The Variation of Heating Load Coefficient for a Greenhouse and Overall Heat-Transfer Coefficient through Plastic Film

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Abstract

The heating load coefficients were measured using a practical plastic greenhouse in 1974 and 1975. In the first year a fuel capacity of 89,000 kcal/hr for heating was used. A large variation of measured values appeared. However, the heating load coefficient can be expressed statistically by equation (3). In the next year a capacity of 26,400 kcal/hr was used to accurately determine the heating load coefficient. It was of insufficient capacity so that the inside temperature dropped slightly below the design temperature. The results were that the variation of each measured point increased over that of the test in the first year.

For investigating the variation of the heating load coefficient, model tests were performed using polyvinyl chloride (p.v.c.) film. In the model tests only the overall heat-transfer coefficient, which greatly affected the heating load coefficient, was able to be investigated. A large variation in the values of the overall heat-transfer coefficient from the model tests was shown when they were plotted against wind velocity. However, when the overall heat-transfer coefficient was plotted against the ratio of the convective heat-transfer to the radiative heat-transfer, a regular curve was able to express with sufficient accuracy the overall heat-transfer coefficient. Moreover, in tests using the various materials the same results were obtained. According to them, a large overall heat-transfer coefficient appeared when the radiative heat-transfer was large in comparison to the convective heat-transfer. On the contrary, the overall heat-transfer coefficient was nearly constant, if the convective heat-transfer was large.

1. Introduction

Recently, plastic greenhouses equipped with heating systems have come into wide use. For determining the capacity of heaters the so-called heating load coefficient is of considerable importance. Many investigators have studied this subject and the determination of its standard values for designing the heating system was tried by the Society of Agricultural Meteorology of Japan (SAMJ 1977). However, a wide variation in the values of heating load coefficient has been reported (Nakagawa et al. 1974, Sheldrake et al. 1962,

Takakura et al. 1971, Vogel et al. 1961, Whittle et al. 1960, Yamamoto 1970). This variation may be related to the use of different heating systems, the method of measurement, experimental error, non-constancy of heating load coefficient and possibly other factors.

This paper discusses the variation of the heating load coefficient and the overall heat-transfer coefficient through plastic film. First we measured the heating load coefficient for a practical plastic greenhouse and second the variation of overall heat-transfer coefficient by using a model.

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2. Measurement of heating load coefficient for a practical plastic greenhouse

To calculate the greenhouse heating load the following equation has been used

$$H = U \cdot A \cdot (t_i - t_o), \quad (1)$$

where H is the heat consumption, A the wall and roof surface area, U the heating load coefficient, t_i inside air temperature and t_o outside air temperature.

When U is known, it is relatively easy to calculate the total heat loss. Therefore, it is important to accurately determine the heating load coefficient U . Generally, U is given by an equation

$$U = a + bV, \quad (2)$$

where a and b are empirical constants and V is wind velocity. The author tried to determine the constants a and b by using a practical plastic greenhouse.

(a) Methods and materials

The measurements were performed for 20–30 nights in May 1974 and April and May 1975. A description of the plastic greenhouse is given in Fig. 1.

Fig. 1. A description of the plastic greenhouse for measuring the heating load coefficient. (plastic cover, polyvinyl chloride film of 0.1 mm, surface area of wall and roof 455.6 m², area of floor 292.8 m², capacity of heater 87,000 kcal/hr (1974), 26,400 kcal/hr (1975))

The heating installations were of an air heating type, which were controlled by an on-off thermostat. A different fuel capacity was used each of the two years. In 1974 the capacity was 89,000 kcal/hr and in 1975 it was 26,400 kcal/hr.

Temperature, inside and outside, was measured with a recording electrical resistance thermometer. In addition five and ten thermocouples respectively in 1974 and in 1975 were used to measure the difference between inside and outside temperatures. The data of temperature were integrated for one hour and the hourly mean temperature was then calculated from the integrated data. The difference between inside and outside temperatures and the data from the resistance thermometer and five or ten thermocouples were averaged and used for calculating the heating load coefficient.

Total heat supplied to the plastic greenhouse was calculated from the fuel consumption by the heater minus the heat loss through the ventpipe. Wind velocity was measured at a height of 4 meters above ground.

