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Determination of Greenhouse Time Constant Using Steady-state Assumption

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ABSTRAK

Satu kajian dijalankan untuk menentukan kebolehgunaan penyelesaian keadaan mantap untuk meramal perubahan suhu udara dalaman dan jisim terma sebuah rumah kaca berbangku panas sebagai respons kepada satu perubahan tetap pada suhu luaran. Ini adalah kerana analisis keadaan mantap adalah lebih mudah daripada analisis fana. Walau bagaimanapun, penyelesaian keadaan mantap hanya sesuai jika pemalar masa rumah kaca pendek berbanding jumlah masa pada mana keadaan luaran rumah kaca dikira lebih kurang tetap. Satu kaedah berparameter tergumpal berdasarkan Albright *et al.* (1985) digunakan untuk menganggar pemalar masa bagi rumah kaca berbangku panas. Pemalar masa ini didapati amat sensitif kepada pekali pemindahan haba, h_m, di antara jisim terma dan udara dalaman. Nilai h_m yang tinggi menghasilkan pemalar masa yang lebih panjang. Bagi sifat-sifat jisim terma yang dianggarkan, nilai h_m bagi keadaan luaran yang lebih kurang mantap secara sementara ialah 0.23 $Wm^{-2}K^{-1}$ dengan pemalar masa lebih kurang 0.75 jam. Jangka masa ini dikira pendek berbanding tempoh ujian selama 6 jam. Oleh itu analisis keadaan tetap adalah sesuai.

ABSTRACT

A study was conducted to determine the applicability of a steady-state solution in predicting the changes in temperatures of the inside air and thermal mass of a bench-top-heated greenhouse in response to a step change in outside temperature. The steady-state analysis is simpler than that of the transient. However, a steady-state solution would only be appropriate if the time constant of the greenhouse is short compared to the total time under which the conditions outside the greenhouse are considered to be approximately constant. A lumped parameter method based on Albright *et al.* (1985) was used to estimate the time constant of the bench-top-heated greenhouse. The time constant was found to be very sensitive to the heat transfer coefficient, h_m, between the thermal mass and inside air. A high value of h_m results in a longer time constant. For the estimated thermal mass properties, the value of h_m for the temporarily approximately constant outside conditions was calculated to be 0.23 $Wm^{-2}K^{-1}$ for which the estimated time constant was about 0.75 hour. This time was reasonably short compared to the six-hour experimental period; thus the steady-state analysis was appropriate.

Keywords: Bench-top heating, greenhouse time constant, greenhouse thermal mass

INTRODUCTION

As the outside temperature changes, the greenhouse interior air temperature will be forced to change accordingly if there is no control system in the house. If the outside temperature reaches a steady state, the interior air temperature will also eventually come to a steady state. The time constant of a greenhouse is the time taken for the greenhouse to reach 63% of its steady-state value in response to a step change in the corresponding outside condition. If the time constant is very long, say in the order of days, then a steady-state numerical solution would be meaningless as the greenhouse would never achieve steady state before the outside temperature changes again. If the time constant is short, the inside temperature would tend to rapidly follow the outside condition.

In practice, the outside air temperature continually changes and the greenhouse may never achieve a truly steady-state condition even if the time constant were short. A steady-state value obtained by simulation would be that which the house was supposed to have reached had the outside temperature not changed. However, if the outside conditions become relatively stable, then at least a pseudo steady-state inside condition will be observed (assuming the control state is constant), which is the case for the experimental data reported.

Greenhouse temperature can be presented either as single average temperature of the inside air or as a temperature distribution throughout the greenhouse space. The ever changing outside environmental factors influence environmental conditions inside the greenhouse. A number of techniques exist for predicting the interior response for steady or transient outside conditions. Steady-state analyses have been done by many researchers including Walker (1965), Short and Breuer (1985) and Jolliet *et al.* (1991). Many others have used transient analyses, including Takakura *et al.* (1971), Deltour *et al.* (1985) and Garzoli (1985). In these analyses the greenhouse is generally divided into four basic elements making up the greenhouse system, i.e., the floor, the plant, the inside air and the cover. On each of these systems heat balance equations are established and the resulting set of equations solved simultaneously to obtain the desired quantities such as temperature and humidity. The intent is typically to obtain an estimate of the bulk air, soil or crop temperature and air humidity.

