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# FACTORS INFLUENCING THE CONDUCTIVE DUCTIVE HEAT TRANSFER THROUGH HYACINTH BULBS PACKED IN CLOSED OR VENTED CARTONS

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## SUMMARY

Experiments were carried out with hyacinth bulbs, with the aim to determine the influence of the bulbs' heat produced by respiration and of the carton vent holes, on the bulbs cooling rate, and on the effective thermal conductivity. For the first and third experiment a closed carton was used. For the second experiment 6% vent holes were provided on the carton bottom and for the fourth experiment the carton cover had the same percent of vent holes.
In all these experiments the cartons containing flower bulbs were stacked on a cold plate with a constant temperature (3-4°C) and one dimensional heat flow perpendicular to the cold plate, was ensured.

Two finite differrence models were used to calculate the bulb temperature (from all the seven layers) and the surrouonding air temperature.

The results show that the cooling process based on heat conduction (in one direction only) is influenced by the bulbs' respiration rate. When the heat produced by respiration was high (during the first experiment) the bulbs' temperature from the last layers was increased instead of decreased.

The vents provided in the carton bottom or in the cover have some positive influence on the bulbs' cooling rate, in particular the layers near the vents.

A good agreement was found between the calculated and measured temperature of the bulbs in all layers.
For the air surrounding the bulbs a good agreement was found between the measured and calculated temperature for some layers only.

## SAMENVATTING

Temperatuurmetingen zijn uitgevoerd aan hyacintebollen om de invloed na te gaan van de warmteproduktie en de toepassing van ventilatiegaten in de dozen op de afkoeling en de effectieve warmtegeleiding.
Tijdens experiment 1 en 3 werd een gesloten doos gebruikt. Voor experiment twee is een doos met 6% ventilatie-opening in de bodem toegepast en in het vierde experiment is het deksel voorzien van 6% ventilatie-opening.
Tijdens alle vier experimenten waren de dozen met bloembollen op een koude plaat gestapeld met een constante temperatuur (3-4°C). Hierbij is gezorgd voor een ééndimensionale warmtestroom loodrecht op de koude plaat.
Twee eindige differentiemodellen zijn gebruikt om de boltemperaturen (in alle zeven lagen) te berekenen evenals de omgevende luchttemperaturen.

De resultaten laten zien dat het koelproces gebaseerd op warmtegeleiding (in een richting) wordt beïnvloed door de warmteproduktie van de bloembollen. Bij een hoge warmteproduktie (experiment 1) namen de boltemperaturen toe in plaats van af.
De ventilatiegaten in de bodem of in het deksel hebben beide een positieve invloed op de afkoelsnelheid vooral in de lagen bij de openingen.

Een goede overeenstemming werd gevonden tussen de berekende en gemeten temperaturen in alle lagen. Ook voor de luchttemperaturen rond de bollen werd een goede overeenkomst gevonden tussen de metingen en de berekeningen maar slechts in enkele lagen.

## INTRODUCTION

All the hyacinths bulbs used for forcing in the U.S. and Canada are produced in The Netherlands (3).
For Ocean transport two types of packing materials are widely used: wooden or plastic trays and cardboard boxes.
Since the spring flowering bulbs require ventilation which is essential for proper development of the bulbs during transport the cartons are provided with vent holes.
Several research works have shown that by providing the carton wall perpendicular to the air flow direction with vent holes it is possible to reduce the pressure drop across the package and to improve the air and temperature distribution in the cargo (4-7). But generally the cartons are stacked in a shipping container in such a way that the cooling or heating process is determined by heat conduction only in the center of the stack (2). In this case it is interesting to know the factors which influence the cooling rate.

The aims of the research were:

1. To determine the cooling rate of hyacinths bulbs packed in a closed or vented carton.
2. To evaluate the influence of the bulbs respiration rate and of the vent holes provided on the top or the bottom of the carton on the cooling rate and on the effective thermal conductivity.
3. To compare the measured cooling rate of the bulbs and the air from different layers with the calculated one based on a finite difference model.

## TEST PROCEDURE AND PRESENTATION OF RESULTS

In this research only the case of one-dimensional conduction heat flow was considered. Therefore the experimental carton with the dimension of 48 x 30 x 25 cm was placed in the middle of a cold plate.
Through this plate a constant temperature liquid (water with glicol) was pumped by a Colora Cryostat.
To ensure one-dimensional heat flow in the direction perpendicular to the cold plate, the bottom of the cold plate was insulated and around the experimental carton containing hyacinth bulbs six other cartons containing the same bulbs were placed (Fig. 1). The exterior walls of these cartons were insulated with a 10 cm polystyrene layer. A polystyrene 10 cm layer covered also all the cartons.
In each carton, the bulbs were arranged in 7 layers each containing 120 bulbs arranged as uniformly as possible. The temperature of two bulbs (measured in the bulb center) and of the air surrounding them (two points) were measured with fine copper constantan thermocouples (0,5 mm diameter of the wire), in each layer.
The plate surface temperature was measured at five different points and the average value was used. A "Fluke" datalogger recorded all the thermocouples every hour.
The cold plate non-insulated surface was provided with a heat flow meter which was also connected to the same data logger.
Two finite difference model were used to calculate the cool down of the bulbs and to calculate the surrounding air temperature. The model used to calculate the bulbs temperature takes into account the convective heat transfer between the bulbs and the cold air from the void spaces, the conduction heat between

the bulbs, but also the bulbs' heat production. Each bulb is simulated as a note located at the center of the bulb.
In the case of flower bulbs which continue to respire and to lose water the energy balance for each node is given by ec. 1.