(b) Results and discussion

A summary of the work done in 1974 is shown in Fig. 2.

Fig. 2. Relationship between heating load coefficient and wind velocity using a fuel capacity of 89,000 kcal/hr.

U is expressed by the following equation which is derived statistically

$$U = 5.7 + 0.16V. \quad (3)$$

Each measured point, however, varied over a wide range, about 3.0 to 10.0 kcal/m²·hr·°C. It is problematical whether the variation is caused by experimental error or it actually takes place under certain conditions. If it is only the experimental

error, more reliable measurements of U must be made. It appears that the calculation of the total heat supplied is a possible source of error. For example, if the controller operates on-off 3 or 4 times per hour under a certain meteoric condition, there is much difference in the heat supplied between the case of 3 times per hour and the case of 4 times per hour in spite of the stationary meteoric condition. Moreover, it was difficult to calculate the residual heat in the heater when it was off.

For a more exact determination of the heating load coefficient the plastic greenhouse was heated continuously with the small heater which operated nearly continuously during the experiment. The heater did not have enough capacity so the inside temperature dropped slightly below the design temperature. But, it allowed U to be accurately determined as compared with the previous experiment. The results are shown in Fig. 3.

Fig. 3. Relationship between heating load coefficient and wind velocity using a fuel capacity of 26,400 kcal/hr.

According to Fig. 3, the variation of each measured point increased over that in the previous measurement so that the error in the calculations of the total heat supplied and the residual heat in the heater do not appear to have caused the wide variation illustrated in Fig. 2.

For investigating the cause of the variation of U the model tests were performed.

3. Measurement of the overall heat-transfer coefficient using model

The heat consumption of a greenhouse H can also be shown by the following equation

$$H = H_s + H_v + H_o \quad (4)$$

where H_s is the heat loss into the soil, H_v is the heat loss due to ventilation and H_o is the overall heat-transfer through the plastic film. These terms can be expressed as functions of temperature difference. They can then be rewritten into following forms

$$H_s = h_s \cdot A_g \cdot (t_i - t_s) \quad (5)$$

$$H_v = h_v \cdot A \cdot (t_i - t_o) \quad (6)$$

$$H_o = h_o \cdot A \cdot (t_i - t_o) \quad (7)$$

where h_s is the heat-transfer coefficient into soil, h_v is the heat-transfer coefficient due to ventilation, h_o is the overall heat-transfer coefficient, t_s is the soil surface temperature and A_g is the area of the floor.

The value of H_s is small compared with the others, being about 5–10% of total heat loss (Businger 1966, Takakura et al. 1971, Yamamoto 1973). Therefore, H_s can be replaced by the following approximate equation

$$H_s = a'' \cdot A \cdot (t_i - t_o), \quad (8)$$

where a'' is an empirical constant.

The ventilation rate is a function of wind velocity, temperature difference and the size and number of air leaks in the wall. Both the wind velocity V and the temperature difference $t_i - t_o$ will cause a pressure difference over the greenhouse wall, which is actually the cause of the ventilation. Therefore, the following equation may be substituted for the heat-transfer coefficient due to ventilation (Okada et al. 1973).

$$h_v = a' + b'V, \quad (9)$$

where a' and b' are empirical constants. About 20–30% of the total heat loss from a greenhouse is due to ventilation (Takakura et al. 1971).

About 60–80% of the total heat loss is due to the overall heat-transfer through plastic film, so a great part of U is occupied by the overall heat-transfer coefficient (Takakura et al. 1971). Thus, it is important to correctly calculate it. If h_o is constant or is a function of wind velocity, then by combining equations (6), (7), (8) and (9), U can be expressed as equation (2).

In the following experiments the overall heat-transfer coefficient which greatly affects the heating load coefficient was investigated.

(a) Methods and materials

The three boxes shown in Fig. 4 were designed for the experiments. To simplify experimentation only the upper face was covered with plastic film. The side and bottom walls were made of three layers of insulating materials with the inside and outside surfaces of the walls covered with silver p.v.c. film to prevent leakage of air.

Fig. 4. A description of model box for measuring the overall heat-transfer coefficient.

