < 20°C), while the lowest was for the range (1 to < 5°C). On the average, the frequency of the temperature ranges (1 to < 5°C), (5 to < 10°C), (10 to < 15°C), (15 to < 20°C) and (20 to < 25°C) were 31, 285, 1010, 1340 and 953, respectively. Peak occurrence (79) of the interval (1 to < 5°C) was during the winter season 1997-1998. No frequency of the sub-zero temperatures occurred.

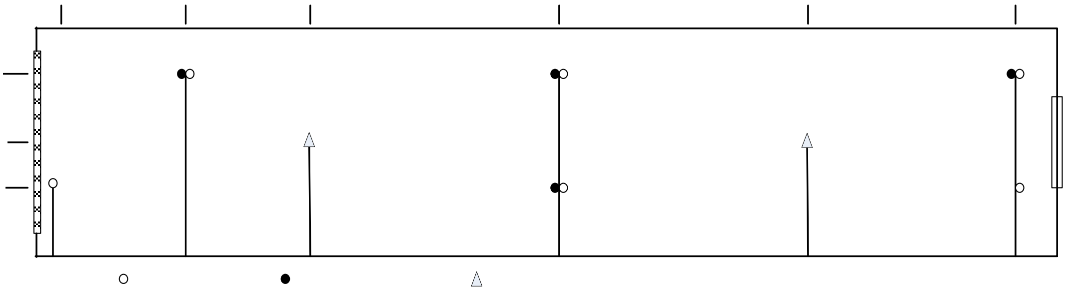

Fig. 2. The arrangement of sensors inside the greenhouse.

Table 2. Averages (standards deviations) of monthly day and night temperatures, and solar radiation for Uuaina for six months (November to April) over the period 1996-2000

Month	Temperature (°C)		Solar radiation (W/m^2)
	Day	Night	
November	20.1 (1.4)	17.7 (1.2)	368.5 (41.3)
December	17.2 (1.2)	14.3 (1.1)	361.5 (36.7)
January	15.1 (0.6)	12.5 (1.1)	359.0 (5.1)
February	17.2 (0.9)	14.9 (1.0)	441.8 (15.5)
March	21.2 (1.5)	18.5 (1.2)	466.8 (23.3)
April	26.6 (2.2)	23.9 (2.1)	492.2 (15.6)

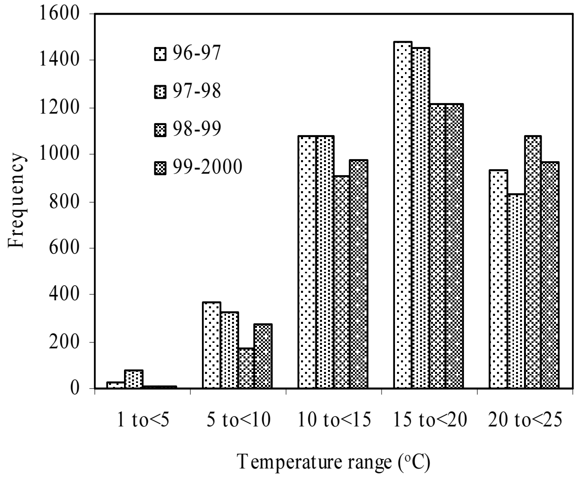

Fig. 3. Frequency distribution of different ambient temperature ranges for the four winter seasons.

The estimated annual heating requirements (kW per m^2 of the greenhouse floor area) for different greenhouse covers are shown in Fig. 4. The predicted heating requirement using single fiberglass (111 kW/m^2) was found to be the highest among all covers. Although they have the same U-value (6.8 W/m^2 °C), the heat requirement using fiberglass was slightly higher (by 1.7%) than that required using polyethylene. This was because polyethylene has higher light transmittance, which results in the increase of solar heat in the greenhouse, thus reducing the heat daylight demand. The figure also shows the simulated influence of temperature set points in the greenhouse on heating demand. For all greenhouse covers, the annual heating requirements increased by 65% with 18°C set point temperature at night compared to a set point temperature of 10°C. For single fiberglass glazing approximately 111 kW per m^2 of the greenhouse floor area of energy is needed at 18°C set point temperature compared to 39 kW per m^2 of the greenhouse floor area 10°C at set point temperature. Figure 4 shows that the use of double covering and the introduction of the thermal blanket at night reduced greenhouse nighttime heat requirements. An energy saving of 8% and 34% in a greenhouse could be obtained using thermal blanket curtain under the glass at 10°C and 18°C set point temperatures, respectively. Also, the use of double glass reduced the annual heat use by 56% and 50% at 10°C and 18°C set point temperatures, respectively.

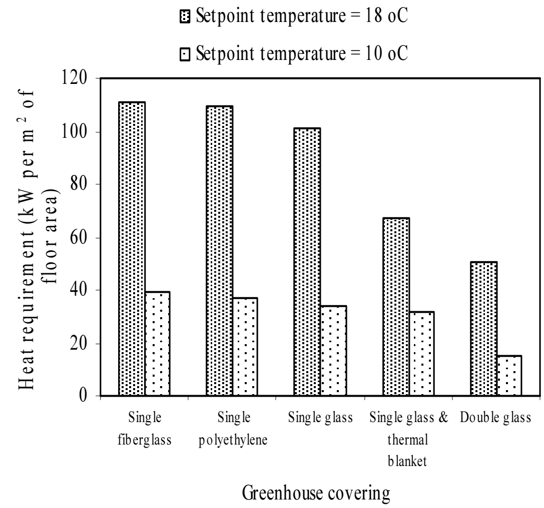

Fig. 4. Estimated annual heating requirements (kW per m^2 of the greenhouse floor area) under different greenhouse covers.