The thermal parameters of the greenhouse are usually described in terms of the overall heat transfer coefficient and a number of other factors such as the solar transmission of the greenhouse cover, solar heating efficiency or absorbency, and heat capacity of the soil. Depending upon the individual situation faced, the overall heat transfer coefficient may or may not include the convective, radiative and ventilation losses, and condensation. Since each coefficient is usually calculated for a specific greenhouse with specific geometry and specific nature of heat requirement the values of the overall heat transfer coefficients reported are quite variable.

The objectives of this study are to calculate the overall heat transfer coefficient (h_m) and time constant of the bench-top-heated greenhouse and to observe the effect of a step change in outside temperature on the temperatures of the inside air and thermal mass.

METHODS

Experimental data used in the analysis were those of the works of Jenkins *et al.* (1988 and 1989). Jenkins *et al.* (1989) experimentally examined the two-dimensional overall heat transfer of a bench-top-heated greenhouse. In the bench-top heating system, heat is applied to areas where it is needed most, i.e., the plant canopy, by circulating hot water through tubing running through or on the bench. A gable-roof greenhouse with a floor area of 217 m^2 and longitudinally oriented in the east-west direction, was gutter-connected to identical houses on the north and south sides. It was clad with 3 mm thick glass. The benches were 0.69 m above the floor. Each bench carried a bench-top heat exchanger consisting of 8 mm diameter plastic tubes (wall thickness 1.5 mm) which made four passes up and down the length of the bench. To improve the uniformity of the canopy heating and reduce heating of the pots and soil, an expanded steel mesh was mounted 25 mm above the top bench surface and above the heater tubing. Potted plants were placed on this mesh. The greenhouse was not ventilated and all opening and fan shutters were covered with plastic sheet to reduce infiltration losses. To check for heat transfer across the connecting sidewalls and roof, thermocouples were fixed on the inside and outside surfaces of each wall and ceiling. A detailed description of the bench-top heating system and its instrumentation is described in Jenkins *et al.* (1988 and 1989).

Only night time data from 0000 hours to 0600 hours (both inclusive) were used in the analysis because the outside temperature during this period was reasonably constant at somewhat below 0°C. As shown in the data of Table 1, the outside temperatures during this period were also fairly constant ranging from –0.2°C to –1.5°C with an average of –0.8°C. This condition enabled the actual bench-top heating system to work continuously and steadily at full capacity. The various temperatures inside the greenhouse were also fairly constant at each hour in the period. Thus the greenhouse was essentially already at steady state at 0000 hours. According to Jenkins *et al.* (1989), the temperature distributions in the greenhouse remained nearly steady from midnight to 0600 hours. Therefore the average condition of the greenhouse was calculated to steady state.

TABLE 1

Hourly average outside temperature and wind speed for the experimental greenhouse during the period studied

Hours of night	0000	0100	0200	0300	0400	0500	0600
Outside temp., °C	-0.2	-0.4	-0.7	-1.5	-1.1	-1.5	-0.6
Wind speed, m/s	2.797	3.134	3.202	3.167	3.472	3.399	3.087

A constant temperature boundary condition was assumed for all walls, floor and ceiling. Air temperature at the lower boundary (the bench surface) was approximately constant at 30°C. Boundary temperatures at the top, left and right were 6.5°C, 16°C and 15°C, respectively. These values were obtained by taking the average of the seven hourly values (from 0000 to 0600 hours, both inclusive) of the air at the inside surfaces of the ceiling, left wall and right wall, respectively.

A lumped parameter representation of the greenhouse based on Albright *et al.* (1985) was used to estimate the time constant of the greenhouse. The greenhouse was divided into two subsystems, namely a) the interior air and b) the thermal mass, which included the crop mass, structural mass, floor mass and all other non-air elements in the greenhouse. Energy balances were carried out on each subsystem by considering each as a control volume. Since the greenhouse was analyzed for the nighttime condition only, no solar radiation was involved.

