AN EFFICIENT GREENHOUSE DESIGN FOR HOT CLIMATES

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Abstract—Greenhouses are needed in hot climates to protect plants from excessive heat, which limits productivity, and to reduce the excessive energy and water requirements associated with controlled environment agriculture under such conditions. In Kuwait, where ambient air temperature can reach 50°C during the summer and where fresh water is scarce, a new approach to greenhouse design was used. This approach included passive, as well as active, energy conservation measures, which made the utilization of such a greenhouse economically feasible. A computer program is proposed here for greenhouse design in Kuwait, aimed mainly at reducing the cooling load in an arid climate. It takes into consideration the climate, the material and the geometry of the greenhouse. The concept is to reduce the amount of intense solar radiation received in Kuwait (infrared radiation) but to maximize the amount of the solar spectrum needed for plants, as well as control the other environmental factors.

Kuwait Greenhouse Design Cooling Computer program

INTRODUCTION

Kuwait is located at northwest of the Persian Gulf, at lat 30°N. It is all desert land except for the coastal strip, which has scarce vegetation. Kuwait has a high level of solar insolation with a maximum value of 1050 W/m². The ambient temperature can reach as high as 50°C during the summer. In Kuwait, as in most of the Gulf Region, fresh water is scarce and outdoor irrigation is expensive. No waterways exist in Kuwait. Indoor agriculture, i.e. greenhouses, becomes an attractive venture under such conditions.

Recently, [1] a new design tool, a computer program, was developed that takes into consideration both outdoor environmental factors and greenhouse geometry and computes the various design parameters according to the plants' environmental requirements. This paper includes a description of the design process in which the computer model shows the various steps involved in the design.

COMPUTER PROGRAM

Calculations are done through a computer program. The requirements for the greenhouse design are fed to the computer program as input data. The design requirements are materials and their required characteristics (walls, roofs, windows, door), geometry (orientation, dimensions, shape), inside design conditions (air temperatures during the day time, air temperature during the night, relative humidity, moisture, illumination, number of air changes per unit time, air velocity) and outside design conditions (dry bulb temperature, wet bulb temperature, air velocity, relative humidity, radiation, ground temperature, long wave radiation loss, moisture). The ground temperature is found from the relationship between the air dry bulb temperature and the ground temperature.

The window area necessary for free ventilation is limited to the number of air changes per unit time important for plant growth. When the inside design dry bulb temperature is greater than the ambient dry bulb temperature, there is no need for cooling, and hence, the running of the program should be stopped.

The effects of the material, geometry, outside and inside design conditions on the cooling load and on environmental factors are studied. This is done by changing one of the input data and fixing the other, and so on.
The sol-air temperature is computed. The ratio of shading the greenhouse from solar radiation is limited by the amount of light needed by the plants. The kind of plants influences the amount of light and the amount of solar radiation needed. It was found that 1076 lx are approximately equivalent to 9.5 W/m² [2].

The heat from the solar radiation is calculated by taking into consideration the transmissivity of the unshaded part of the greenhouse. It is assumed that 50% of the solar radiation entering the greenhouse is sensible heat, 48% is latent heat, and the remaining 2% is chemical energy needed by the plants in the photosynthesis process [2].

When air is extracted by the fans from the greenhouse for cooling purposes, infiltration air is expected from the sidewalls, windows and doors because of the negative pressure inside the greenhouse. Hence, the sensible heat and latent heat loads due to infiltration have to be calculated.

The air temperature from the cooling system is calculated; this depends on the system itself. When the air temperature from the cooling system is greater than the design temperature inside the greenhouse, the design temperature inside the house is assumed equal to the air temperature from the cooling system plus 1°C. This assumption is correct only when the assumed design temperature inside the greenhouse is in the optimum range. Otherwise, the assumed temperature might affect plant growth.

The air flow rate needed for cooling the greenhouse is calculated. The air flow rate is necessary to determine the pad area and the water flow rate needed by the pad (in the case of evaporative cooling). The air velocity and the air change per unit time, which are important factors for plant growth, are also calculated from the air flow rate.

The sensible heat factor (SHF) is calculated to find the other conditions inside the greenhouse, or to find if the cooling system is efficient enough to provide design conditions inside the greenhouse.

To find the required electrical power needed for the fan(s) to deliver the necessary amount of air flow, the static pressure of the fan(s) is calculated. The computed value of the air flow rate and the static pressure of the fan(s) are checked to find if these values equal one of the input data values (part of the cooling system data). If it is not, interpolation is made and the electrical power is found.