$$\frac{k_f A_{i+1} (T^n_{i+1} - T^n_{i-1})}{\Delta x_{i+1}} - \frac{k_f A_i (T^n_i - T^n_{i-1})}{\Delta x_i} - hA_s (T^n_i - I^n_i) + Q^n_r = \frac{m_i c_f (T_i^{n+1} - T^n_i)}{\Delta t} \qquad (1)$$

The value of $T_i^{n+1}$ can be calculated from formula 2.

$$T_i^{n+1} = \frac{k_f A_{i+1} \Delta t}{m_i c_f \Delta x_{i+1}} (T^n_{i+1}) + \left(1 - \frac{k_f A_{i+1} \Delta t}{m_i c_f \Delta x_{i+1}} - \frac{k_f A_i \Delta t}{m_i c_f \Delta x_i} - \frac{h A_s \Delta t}{m_i c_f}\right) T_i^n + \frac{k_f A_i \Delta t}{m_i c_f \Delta x_i} T^n_{i-1} + \frac{h A_s \Delta t}{m_i c_f} I^n_i + \frac{Q_r^n \Delta t}{m_i c_f} \qquad (2)$$

where
$k_f$ = fruit thermal conductivity [W/mK]
$A_s$ = exposed surface area of the fruit [$cm^2$]
$A_i$ = average cross section area for conduction between fruit i and i-1 [$cm^2$]
$\Delta x_i$ = distance between nodes i and i-1 [cm]
$\Delta t$ = length of time step [h]
$T^n_i$ = temp of node i and step n [K]
$I^n_i$ = temperature of the air surrounding node i at time step n [K]
h = convective heat transfer coefficient [$W/m^2K$]
$m_i$ = mass of fruit [kg]
$c_f$ = fruit specific heat [Wk]
$Q^n_r$ = heat of resperation at time step n [W]

By taking $\Delta t = 1$ hour

$A_{i+1} = A_i$; $\Delta x_{i+1} = \Delta x_i$

for the layers 2 to 6

$\Delta x_i = \frac{\Delta x_i}{2}$ for layer 1 and $\Delta x_{i+1} = \frac{\Delta x_{i+1}}{2}$ for layer 7

and by noting $\frac{k_f A_i}{m_i c_f \Delta x} = P$

$\frac{h\ As}{m_i c_f} = N$ and $\frac{Q_r^n}{m_i c_f} = R$

Equation 2 becomes

$$T_i^{n+1} = T^n_{i+1}P + T^n_i (1-P-P-N) + P\,T^n_{i+1} + NI^n_i + R \tag{3}$$

This equation was used only for the layers 2-6.

For the first and last layer was used also

$$Pl = \frac{K_f A_i}{m_i c_i (\Delta x/2)}$$

For the first layer equation 2 becomes:

$$T^{n+1} = T^n_{i+1} P + T_i^n (1 - P - P_1 - N) + P_1 T_{i-1} + NI_i^n + R \tag{$3_1$}$$

For the last layer equation 2 becomes:

$$T_i^{n+1} = T^n_{i+1} P_1 + T_1^n (1 - P_1 - P - N) + P\,T^n_{i-1} + NI_i^n + R \tag{$3_2$}$$

For the calculation of heat and mass transfer in the void space each bulb is assumed to be surrounded by air whose volume is equal to the volume of the void space increased with some slow air movement (3 cm/sec were measured with a DISA hot wire annemometer in the carton with 6% vent holes in its bottom). Each node is subjected to convection heat flow from the bulb toward the plate and evaporative cooling due to water losses.

The nodes are located at the same levels from the cold plate as the bulb nodes, fig. 2.

The energy balance for each node is:

$$\frac{k_1\ A_{i+1}\ (I^n_{i+1} - I^n_i)}{\Delta x_{i+1}} \quad \frac{k_1\ A_i\ (I^n_i - I^n_{i-1})}{\Delta x_i} + h\ S\ (T^n_i - I^n_i) - L_1 WS =$$

$$\frac{m_1\ c_1}{\Delta t}\ (I_i^{n-+1} - I^n_i) \tag{4}$$

The value of $I_i^{n-1}$ can be calculated from formula:

$$I_i^{n+1} = \frac{k_1\ A_{i+1}\ \Delta t}{m_1\ c_1\ \Delta x_{i+1}}\ (I_{i+1}) + (1 - \frac{k_1\ A_{i+1}\ \Delta t}{m_1\ c_1\ \Delta x_{i+1}} - \frac{k_1\ A_i\ \Delta t}{m_1\ c_1\ \Delta x_1} -$$