RESULTS AND DISCUSSION

Symbols:

m_a – mass of air in greenhouse, kg
c_a – heat capacity of inside air, J kg^{-1} K^{-1}
T_i – mean temperature of inside air, °C
t – time, s
h_m – heat transfer coefficient between thermal mass and inside air, $W\ m^{-2}\ K^{-1}$ of floor area
A – greenhouse floor area, 217 m^2
T_m – mean temperature of thermal mass, °C
U – overall heat transfer coefficient between inside air and outside air, $W\ m^{-2}\ K^{-1}$ of floor area
T_o – outside air temperature, °C
k_a – thermal conductivity of air at 1 atm and 15°C = 0.0253 $W\ m^{-1}\ K^{-1}$ (Incropera and De Witt 1985)
m_m – thermal mass, kg
c_m – heat capacity of the thermal mass, J kg^{-1} K^{-1}
m_c – mass of concrete, kg
m_s – mass of soil, kg

A transient energy balance on the interior air gives the following equation:

$$\frac{dT_i}{dt} = \frac{A}{m_a c_a}\{h_m(T_m - T_i) + U(T_o - T_i)\} \tag{1}$$

Air properties inside the greenhouse were taken at one atmospheric pressure and 15°C. The overall heat transfer coefficient of the greenhouse per unit floor area is U=5+1.2v (Jenkins *et al.* 1989), where v is the outside wind speed in m s^{-1}. Average wind speed for the six-hour period under study was 3.18 m s^{-1} giving U = 8.82 $W\ m^{-2}\ K^{-1}$.

According to Albright *et al.* (1985), the thermal mass of a greenhouse is comprised, to a large extent, of the greenhouse floor. In the present study, the heat transfer coefficient between the floor and the inside air was assumed to be the coefficient between the thermal mass and the inside air. Further, the greenhouse floor was assumed to be similar to a heated horizontal plate. Incropera and De Witt (1985) gave the Nusselt number correlation for a heated horizontal plate as: $Nu = 0.54Ra_L^{0.25}$, where Ra_L is the Rayleigh number. Computing for the Pr and the highest Gr used by Janius (1996) in a numerical study of the same greenhouse:

$$Nu \equiv \frac{h_m L}{K_a}$$
$$= 0.54(\text{Pr}*\text{Gr})^{0.25}$$
$$= 0.54(0.715*10^9)^{0.25}$$
$$= 88.3$$

Thus, $h_m = 0.23\ W\ m^{-2}\ K^{-1}$.

A transient energy balance on the thermal mass at night yields:

$$\frac{dT_m}{dt} = -\frac{A}{m_m c_m}\{h_m(T_m - T_i)\} \tag{2}$$

The 217 m^2 floor area is made up 67% of 0.1 m deep concrete and 33% soil (for thermal mass purposes a depth of 1 m is assumed). Taking the density of concrete to be 2300 kg m^{-3} and that of soil to be 2050 kg m^{-3}, the estimated thermal mass, m_m, is 180,240 kg. The value of c_m is taken to be the average of the specific heat capacities of concrete and soil whose values are 880 J kg^{-1} K^{-1} and 1840 J kg^{-1} K^{-1}, respectively. Thus c_m = 1360 J kg^{-1} K^{-1}.

A numerical integration scheme employing a simple Euler predictor-corrector method was used to solve both equations (1) and (2) simultaneously. Step changes in the outside air temperature were imposed and the response of the interior air was obtained. The time taken for the interior temperature to reach 63% of its steady-state value after imposition of the step change in outside temperature was the time constant, t, of the greenhouse.

The estimated time constant for the greenhouse air under nighttime condition is 0.75 hour. Simulation results, at various values of h_m, of the response of the greenhouse to a step change in outside temperature, are shown in *Figs. 1a-1e.* A plot of the various time constants obtained against their respective heat transfer coefficients, h_m, shows the greenhouse response to outside forcing temperature to be very sensitive to the value of h_m (*Fig. 2*). For the lower time constants and a relatively constant outside temperature, an assumption of steady state is probably reasonable. At larger time constants,