It is evident from Figs. 5 and 6 that simulated total heat requirement was the greatest in January with a gradual decrease towards summer. This pattern was common for all greenhouse covers and temperatures. The results showed that between 35 to 41% of annual heating is required during the month January because it has the lowest average of ambient temperatures.

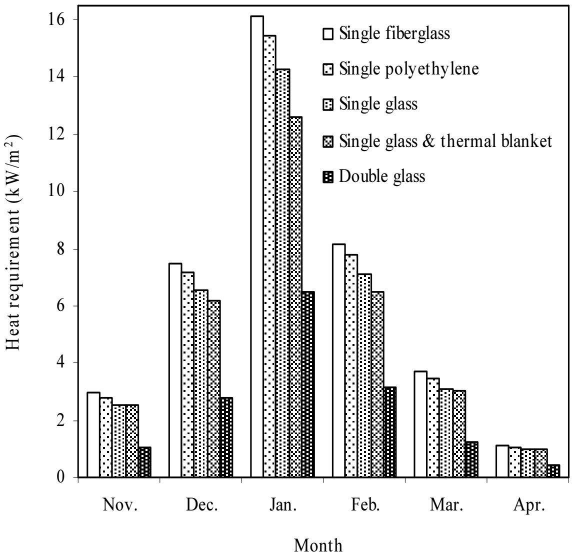

Fig. 5. Predicted monthly heat requirements under different covers at set point temperatures of 22°C during day and 10°C during night.

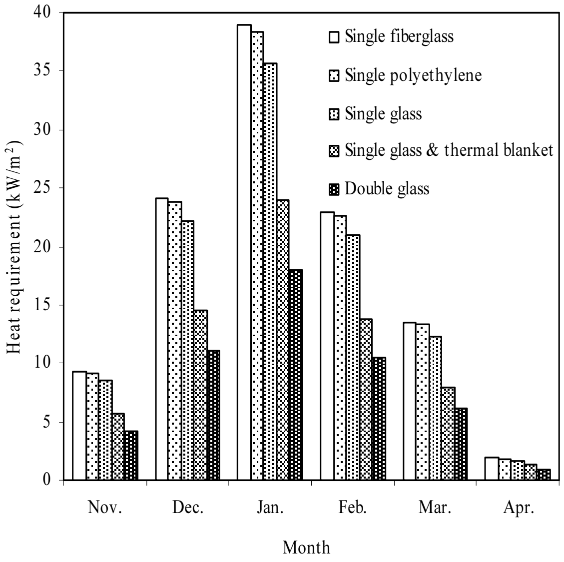

Fig. 6. Predicted monthly heat requirements under different covers at set point temperatures of 22°C during day and 18°C during night.

The model was capable of plotting average hourly heat and ventilation requirement curves for each day. For illustration, however, the curves were plotted for two typical winter days; a sunny day (January 7, 1998) and a cloudy day (January 9, 1998). The curves are shown in Figs. 7 and 8. For the sunny, cold winter day, a greenhouse can be maintained at high temperature with no addition of heat (except morning hours) because a greenhouse can act as a solar collector and can store heat. This would indicate that the daytime could become the most significant period for reducing heat requirements, especially during low light months such as December and January. The model predicted no heating requirement between 10:00 and 16:00 h for the greenhouse under all covers excluding double glass cover where heat is not required between 9:00 and 17:00 h. The model showed a peak of heating load at 7:00 AM in the morning, where ambient temperature was at the lowest value of 5.5°C. During the period from 10:00 and 16:00 h, ambient temperature varied between 9°C at 10:00 h to 14°C at 16:00 h, and solar radiation level at ambient varied between 324 W/m^2 at 16:00 h to 709 W/m^2 at noon. For the period from 9:00 and 17:00 h, ambient temperature had the lowest value of 7.8°C at 9:00 h with a peak at 16:00, and solar radiation level at ambient varied between 120 W/m^2 at 17:00 h to 709 W/m^2 at noon. This level of solar radiation was predicted to keep the inside temperature at high levels so that ventilation is required during that period at clear winter days. The maximum simulated ventilation load occurred between 12:00 and 14:00 h. Simulated ventilation load reached zero during the periods (0:00 to 9:00 h) and (17:00 to 23:00 h). On the cloudy day (Fig. 8), greenhouse heating is required during daytime due to the reduction of solar radiation intensity falling on the greenhouse (0 to 58 W/m^2). So, supplemental heat is needed to maintain 22°C inside the greenhouse. The model predicted a peak of heating load at 7:00 (I = 0.0 and T_o = 9°C). The heating load was at its lowest value at midnight where the ambient temperature was at its highest value of 11.6°C. The energy balance model predicted no ventilation requirement for temperature control during winter cloudy days.