$$\frac{h\ S\ \Delta t}{m_1\ c_1})\ I^n_i + \frac{k_1\ A_i\ \Delta t}{m_1\ c_1\ \Delta x_i}\ I^n_{i-1} + \frac{h\ S\ \Delta t}{m_1\ c_1}\ T^n_i - \frac{L_1 WS\ \Delta t}{m_1\ c_1} \tag{5}$$

where:
$k_1$ = air thermal conductivity [W/m.K]
$A_i$ = average cross section area for the air surrounding the bulb [$cm^2$]
$I^n_i$ = air temperature at node i and time step n [$^oK$]
$m_1$ = mass of volume of air at node i [kg]
$c_1$ = air specific heat [W/kg]
W = weight losses for a bulb [kg]
L = X = distance between nodes [cm]
S = As = exposed surface area of the fruit [$cm^2$]

To calculate the effective thermal conductivity of a layer of 25 cm hyacinth bulbs packed in a corrugated carton with or without vent holes the following formula was used.

$$E = \frac{qs}{U}$$

where
E = effective thermal conductivity [W/m.K]
q = heat flow through the carton with flower bulbs (measured by the heat flow meter) [$W/m^2$]
s = thickness of the bulbs layer [m]
U = temperature difference over the product layer [K]

$U = T_t - T_p$

where:
$T_t$ = temperature on the top of the carton
$T_p$ = temperature of the cold plate

The factors which can influence the cooling rate are the heat produced by respiration, the evaporative cooling of the water losses and the carton vent holes.
Before each experiment the bulbs' respiration rate was measured using the head space accumulation method.
In this method a stainless steel vessel with volume of 68 l is used. Into this vessel 10 kg of hyacinth bulbs, with a known specific weight are introduced. The bulbs are arranged in a wire mesh container which is in contact with the vessel in four points only, in order to allow a good air penetration through the bulbs, and to assure a uniform climate.
The vessel is closed hermetically only a P.V.C. tube connects it with an Infra Red $Co_2$ analyzer type ADC-SS1 with the range 0-10%.
The accumulation of $CO_2$ in time is measured in the range 0-1% only since higher levels can have some influence on the respiration rate. The $CO_2$ production can be calculated with the formula:

$$PCO_2 = \frac{Vl - VP}{m} \times \frac{\Delta CO_2}{\Delta t} \times 60$$

where:
$PCO_2$ = $CO_2$ production, ml/kg.h
Vl = volume of the vessel, ml
Vp = volume of product, ml
m = mass of bulbs in kg
$\Delta CO_2/\Delta t$ = % $CO_2$/min

The $CO_2$ production as a result of respiration is transformed in heat production divided by a coefficient of 0.168 [$lCO_2$/h.W] which was given for apples in (1).
The weight losses of each layer of bulbs were determined by weighing the bulbs before and after each experiment.
The bulbs specific weight was measured by using the water deplacement method.
The two principal dimensions of 100 bulbs, the maximal diameter and the length (fig. 3) were measured at the beginning and the end of the experiments with a vernier Caliper.
The exterior surface of the bulb was calculated. The data are presented in table 1.
Table 2 shows the changes occurred during the experiments concerning the bulbs' characteristic data.

## RESULTS AND DISCUSSION

Four experiments were carried out. During the first two experimnents the bulbs' respiration rate was higher (see table 2) and during the last experiments the bulbs' respiration rate became slower. It is possible to compare the cooling rate of the bulbs and of the surrounding air from different layers during the first two experiments in fig. 4-6. For the first experiment the bulbs were packed in a closed carton and for the second experiment a carton provided with 6% vent holes in its bottom was used.

In fig. 7-9 the cooling rate of the bulbs and surrounding air are compared during the two last experiments.

For the third experiment the bulbs were packed in a closed carton and for the fourth one a carton provided with 6% vent holes area uniformly distributed on the carton cover was used.

Important to note that all the fig. 4-9 present not only the measured temperature but also the calculated one using two finite difference computer programmes. One for bulbs temperature and the other for air temperature.

These programmes are given in annexe 1 and 2.

The correlation between the effective thermal conductivity E calculated with eq 6 and the temperature difference U for the first two experiments was given in fig. 10 and for the last one in fig. 11.

Figs. 4 and 5 show that when the bulbs repirations rate was not so high (experiment two) and a carton with 6% vent holes in its bottom was used, the bulbs cooling rate, from all the layers was faster and more uniform.

During the first 10-15 h the bulbs temperature from the last four layers was increased with 1.5-2.7°C during the first experiment (fig. 5).

The temperatures increase was slower during the second experiment (only 1°C).

It is not sure that this is the effect of the carton vent holes perhaps also the respiration rate has some influence.

From fig. 5 is also possible to see that 50 hours after the carton was put on a cold plate (with a temperature of 3-4°C) the temperature of the bulbs from the last layer was still 25°C, as it was at the beginning of the first experiment.

This fact shows that the conduction heat transfer cannot assure the cooling of products with high respiration rate during a short time 50 h. Important to note that for the same time period, during the second experiment the bulbs temperature from the last layer decreased till 19°C.