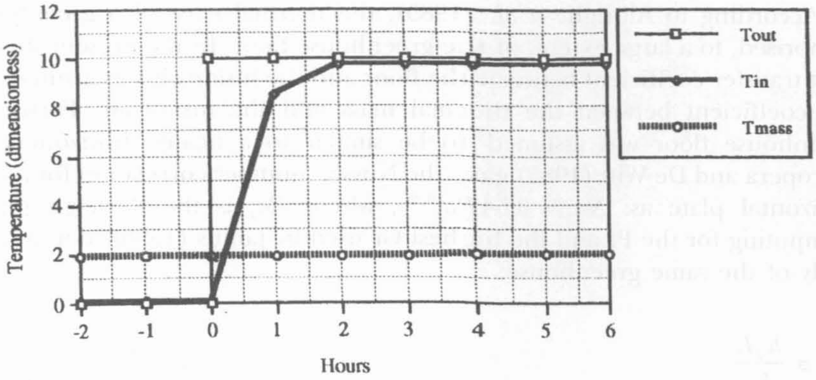

Fig. 1a: Greenhouse response to step change in outside temperature
h_m=0.23 W m^{-2} K^{-1}, U=8.8 W m^{-2} K^{-1}

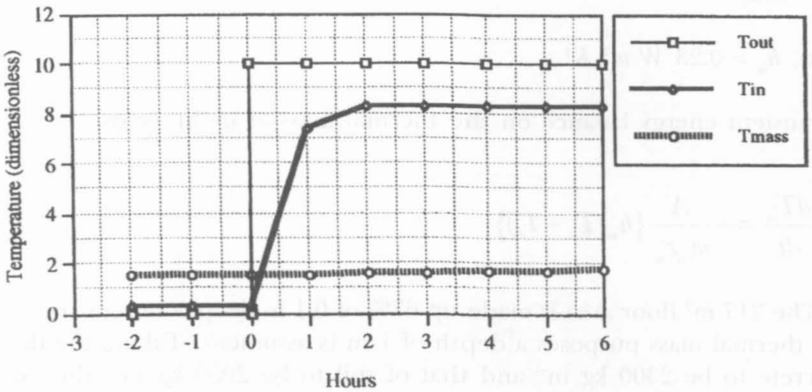

Fig. 1b: Greenhouse response to step change in outside temperature
h_m=2.3 W m^{-2} K^{-1}, U=8.8 W m^{-2} K^{-1}

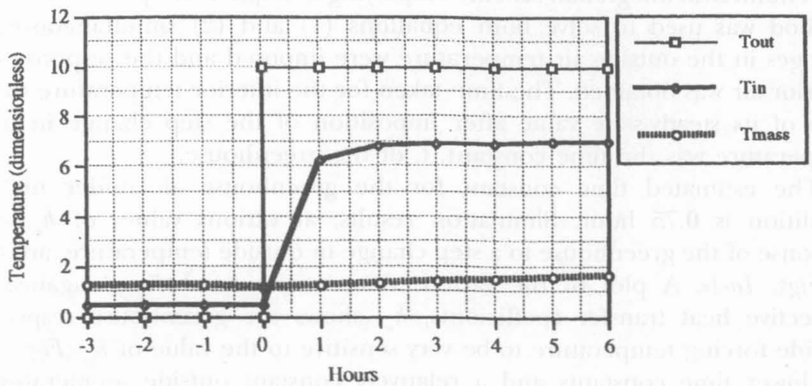

Fig. 1c: Greenhouse response to step change in outside temperature
h_m=5 W m^{-2} K^{-1}, U=8.8 W m^{-2} K^{-1}

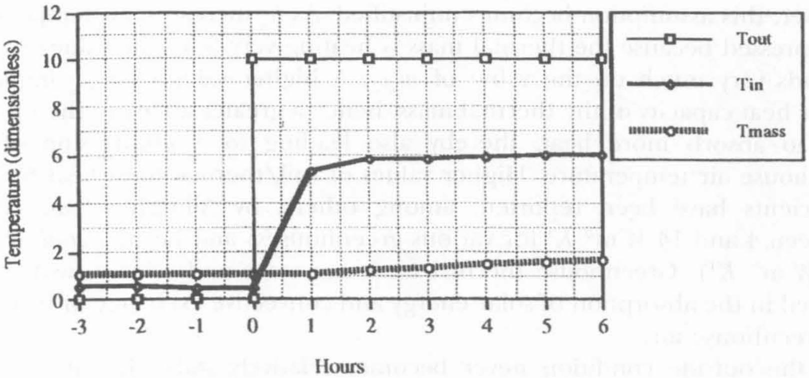

Fig. 1d: Greenhouse response to step change in outside temperature
h_m=8 W m^{-2} K^{-1}, U=8.8 W m^{-2} K^{-1}