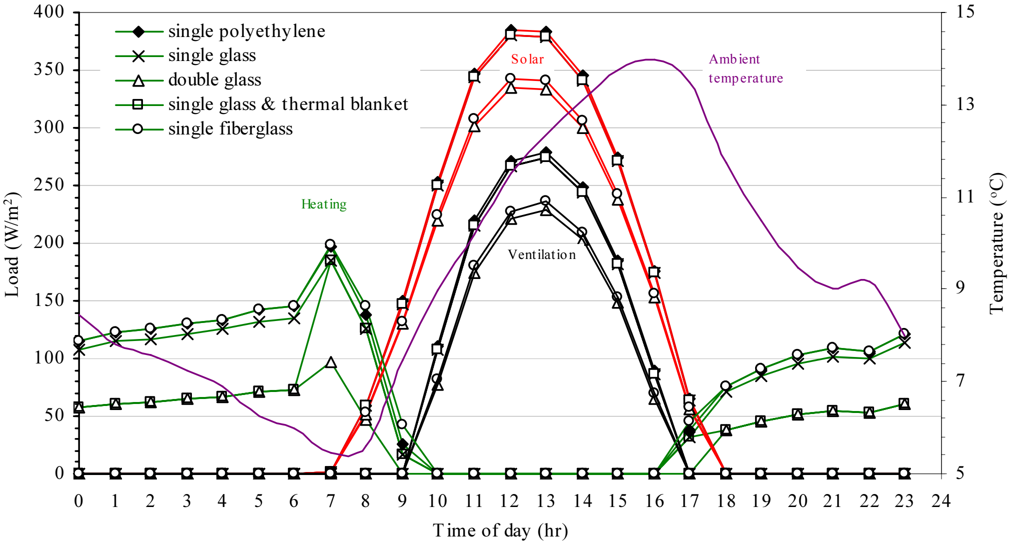

Fig. 7. Temperature, solar radiation, and greenhouse heat and ventilation requirements obtained from the model. The selected data were for a winter sunny day (January 7, 1998) at set point temperatures of 18/22°C (night/day).

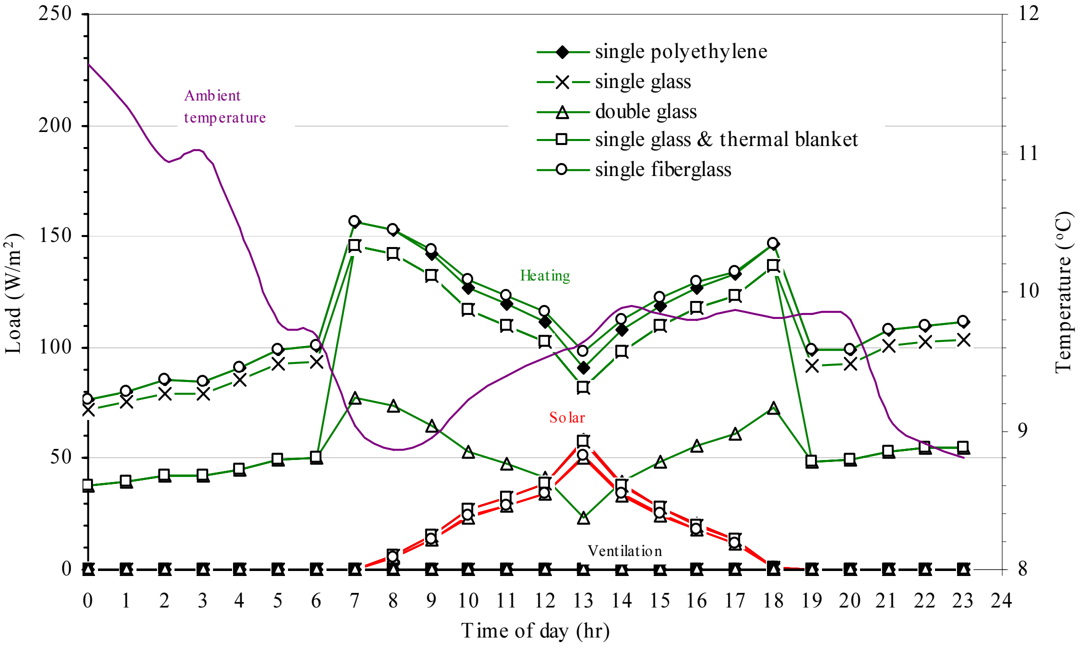

Fig. 8. Temperature, solar radiation, and greenhouse heat and ventilation requirements obtained from the model. The selected data were for a cloudy winter day (January 9, 1998) at set point temperatures of 18/22°C (night/day).

Experimental data

Figure 9 shows a one-day sample of temperature (average), solar radiation, and greenhouse heat and ventilation requirements for the experimental greenhouse for a sunny day of January 3, 2003 with set point temperatures of 18/22°C (night/day). During daytime (8:00 to 17:00 h), the greenhouse was maintained at temperatures between 18°C and 27°C with no supplemental heat due to the accumulation of solar energy inside the greenhouse. Estimated amount of heat supplied to the greenhouse from the heater peaked (172 W/m^2) at 6:30 h where ambient temperature was at the lowest value of 3.5°C. Air temperature inside the greenhouse reached its lowest average value of 10.7°C. The greenhouse temperature showed a rapid increase (11 to 18°C) from 5:30 h to 6:30 h, another increase (12.6 to 27°C) was observed from 7:30 h to 10:30. Ventilation was required during the period from 9:30 and 16:30 h of a clear sky winter day. During this period, solar radiation intensity reduces, Q_{sr} varied between 44 W/m^2 at 16:30 to 330 W/m^2 at 12:30, and the ambient temperature varied between 13.8°C at 9:30 h and 21.5°C at 14:30 h. The maximum ventilation load of 195 W/m^2 occurred at 12:30 hour. For the cloudy day of January 22, 2003 (Fig. 10), the greenhouse temperature (average) during daytime were in the 19-25.4°C region. Figure 10 shows that no heating requirement between 8:30 and 14.30 h for the experimental greenhouse. The figure showed heat input from the heater peaked at 5:30 h with an estimated value of 103 W/m^2 where ambient temperature was 13.8°C and the availability of solar radiation was zero. Air temperature inside the greenhouse reached its lowest value of 13.6°C. Solar radiation load (Q_{sr}) peaked at 10:30 with a value of 226 W/m^2. At this time, the maximum ventilation load was 89 W/m^2. Ventilation was only required during the period from 9:00 and 15:00 h of the cloudy day.