The differences between the measured and calculated temperatures for different layers were smaller for the second experiment, 0.3-0.5°C. Perhaps this is the effect of more uniform respiration rate of the bulbs from different layers, as A result of a more uniform cooling temperature.Fig. 6 shows that by using the data from Annex 2for the computer model it is possible to calculate also the temperature of the air.

It is necessary to note that it is difficult also to measure the air temperature since the thermocouple can touch a bulb so that for some layers the difference between the calculated and measured value is higher. Two factors have an important influence on the calculated air temperature. The quantity of air which is near the bulb and the evaporative cooling of the water lost by the bulbs. By trying different values for the mass of air present in the space around each bulb it was found that 0,04 kg/h is the best one. The mass of air was calculated from the average cross section area for the air surrounding the bulb multiplied by the air velocity and density. The value shows that the air around the bulbs has some velocity. In fact at the end of the second experiment the air velocity on the top of the bulbs was measured with a DISA hot wirre annemometer and it was found that the air velocity into the carton was 3 cm/sec when the carton bottom is provided with 6% vent holes.

From fig. 7 it is possible to see that when the bulbs respiration rate is reduced the cooling rate of the first three layers is quite the same in a closed or in a carton with 6% vent holes area on its cover. But by regarding fig. 8 it seems that the vent holes provided on the top of the carton have some positive effect on the cooling rate of the last four layers and on the cooling rate uniformity, so that the temperature differences between the layers became smaller.

Fig. 9 shows that the vent holes from the carton cover have a positive influence on the air cooling rate. This influence is not only in the last layers but also in the second layer.

Fig. 10 compares the effective thermal conductivity of a 25 layer hyacinth bulbs packed in a closed carton or in a carton with 6% vent holes in its bottom and it is possible to remark that the high respiration rate during the first experiment has a negative influence on the uniformity of the quantity of heat flowing through the carton.

When the heat of respiration decreases to 0.104 W/kg (see Table 2) and a carton with 6% vent holes in its bottom is used the effective thermal conductivity remains quite constant for a temperature difference of 16-21$^{o}$C.

The effective thermal conductivity decreased when the bulbs' respiration rate is reduced but its value remains quite the same when the bulbs are packed in a closed carton (fig. 11).

From the same figure can be seen that the vent holes provided on the carton cover have a negative influence on the uniformity of the effective thermal conductivity.

## CONCLUSION

The cooling process based on conductive heat transfer is influenced by the bulbs' respiration rate. When the respiration rate was high the temperature of the last layers was increased instead of decreased.

At the end of the cooling time (50 hours) a large range of temperatures are found in a small carton (25 cm height).

The air into the carton especially in a carton with 6% vent holes in its bottom has a slow velocity of 3 cm/sec.

Two finite difference models were developed one for the bulbs and one for the air surrounding them, for calculating the conductivity heat transfer through a carton with seven layers of hyacinth bulbs with different respiration rate and weight losses.

A good agreement was found between the calculated and measured bulbs' temperature from all the layers.

For the air surrounding the bulbs, a good agreement was found between the measured and calculated temperature of some layers only.

It seems that the vent holes provided in the top or bottom of the carton have some positive influence on the cooling rate of the air from the layers near the vent holes, so that for conductivity heat transfer it is also recommended to use cartons with vent holes.

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**TABLE 1**

Flower bulbs characteristic data
(Hyacinth cv. Pink Pearl, size 10-12)

| Time of measurement | Before the first experiment | | | After the last experiment | | | Mean Decrease in % |
|---|---|---|---|---|---|---|---|
| Data | Mean | Minimun | Maximum | Mean | Minimum | Maximum | |
| Bulbs' diameter (cm) | 3.46 | 3.02 | 3.90 | 3.39 | 2.97 | 3.75 | 2.02 |
| Bulbs' length (cm) | 3.92 | 3.45 | 4.32 | 3.85 | 3.14 | 4.25 | 1.78 |
| Bulbs' lateral surface calculated (cm$^2$) | 33.89 | 27.01 | 41.03 | 33.06 | 25.37 | 38.66 | 2.45 |