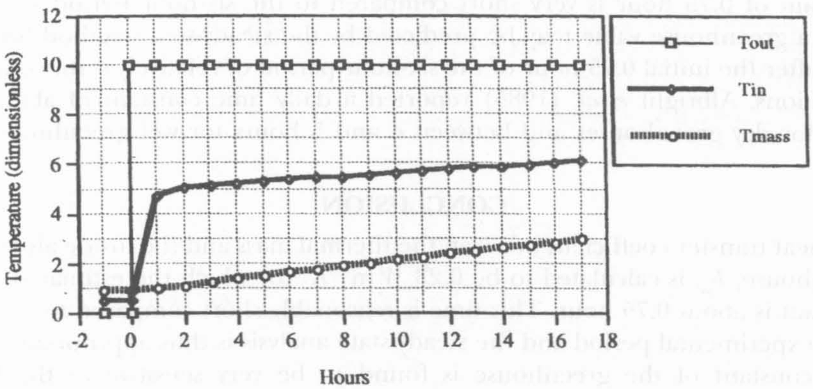

Fig. 1e: Greenhouse response to step change in outside temperature
h_m=11 W m^{-2} K^{-1}, U=8.8 W m^{-2} K^{-1}

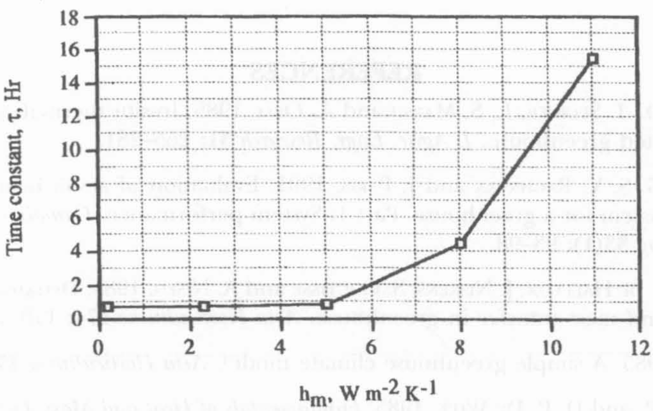

Fig. 2: Sensitivity of the greenhouse time constant to the heat transfer coefficient between the thermal mass and inside air

however, this assumption becomes unjustified. As h_m increases, air temperature is suppressed because the thermal mass is heating very fast. The value of t also depends very much on the value of $m_m c_m$. A higher value of $m_m c_m$ implies a higher heat capacity of the thermal mass, hence a greater ability of the thermal mass to absorb more heat, thereby also leading to a suppression of the greenhouse air temperature. Higher values of soil/thermal mass heat transfer coefficients have been reported, among others, by Albright *et al.* (1985) (between 4 and 14 $W\,m^{-2}\,K^{-1}$ for various greenhouses) and Bernier *et al.* (1991) (5.4 $W\,m^{-2}\,K^{-1}$). Greenhouse thermal mass can store and release heat and is involved in the absorption of solar energy and convective exchange of heat with the greenhouse air.

If the outside condition never becomes relatively stable for at least the length of the time constant, then, no matter how short the time constant is, the steady-state assumption would be invalid. At the estimated h_m, the steady-state assumption for the greenhouse under study is appropriate because the time constant of 0.75 hour is very short compared to the six-hour period studied. Thus a greenhouse value may be predicted by the steady-state method for any time after the initial 0.75 hour of the six-hour period of relatively stable outside conditions. Albright *et al.* (1985) reported a daily time constant of about 40 min. for dry greenhouses and between 4 and 5 hours for wet greenhouses.

CONCLUSION

The heat transfer coefficient between the thermal mass and the inside air of the greenhouse, h_m, is calculated to be 0.23 $W\,m^{-2}\,K^{-1}$ for which the estimated time constant is about 0.75 hour. This time is reasonably short compared to the six-hour experimental period and the steady-state analysis is thus appropriate. The time constant of the greenhouse is found to be very sensitive to the heat transfer coefficient between the thermal mass and the inside air, h_m. For the estimated thermal mass properties, if h_m is low then a steady-state assumption for the analysis is more readily established for temporarily constant outside conditions.

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