The results showed that the heater was not sufficient to maintain 18°C inside the greenhouse during the coldest periods (from 00:30 to 5:30 h for the sunny day, and from 19:30 to 24:00 h for the cloudy day). Possible reasons for this were: (1) the low design capacity of the heating system, (2) the operation of the heater was unintentionally stopped, and (3) the high heat loss by air infiltration through the door, cooling pads, louvers and fan shutters, and other openings. The door of the greenhouse under investigation had no proper weather strips, and hence became the least resistance to infiltration. Therefore, more cool ambient air flowed to the greenhouse via the door, allowing thermal mixing of the fresh ambient air with the greenhouse air. Also, air passages in the pads allowed air exchange since they were not closed at night. Therefore, the greenhouse may have a higher infiltration rate than that used in heat loss calculations (1.0 air exchange per hour).

Observed ventilation load reached zero during nighttime hours. This can be shown clearly from Fig. 11 that represents the amount of electrical power consumption for the ventilating fans for the sunny day of January 3, 2003 and the cloudy day of January 22, 2003. During sunny days, fans ran continously during the time between 12:30 to 14:30 h, consuming the maximum amount of electrical power of around 2500 W. For the case of the cloudy day, fans ran intermittently during the time between 10:30 to 11:30 h. Electricity consumption for ventilation during cloudy days was reduced by around 90% when compared to sunny days, a direct result of the solar energy gain reduction.

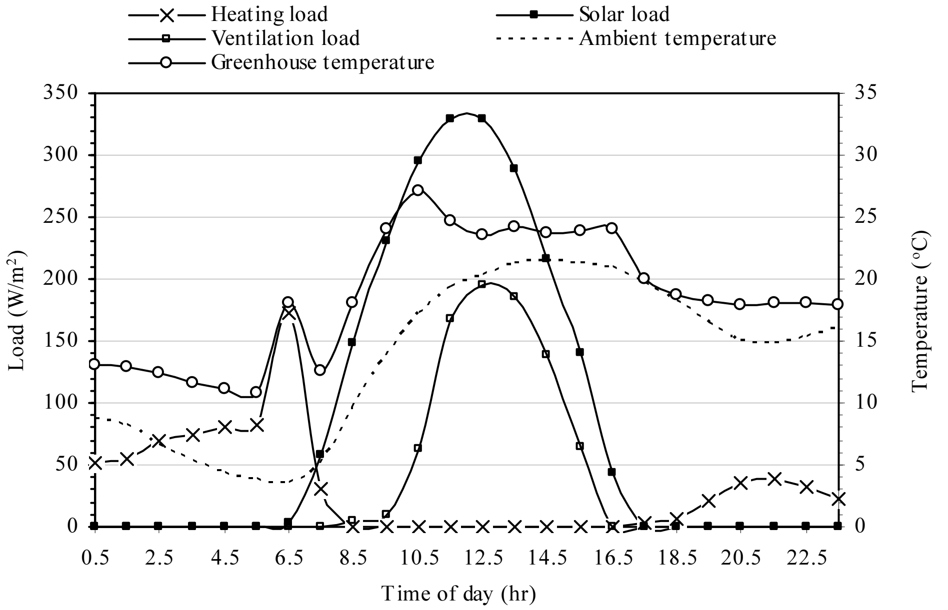

Fig. 9. Hourly variation of temperature, solar radiation, and greenhouse heat and ventilation requirements for the experimental greenhouse during a sunny winter day (January 3, 2003). Set point temperatures were 18/22°C (night/day).

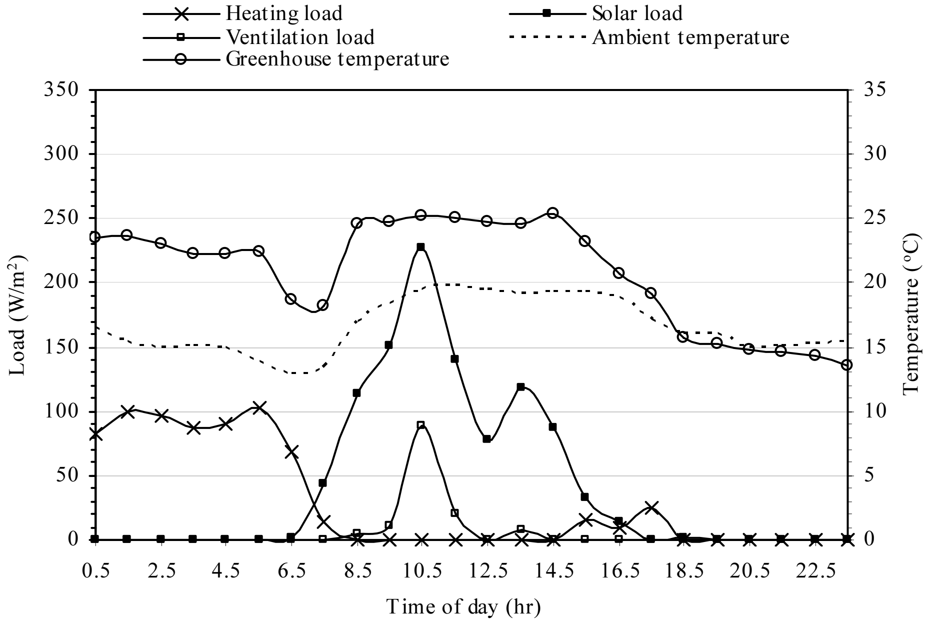

Fig. 10. Hourly variation of temperature, solar radiation, and greenhouse heat and ventilation requirements for the experimental greenhouse during a cloudy winter day (January 22, 2003). Set point temperatures were 18/22°C (night/day).