Thermocouples were set in the insulation layers for calculating heat loss through the walls. Heat was supplied using a sheet of carbonic heating film placed in the bottom of each box. Each sheet was connected to an on-off controller.

The difference between inside and outside temperatures was measured by the thermocouples. The electric current supplied to the boxes for heating and all temperature readings were integrated for thirty minutes and then used to calculate the overall heat-transfer coefficient. The anemometer was set at the same level as the upper film surface of the boxes and the radiometers (Funk type) were located at 10 cm above the plastic film of each box.

If the amount of heat loss due to ventilation is disregarded, the heat budget of the experimental box can be expressed by the following equation

$$Q = H_b + H_w + H_m, \quad (10)$$

where Q is the heat supplied by the electrical heater, H_b and H_w are the heat losses through the bottom and side walls respectively, and H_m is the overall heat-transfer. It is also expressed as the function of the difference in temperatures between inside and outside $t_i - t_o$. So, the overall heat-transfer coefficient h_m is given by the following equation

$$h_m = \frac{Q - H_b - H_w}{A_o (t_i - t_o)}, \quad (11)$$

where A_o is the area of plastic film. In this experiment h_m was calculated by equation (11).

(b) Results and discussion

The results of a model test using clear p.v.c. film of 0.1 mm are shown in Fig. 5.

Fig. 5. Relationship between the overall heat-transfer coefficient and wind velocity in model tests.

There was a large variation of h_m and h_m could not be expressed as a function of wind velocity. This fact suggests that the overall heat-transfer for the plastic film may not be expressed as equation (7).

The overall heat-transfer is composed of two parts of heat-transfer, that is, the convective heat-transfer and the radiative heat-transfer. The convective part including the conductive transfer in the film can be expressed as a function of temperature difference $t_i - t_o$ as in equation (7), but the radiative heat-transfer is a function of surface temperature and radiation from the atmosphere. Consequently, if the value of the convective heat-transfer is very large in comparison with the value of the radiative heat-transfer, the overall heat-transfer can then be accurately calculated by equation (7). If the value of the radiative heat-transfer is larger than the value of the convective heat-transfer, the result calculated using equation (7) will be inadequate. So, the author investigated the relationship between h_m and the ratio of the convective part to the radiative part.

The value of the convective part was calculated by the following equation

$$H_c = \frac{A_0}{\frac{1}{\alpha_i} + \frac{l}{\lambda} + \frac{1}{\alpha_o}} (t_i - t_o), \quad (12)$$

where H_c = the convective heat-transfer,

α_i = the heat-transfer coefficient of the inside air calculated by $\alpha_i = 2.8 \sqrt{\Delta t}$, Δt being difference between film and inside air temperature, which is assumed that $\Delta t = t_i - t_o$ (Watanabe 1965),

α_o = the heat-transfer coefficient of the outside air calculated by $\alpha_o = 2.8 \sqrt{\Delta t} + 3.3 V^{0.8}$ by use of $\Delta t = t_i - t_o$ (Mikheyev 1966, Watanabe 1965),

l = thickness of materials (0.1 mm for plastic film and 3.0 mm for glass),

λ = the heat conductivity of materials (0.12 kcal/m·hr·°C for p.v.c. film, 0.14 kcal/m·hr·°C for polyethylene film and 0.64 kcal/m·hr·°C for glass)

The radiative heat-transfer was calculated from the data of the radiometer and equation (13) of the heat budget under the assumption that there was no heat-transfer due to ventilation.

$$H_r = Q - H_w - H_b - H_c, \quad (13)$$

where H_r is the radiative heat-transfer.

The results are shown in Fig. 6, in which the abscissa is the ratio of the convective to the radiative heat-transfer.

Fig. 6. Relationship between the overall heat-transfer coefficient and the ratio of convective heat-transfer and radiative heat-transfer.

The measured points conform closely to a regular curve. The overall heat-transfer coefficient h_m

increases as the proportion of radiative heat-transfer increases in the overall heat-transfer, that is, decrease in the ratio H_c/H_r . On the contrary, when the convective heat-transfer has the larger value in the overall heat-transfer, h_m approaches a constant value. It is considered that the variations in Fig. 5 are caused by the large values of the radiative heat-transfer compared with those of the convective heat-transfer.