**PROPOSED GREENHOUSE DESIGN (250 m²)**

This greenhouse, which is 250 m² in area, is to be utilized for growing tomatoes in Kuwait. Figure 1 shows the layout of the greenhouse. Solar radiation is only allowed to enter the greenhouse from the roof. The sidewalls are made of three layers: sand-cement block (10 cm), polystyrene (5 cm) and sand-cement block (10 cm). The combination of these layers provides high thermal resistance. The windows are opened only in winter and moderate seasons to provide one air change per minute, which is very important for plant growth.

The side walls are lined with aluminium foil to transmit most of the radiation to the plant canopy for absorption by the plants and soil. This helps maximize the use of incoming radiation for plant growth without unnecessarily raising the temperature.

The amount of illumination needed for tomatoes is 40,000 lx [3], so the amount of shading is controlled according to this quantity of illumination. The greenhouse roof is shaded by a screen
mesh of fibreglass, which shades approx. 55% of the solar radiation. The greenhouse roof is covered by 4 mm of clear glass. The design temperature inside the greenhouse is 30°C in day time and 22°C at night [3].

RESULTS AND DISCUSSION

The effect of the greenhouse geometry on the cooling load is shown in Fig. 2. This figure shows that, when the width increases, the sensible heat decreases until the width is equal to the length, where the sensible heat starts rising. This is because the total area of the side walls is at a minimum when the width is equal to the length. This figure also shows that the sensible heat increases slowly after the minimum point. This means that the chosen dimensions are not restricted to the minimum point. The figure also shows the effect of the geometry on the cooling for side walls of different materials. The values of the sensible heat are approximately the same. This is because the ratio of the conduction heat to the total cooling load is very small (approx. 3%).

The values of the temperature inside the greenhouse day and night for all months are shown in Fig. 3. Most of the values at night are not at optimum (22°C), but the effect would be small on plant growth [3]. Figure 4 shows the ratio of the unshaded part of the roof to the roof area with time. The ratio is approximately the same for most of the summer months. Hence, the unshaded part of the roof could not be changed completely until November, when none of the shaded part is needed. The daily variation of illumination inside the greenhouse is found to be sufficient for the plant's needs (Fig. 5).
Figures 6–11 show the relationship between cooling load, pad area, air flow rate, water flow rate, number of air changes per minute and electrical power for one fan with the time of day for May–October. The dimensions of the greenhouse are: length = 15.8 m, width = 15.8 m and the height = 2 m. These values of length and width give the minimum load (see Fig. 2).

Figure 6 shows that the cooling load at night sometimes requires more air flow and, hence, more pad area, air changes per minute, water flow rate and air velocity than that obtained during the day, because the temperature inside the greenhouse should be greater than the temperature of the air from the cooling system. This figure also shows that the cooling load is maximum at noon (higher solar radiation) because the maximum portion of the cooling load is the solar radiation load.

It can be seen from Fig. 7 that the maximum pad area needed for cooling the greenhouse is about 50 m². The dimensions (length and width) of the greenhouse have to be changed. The new dimensions are: width = 10 m, length = 25 m and height = 2 m. This change would increase the cooling load slightly.

The pad area and air flow rate plots (Fig. 8) show that the maximum air velocity is in the order of 0.75 m/s. This is not the desired value. The standard value is 0.5 m/s [3]. At this value the growth would be maximum. The change in the dimensions causes the wall area through which air enters to be 50 m² so the maximum air velocity would be about 0.5 m/s.
The water flow rate plot (Fig. 9) shows that the maximum water flow rate is on the order of 150 g/min. The number of air changes per minute (Fig. 10) is in the order of 4 changes/min. This value gives more CO₂ enrichment but might affect transpiration and evaporation of water from the soil. The average value found is two air changes per minute.

The plot of air flow rate indicates that the maximum air flow rate is about 30 m/s. Hence, sufficient electrical power is needed to deliver this amount. The plot of electrical power (Fig. 11) indicates that the maximum value needed for the fans is approx. 9 kW. This value could be provided by the 100 kW power plant at Sulaibiya. The average value is found to be 3 kW.

Figure 12 shows the relationship between the relative humidity with hours for the summer months. The range of relative humidity is 50–85%, the desired value for the plants.

CONCLUSIONS

Theoretical results show that control of the amount of solar radiation with movable shading, and using highly insulated material, the evaporative cooling system could be used successfully for cooling greenhouses in Kuwait's environment.

REFERENCES