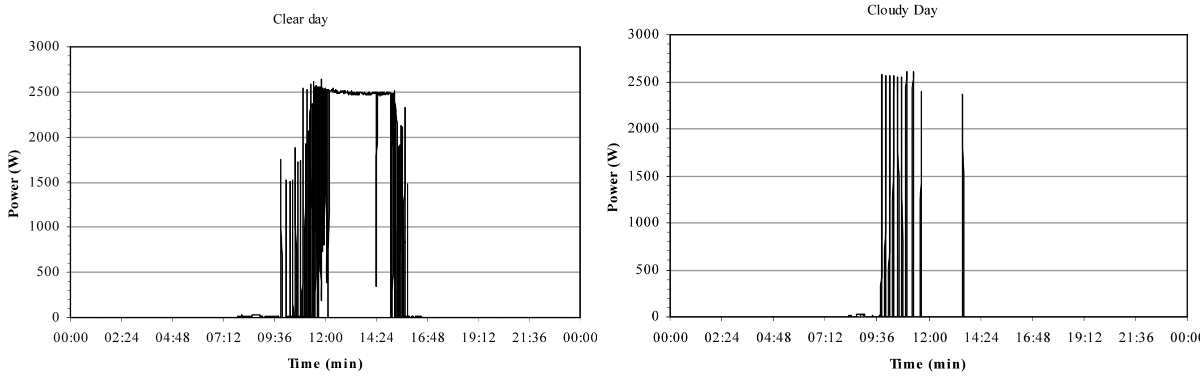

Fig. 11. Electrical power consumption for the ventilating fans during a clear sky winter day (January 3, 2003) and a cloudy winter day (January 22, 2003).

Figure 12 shows the temperature and relative humidity distributions along the greenhouse 2.2 m above the ground at 5, 20 and 38 m from the air inlet, respectively, on a sunny winter day of January 3, 2003. Air temperatures showed a rapid increase from 07:30 to 10:30 h. A temperature drop occurred at 10:30 h when the ventilating fans started to run, and at 16:30 just before sunset. The highest inside air temperature (29.6°C) was recorded at 38 m at 10:30 h, and the lowest was 10.2°C at 5 m at 06:30 h. As a general trend, the air temperature at 38 m showed the overall maximum during periods with high solar intensity. While the 20 m location remained the warmest among the three locations during night and morning times, the air temperature at 5 m was always the lowest during nighttime. It is due to the effect of the cold air infiltration through air passages in the pads, which resulted in the reduced air temperature in that location. Relative humidity recorded on January 3, 2003 at 20 m and at 38 m dropped rapidly from 09:30 to 12:30 h as indicated in Fig. 12. The relative humidity drop at 5 m started at 6:30 h. Relative humidity recordings showed minimum levels inside the greenhouse between 16 to 25% from 12:30 to 15:30 h, then increased to maximum levels between 68 and 78% during nighttime. The relative humidity recordings at 20 m showed the overall maximum during the daytime. The highest relative humidity values during nighttime were occurred at 5 m.

Figure 13 illustrates examples of the measured air temperature and relative humidity distributions inside the greenhouse at 20 m from the vent, with respect to height above the ground for the clear winter day. Air temperature was increasing with height; the greatest difference (around 3°C) was always found in night and morning due to the effect of the hot air stream released from the poly-tube overhead. During the hottest hours of the day (12:30 to 14:30 h), however, temperatures differences between the two heights were minimal. Relative humidity was always decreasing with height; the greatest difference was found in the night.

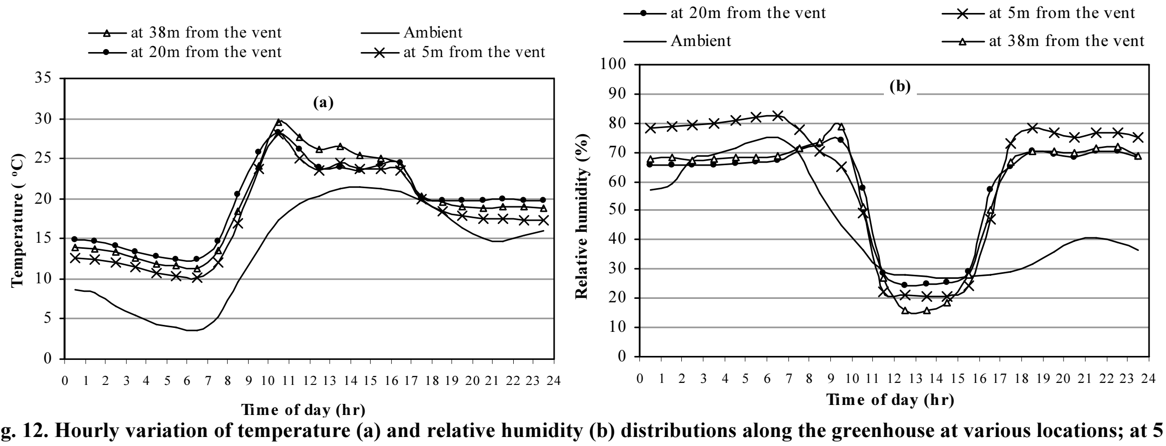

Fig. 12. Hourly variation of temperature (a) and relative humidity (b) distributions along the greenhouse at various locations; at 5 m, 20 m and 38 m from the air inlet, respectively, during a clear sky winter day (January 3, 2003).

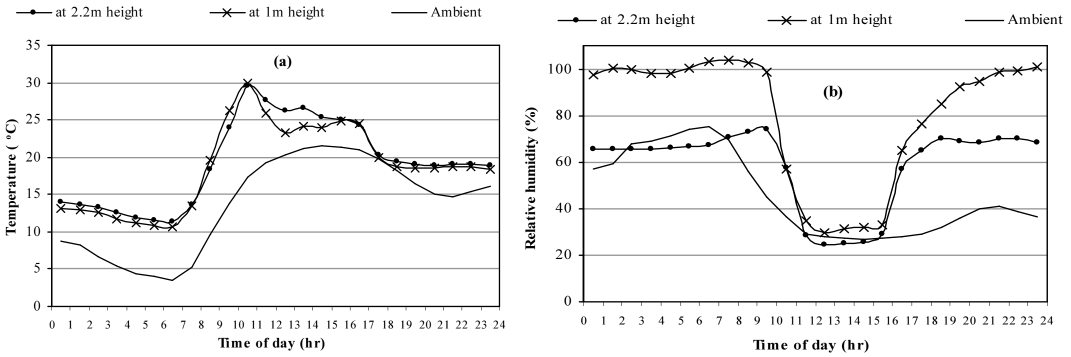

Fig. 13. Hourly variations of air temperature (a) and relative humidity (b) distributions inside the greenhouse at locations 2, with respect to height above the ground during a clear winter day (January 3, 2003).