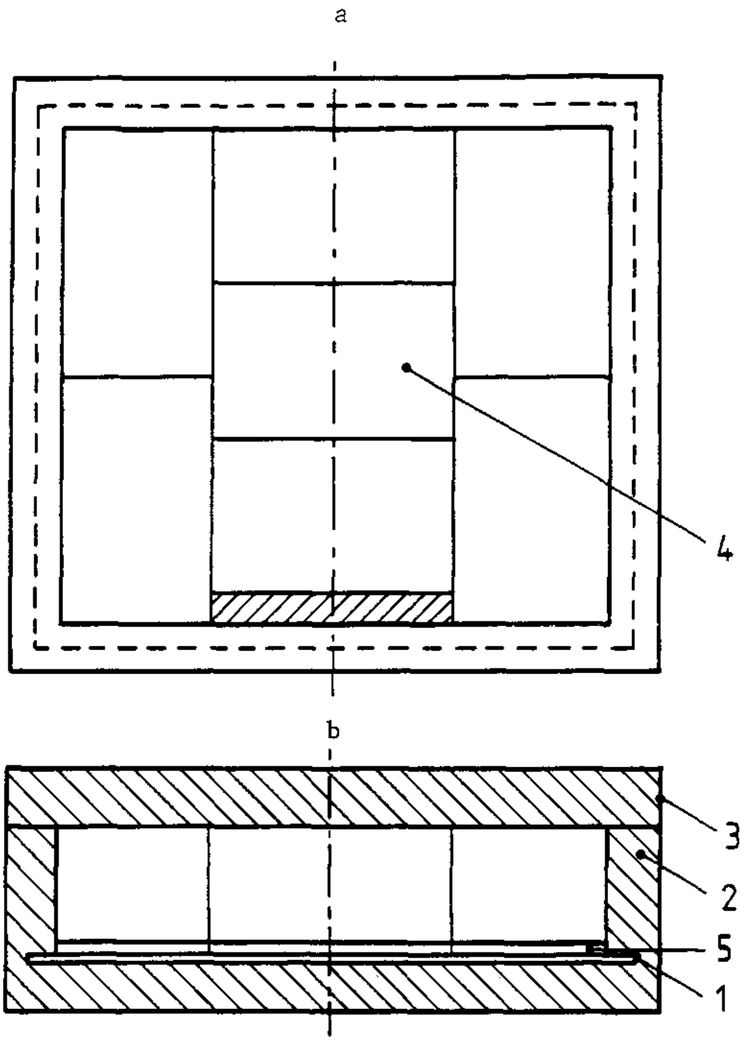
**TABLE 2**

Characteristic date for all the four experiments

| Measuring time | First exp.<br>28.7.1988 | Second exp.<br>8.8.1988 | Third exp.<br>22.8.1988 | Fourth exp.<br>10.10.1988 |
|---|---|---|---|---|
| Bulb mean weight (gr) | 22.3 | 20.6 | 20.1 | 19.1 |
| Weight losses during the exp. (%) | 4.57 | 2.42 | 1.40 | 1.08 |
| Specific weight kg/m | 1.098 | 1.062 | 1.036 | 1.016 |
| Heat of respiration measured (W/kg) | 0.163 | 0.104 | 0.061 | 0.054 |
| Weight of bulbs in the carton (kg) | 18.732 | 17.304 | 16.884 | 17.381* |
| Box | closed | bottom open | closed | top open |
| Duration of exp. | 50 h | 50 h | 50 h | 50 h |

* 130 bulbs in each layer

Wageningen, November, 8, 1988
EH/AvH



1. Cold plate
2. Lateral insulation
3. Polystyrene cover
4. Experimental carton
5. Heat flow meter

Figure 1: Experimental lay out
a. top view without the polystyrene cover
b. vertical section

Figure 2:
The seven layers of bulbs
and the nodes place
T = for bulbs temperature
I = for air temperature
$T_p$ = temp. of the cold plate
$T_o$ = temp of the carton bottom
$T_t$ = temp. of the carton top

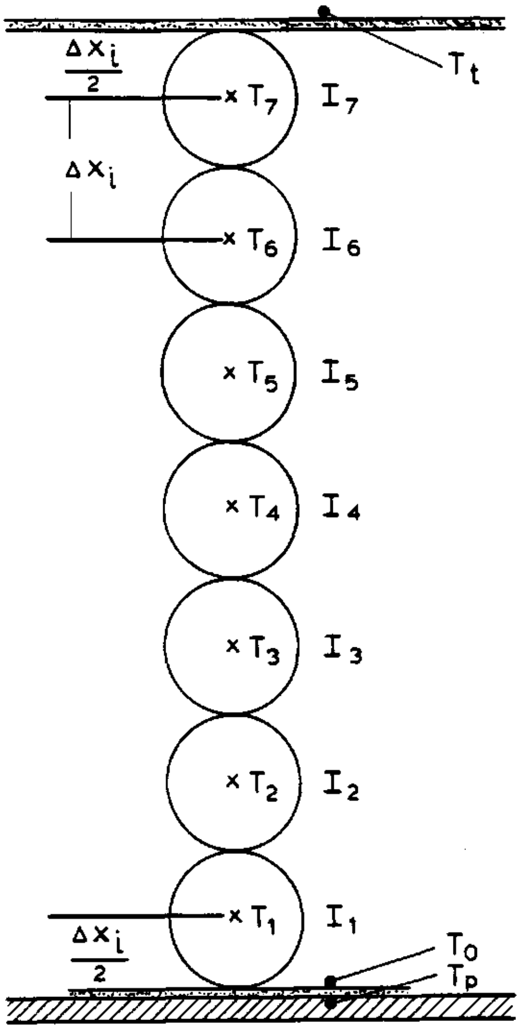
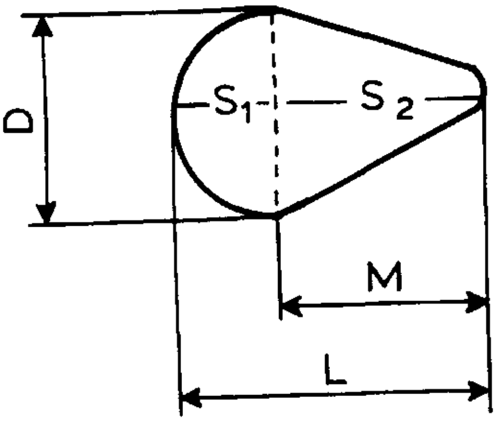