Then, experiments were performed using two boxes. One was maintained at a constant inside temperature. The other one was operated with a constant electric current in the heater by means of a controller. In the latter box, the inside temperature changed with the outside temperature. With the constant current the values of h_m varied to a much greater degree than those in the box at a constant temperature. This was because the inside temperature in the latter decreased with the falling outside temperature and the difference between the inside and outside temperatures became small. Then, there was a relative increase in the radiative heat-transfer in comparison with the convective heat-transfer and the large values of h_m appeared. This is a likely reason that the variations in experiments in 1975 were larger than those in 1974.

Furthermore, experiments with the boxes covered with polyethylene (p.e.) film with 71% transmittance of long-wave radiation, silver p.v.c. film with 0% transmittance (Hagiwara and Horiguchi 1972) and glass with about 7% transmittance (Hanson 1963) were performed in April, May and June of 1976 and 1977. According to the results (see Fig. 7) each measured point fell on a curve in spite of the different properties of materials.

The ratio H_c/H_r varied from 0.1 to 1.0 and many measured points concentrated in the range of 0.4 to 0.7. This illustrates the fact that the relation between h_m and the ratio is not affected by the conductivity and the transmittance of long-wave radiation of a thin material used. And, there are many cases when h_m is not constant.

Computations of h_m using simulated values of wind velocity 1.0 m/s, radiative heat-transfer 0.01–0.20 cal/cm²·min and temperature difference 0.1–15.0°C, were made using equation (12) for the convective heat-transfer. The results are shown in Fig. 8.

Fig. 7. The overall heat-transfer coefficient and ratio (H_c/H_r) obtained by various materials.

Fig. 8. The computation of overall heat-transfer coefficient and ratio (H_c/H_r) using the simulated values; clear p.v.c. film of 0.1 mm, wind velocity of 1.0 m/s, radiative heat-transfer of $0.01-0.20 \text{ cal/cm}^2 \cdot \text{min}$ and temperature difference of $0.1-15.0^\circ\text{C}$.

Nearly the same curve resulted as the one from the data obtained using the model boxes and h_m became nearly constant when the ratio was greater than 1.0.

When calculating the overall heat-transfer, we can use a constant transfer coefficient if the difference between the inside and outside temperature is large. On the other hand, if the

temperature difference is small, the radiative part of the total heat-transfer becomes relatively large and the overall heat-transfer coefficient takes various values. Also, in the case of heating load coefficient consisting mainly of the overall heat-transfer coefficient, the same must be the case. The surface temperature of a roof and wall made with thin materials, e.g., plastic film and glass, is greatly affected by inside temperature. When the inside temperature becomes high, the radiative component of heat-transfer is large and the heating load coefficient is likely to increase to a considerable degree. We must remember that equations (1) and (7) can be adequate only in the case of a large value of the convective heat-transfer in comparison with the radiative heat-transfer.

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ハウスの暖房負荷係数の変動と プラスチックフィルムの熱貫流率について

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要 約

実際に使用しているビニルハウスを使用して、暖房負荷係数の測定を行った。1974年は、89,000 kcal/hrの温風暖房器を使用して測定を行い、式(3)のような値が得られたが、各測点はかなりのバラツキがみられた。これは on-off 調節により供給熱量が正確に測定出来ないことが原因と考え、1975年には正確な測定を行うため、on-off 作動が少ない26,400 kcal/hrの暖房器を使用して測定を行った。しかし図3のように各測定のバラツキはさらに大きくなった。このバラツキの原因を調べるため、モデル箱を使用して、暖房負荷係数に大きな比率をしめ

る熱貫流率を調べた。その結果、熱貫流率を風速の関数として表わした場合、各測点はバラツキのため一定の関係式は得られなかったが、熱貫流量にしろる顕熱損失と放射熱損失の比の関数として表わした場合、一定の曲線上に熱貫流率はならんだ。さらにこの曲線はプラスチックフィルムの種類やガラスによる相違は小さく、ビニル、ポリエチレン、シルバービニル、ガラスともほぼ同じ曲線になった。この曲線から熱貫流量にしろる顕熱損失が多いと一定の熱貫流率になるが、放射熱損失が多いと、熱貫流率が大きく変動することが判明した。