Figure 14 shows the temperature distributions along the greenhouse 2.2 m above the ground at three locations; 5, 20 and 38 m from the air inlet, on a cloudy winter day of January 22, 2003. The air temperature inside the greenhouse during the majority of the time was higher than that of ambient temperature. The inside air temperature curves followed a similar pattern of the ambient temperature curve. Air temperatures showed a drop from 05:30 to 7:30 h, and another occurred at 14:30 h. The highest inside air temperature (28.3°C) was recorded at 20 m at midnight, while the lowest was 13.5°C at the three locations at 06:30 h. The air temperature at 20 m showed the overall maximum. The air temperature at the air inlet side was always the lowest. This might be attributed to the fact that pads have air passages through which cold air may have entered. Relative humidity recordings (Fig. 14) showed minimum levels inside the greenhouse (34.5%) at 10:30 h, and then increased to maximum levels between 68 and 99% during nighttime. The highest relative humidity values during nighttime were occurred at 5 m.

Figure 15 illustrate examples of the measured air temperature and relative humidity distributions inside the greenhouse at 20 m, with respect to height above the ground for the cloudy day. Air temperature was increasing with height; the greatest difference (8.3°C) was found in the morning. The reason was that hot air stream produced by the air heater increased the air temperature at the height of 2.2 m from the ground. During the hottest hours of the day (12:30 to 14:30), however, temperatures differences between the two heights tend to decrease. It is observed from Fig. 15 that a thermal balance occurred between the greenhouse and the outside air (from 18:00 to 24:00 h), and inside temperatures at the two heights were slightly close to each other. This indicates that the heating system might be unintentionally not working. Relative humidity was always decreasing with height; the greatest difference was found in the early morning.

It is observed from Fig. 16 that air velocity inside the greenhouse during the sunny winter day (January 3, 2003) was much higher than that during cloudy winter day (January 22, 2003). It had a maximum value of 0.7 m/s at 12:30 h during the sunny winter day, whereas the value for the cloudy day was 0.1 m/s at 10:30 h. This is because of the solar radiation on the clear day heated up the greenhouse, which increased operation time of the ventilating fans (Fig. 11).

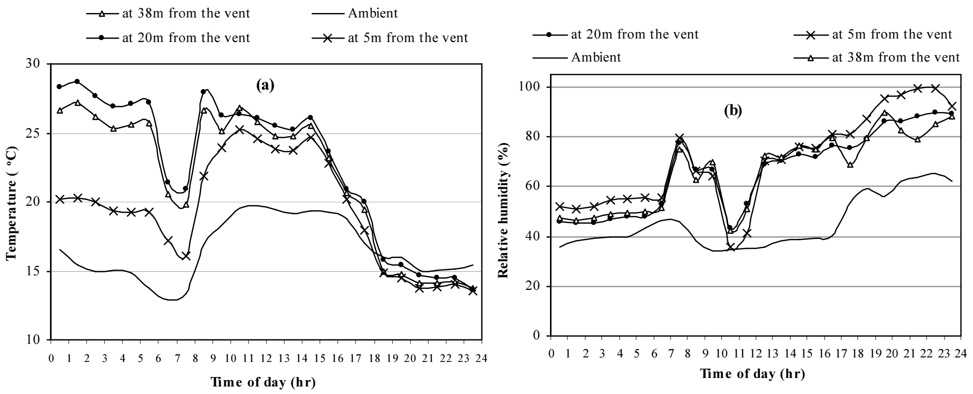

Fig. 14. Hourly variations of temperature (a) and relative humidity (b) distributions along the greenhouse at various locations; at 5 m, 20 m and 38m from the air inlet, respectively, during a cloudy winter day (January 22, 2003).

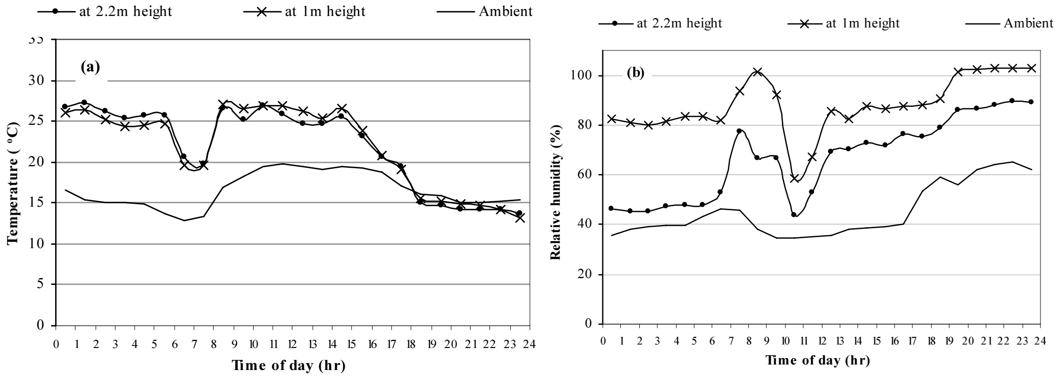

Fig. 15. Hourly variation of air temperature (a) and relative humidity (b) distributions inside the greenhouse at locations 2, with respect to height above the ground during a cloudy winter day (January 22, 2003).