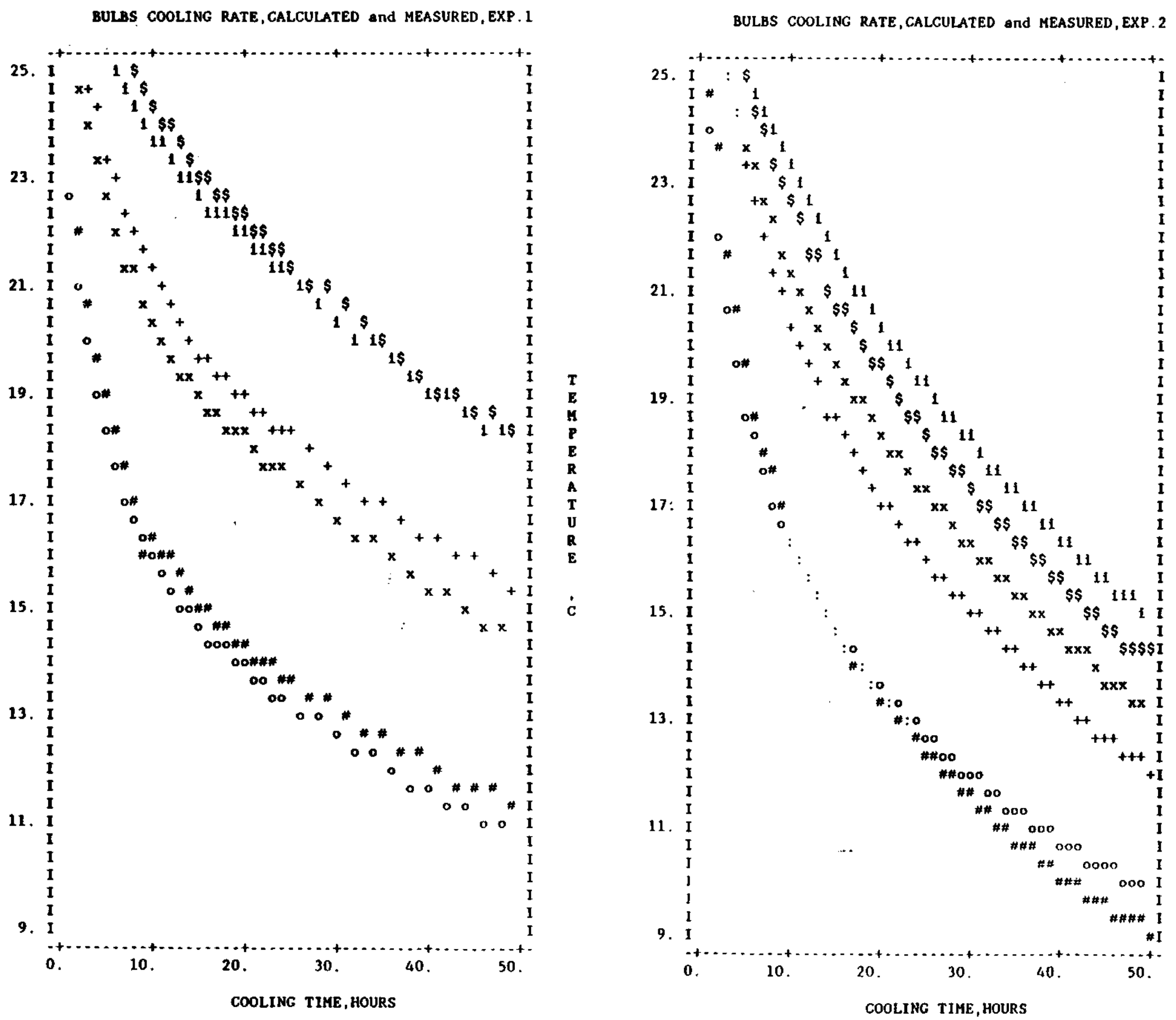
Figure 3:
The exterior surface of a hyacinth
bulb S, and the specific dimension
D = maximal diameter
L = bulbs length

$$S_1 = 2 \times \Pi \times \frac{D}{2}$$

$$S_2 = \Pi \times \frac{D}{2} \times \sqrt{(\frac{D}{2})^2 + m^2}$$

$$S = S_1 + S_2 \quad \ldots\ldots \text{ ec. } 7$$



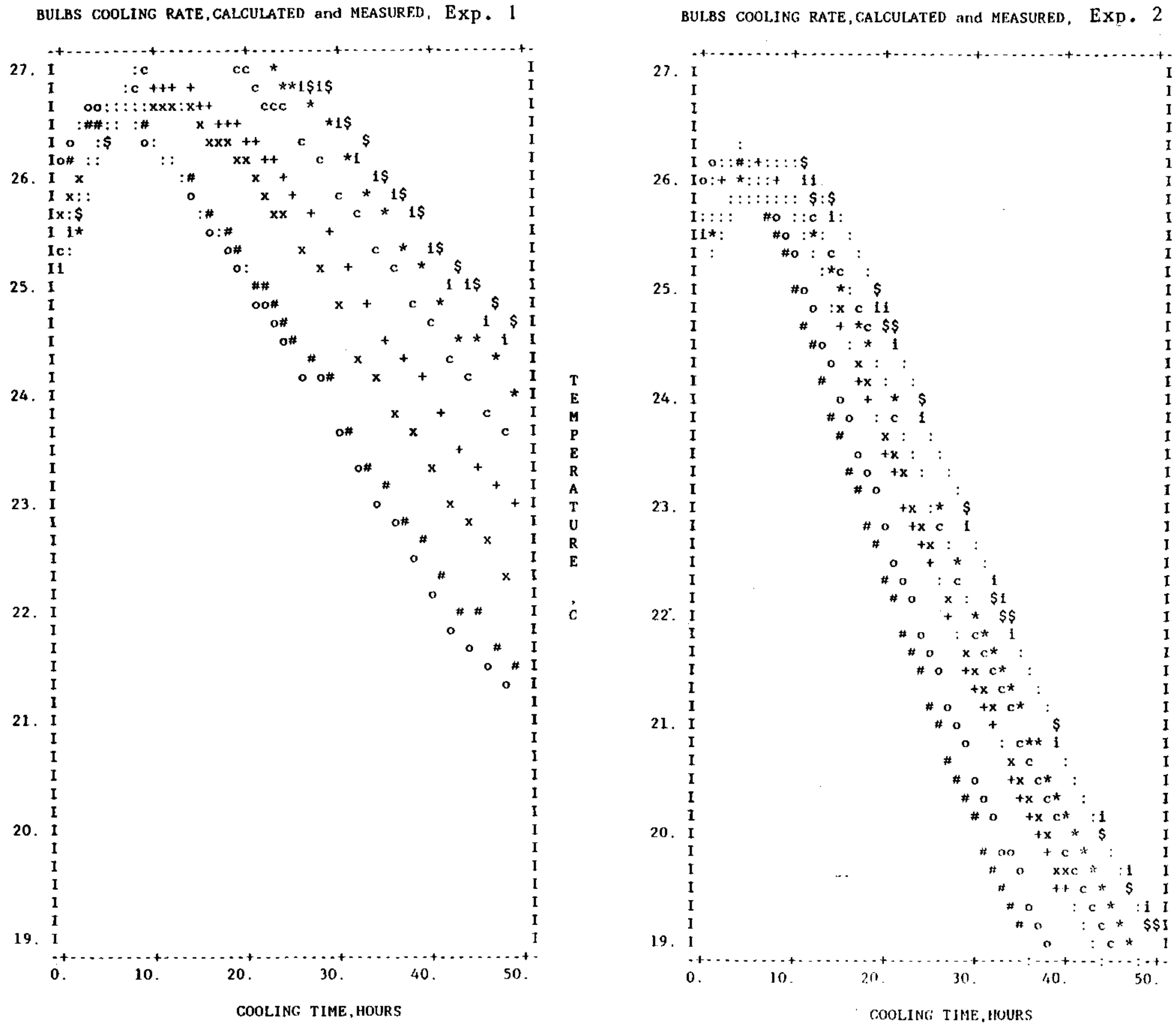


BULBS COOLING RATE, CALCULATED and MEASURED, EXP.1

BULBS COOLING RATE, CALCULATED and MEASURED, EXP.2

Legend
o = measured at the first layer
x = measured at the second layer
i = measured at the third layer
# = calculated for the first layer
+ = calculated for the second layer
$ = calculated for the third layer

Figure 4:
Comparison between the bulbs from the first three layers, cooling rate during the exp. 1-2.