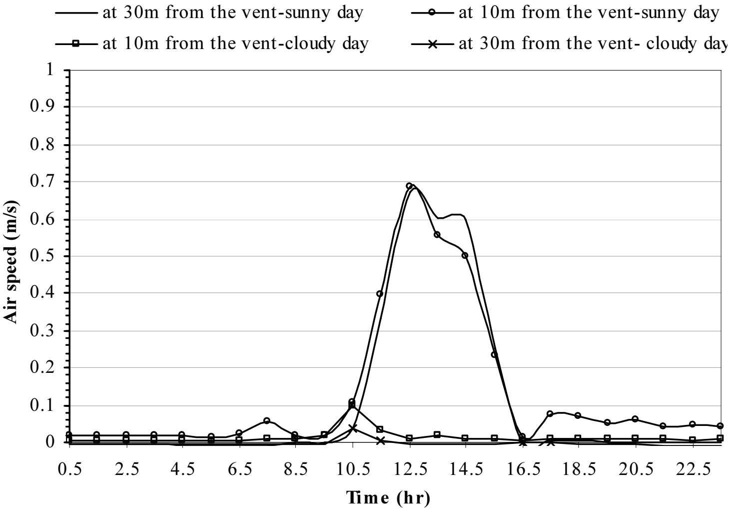

Fig. 16. Hourly variation of air speed inside the greenhouse at 1.5 m above the ground during a cloudy winter day (January 22, 2003) and a sunny winter day (January 3, 2003).

Averages of inside and outside temperature and relative humidity, as well as solar radiation load, heat removed from the greenhouse by ventilation and heat input to the greenhouse from the heater each day during the period 2-24 January 2003 are presented in Table 3. The table shows that on average, ventilation and heating systems were capable of maintaining the inside conditions at acceptable limits for plants growth. For example, on January 9, the greenhouse was maintained at air temperatures of 23/14.6°C (day/night) when the ambient temperatures were 19/10.9°C (day/night). However, the heating system was not capable to maintain the desired temperature of 18°C at night inside the greenhouse. The table shows that during 3 days only out of 24 days of the sampling data, mean greenhouse temperatures during nighttime were equal or higher than 18°C, while during 21 days, the mean greenhouse temperatures were less than 18°C. The table shows that the daytime averages of inside temperature and relative humidity were 21.5°C and 51.7%, respectively, as compared to the outside values of 16.5°C and 33.6%, respectively. Whereas, nighttime averages were 13.7°C and 75.6%, respectively, inside the greenhouse, the averages of outside temperature and relative humidity were 11.3°C and 43.6%, respectively. Also, the table shows that in some nights the heat input to the greenhouse (Q_h) was very small (days 23 and 24) or equaled to zero (days 10 and 16). For this reason, the inside air temperature during these nights was less than ambient temperature. As shown in the table, heat requirement diminished during the day due to the availability of solar energy. Also, there was no ventilation requirement for the greenhouse during nighttimes. The results indicated that the daily consumption of diesel fuel for the period from 2 to 24 January 2003 varied from 0.034 to 0.22 l/m^2 and averaged 0.12 l/m^2 of the greenhouse floor area.

Table 3. Average values of inside and outside temperature and relative humidity, solar radiation load, heat removed by ventilation and heat input from the heater each day during the period 2-24 January 2003

Day	T_o (°C)		T_i (°C)		RH_o (%)		RH_i (%)		Q_{sr} (W/m^2)	Q_v (W/m^2)		Q_h (W/m^2)	
	Day	Night	Day	Night	Day	Night	Day	Night	Day	Day	Night	Day	Night
2	12.3	7.6	21.0	13.2	48.8	62.6	54	76.2	217.1	73.1	0.0	10.8	67.8
3	15.8	11.8	22.2	15.9	40.8	50.1	50.5	77.5	189.0	75.4	0.0	18.5	50.0
4	16.7	13.9	22.0	15.9	41.6	39.5	58.4	75.1	185.4	60.2	0.0	6.8	25.1
5	15.2	9.7	20.5	12.3	38.5	52.9	52	80.1	202.2	59.6	0.0	0.5	31.8
6	18.2	13.3	23.3	18.0	29.4	40.9	40.6	68	223.9	69.0	0.0	3.2	52.0
7	17.8	10.2	21	13.9	30.7	47.8	47.8	72.9	186.7	47.6	0.0	0.8	49.5
8	18.0	11.9	22.1	13.1	29.2	41.4	45.1	76.8	201.9	53.6	0.0	1.8	19.0
9	19	10.9	23.0	14.6	22.2	35.6	40.1	70	186.1	50.3	0.0	12	49.4
10	19	11.4	22.3	9.1	20.4	34.1	42.4	88.6	190.8	61.6	0.0	1.0	0.0
11	17.4	10.7	22.1	10.7	32.9	47.3	43.3	82.9	189.8	98.3	0.0	9	16.0
12	16.3	8.9	21.8	13.7	33.4	47.8	42.8	68.6	191.0	68.3	0.0	13.2	62.4
13	17.1	9.7	21	10.9	27.7	41.6	46.1	76.8	185.5	58.1	0.0	0.6	17.1
14	17.5	10.4	21	13.3	24.2	35.8	44.5	69.5	195.3	80.5	0.0	5	33.3
15	20.1	12.8	23.4	14.0	17.2	26.6	37.2	71	193.0	75.5	0.0	3.8	45.6
16	17.5	15.5	21.1	13.0	34	34.7	56.2	72.8	173.8	70.1	0.0	0.0	0.0
17	13.2	8.8	19.1	10.0	35.9	44.0	61.6	82	190.3	48.8	0.0	3.8	22.4
18	11.2	5.8	20.2	12.1	26.1	39.8	54.4	69.5	199.6	43.1	0.0	16.8	75.9
19	15.2	8.4	19.9	12.8	29.2	40.7	53.8	73	187.3	51.9	0.0	4	55.6
20	14.3	12.1	21.6	14.8	32	37.9	66.9	75	121.3	17.3	0.0	12.7	40.8
21	19.8	16.5	24.0	22.0	26.6	28.6	53	59.5	100.7	21.5	0.0	15	66.1
22	17.7	15.2	22.3	19.0	41.5	49.5	72.1	73.7	77.6	8.7	0.0	10.1	57.2
23	17.0	13.7	21.1	13.6	54.5	64.2	64.6	91.1	197.5	78.4	0.0	2.4	5.8
24	13.4	10.4	19.5	10.3	50.2	60.1	62.4	88.2	203.6	83.5	0.0	2.2	3.6
Avg.	**16.5**	**11.3**	**21.5**	**13.7**	**33.3**	**43.6**	**51.7**	**75.6**	**182.1**	**58.9**	**0.0**	**6.7**	**36.8**
Stdev	**2.4**	**2.6**	**1.3**	**3.0**	**9.6**	**9.9**	**9.4**	**7.4**	**34.9**	**21.7**	**0.0**	**5.8**	**23.2**

Conclusions

The results obtained in this study can be summarized as follows:

1. The annual heating requirements were estimated to be increased by 65% with 18°C set point temperature at night compared to a set point temperature of 10°C, and 35-41% of annual heating is required during the month of January.
2. It was estimated that the use of single glass and thermal blanket covering system and double glass system could give annual heating energy savings of 8-34% and 50-56%, respectively. The ventilation load peaked at midday hours, and reached zero during nighttimes, while heating load peaked in the early morning.
3. Ventilation and heating systems were capable of maintaining the inside conditions at permissible limits for plants growth, but due to some operational problems (e.g., insufficient capacity of heating system, high heat loss by air infiltration), the heating system was not capable to maintain the desired temperature of 18°C during a significant number of nights.
4. The averages of air temperature and relative humidity over the 23-day experimental period inside the greenhouse during daytime were 21.5°C and 51.7%, respectively, as compared to 16.5°C and 33.6%, respectively, outside the greenhouse, whereas the averages at nighttime were 13.7°C and 75.6%, respectively, inside the greenhouse, and 11.3°C and 43.6%, respectively, outside the greenhouse.
5. The daily consumption of diesel fuel varied from 0.034 to 0.22 l/m^2 and averaged 0.12 l/m^2 of the greenhouse floor area.

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تحليل احتياجات التدفئة والتهوية للبيوت المحمية عند الظروف المناخية الشتوية الجافة

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كلمات مفتاحية: بيت محمي، مناخ جاف، تدفئة، تهوية.

ملخص البحث. تم في هذا البحث دراسة الظروف البيئية، واحتياجات التدفئة والتهوية للبيوت المحمية شتاءً بالمناطق الجافة. قدمت نماذج رياضية لتقدير احتياجات التدفئة والتهوية للبيوت المحمية باستخدام خمسة أغطية هي: الليف الزجاجي المقوى المفرد، والبولي إيثيلين المفرد، والزجاج المفرد، والزجاج المفرد مع الستارة الحرارية، والزجاج المزدوج. وقد تم حساب احتياجات التدفئة والتهوية تحت الظروف المناخية لمنطقة الرياض عند درجة حرارة داخلية 22°م نهارًا و18/10°م ليلاً. تم إجراء قياسات في بيت محمي نصف أسطواني (39م × 9م) مزروع بالطماطم ومغطى بطبقة من الليف الزجاجي المقوى المفرد ومزود بوحدة تدفئة ملحق بها أنبوب بلاستيكي مثقب لتوزيع الهواء الدافئ. دلت النتائج التقديرية باستخدام النماذج الرياضية أن احتياجات التدفئة باستخدام غطاء الليف الزجاجي المقوى كانت هي الأعلى قليلاً مقارنة بالأغطية الأخرى، كما ارتفعت الاحتياجات السنوية للتدفئة بمقدار 65٪ عند درجة حرارة ضبط داخلية 18°م مقارنة بدرجة حرارة ضبط 10°م خلال الليل. كما أن 35-41٪ من احتياجات التدفئة السنوية تكون خلال شهر يناير. أوضحت النماذج الرياضية أنه يمكن التوفير في احتياجات التدفئة بمقدار 8-34٪ باستخدام الزجاج المفرد مع الستائر الحرارية، و50-56٪ باستخدام الزجاج المزدوج. تمت مناقشة كل من احتياجات التدفئة والتهوية والتوزيع الرأسي والأفقي لدرجات الحرارة والرطوبة النسبية داخل البيت المحمي للأيام المشمسة والغائمة. كانت أقصى قيمة لحمل التهوية خلال منتصف النهار، بينما انعدمت الحاجة للتهوية أثناء الليل، وأقصى حمل للتدفئة كان قبل شروق الشمس. وكانت أنظمة التهوية والتدفئة قادرة على المحافظة على درجات الحرارة الداخلية عند مستوى مقبول لنمو النبات، بينما لم يكن نظام التدفئة قادرًا على المحافظة على درجة حرارة 18°م ليلاً خلال عدد من الأيام. وكانت متوسطات درجات الحرارة والرطوبة النسبية نهارًا 21.5°م و51.7٪ داخل البيت المحمي، و16.5°م و33.6٪ خارج البيت المحمي، على الترتيب. بينما خلال الليل كانت متوسطات درجات الحرارة والرطوبة النسبية 13.7°م و75.6٪ داخل البيت المحمي، و11.3°م و43.6٪ خارج البيت المحمي، على الترتيب.