Legend

o = measured at the fourth layer

x = measured at the fifth layer

c = measured at the sixth layer

i = measured at the seventh layer

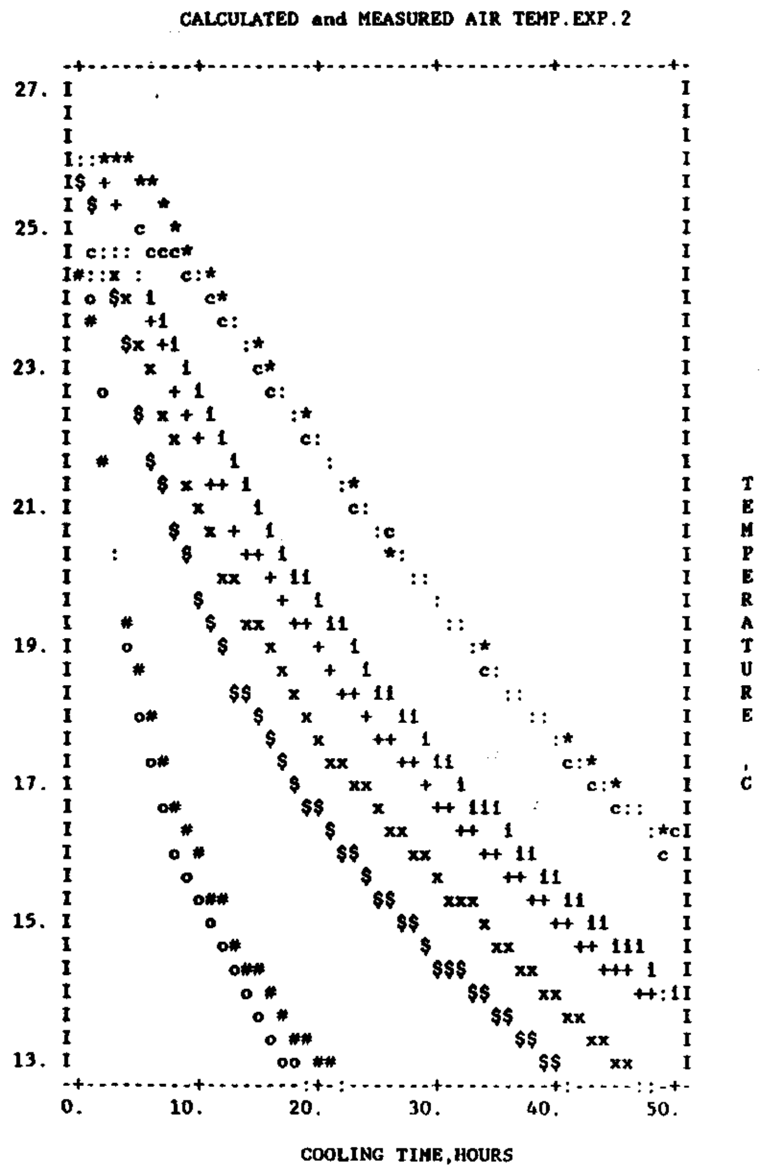
# = calculated for the fourth layer

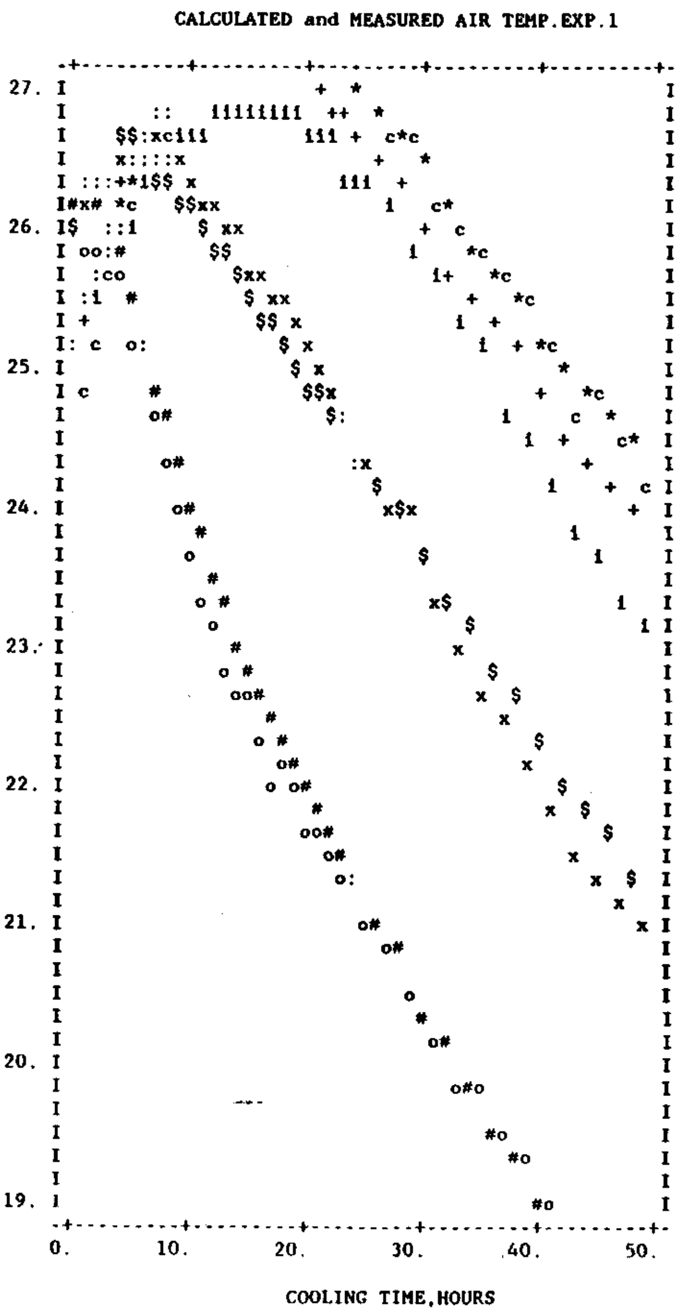
+ = calculated for the fifth layer

* = calculated for the sixth layer

$ = calculated for the seventh layer

Figure 5:
Comparison between the bulbs (from layer 4-7) cooling rate, during the first two experiments.

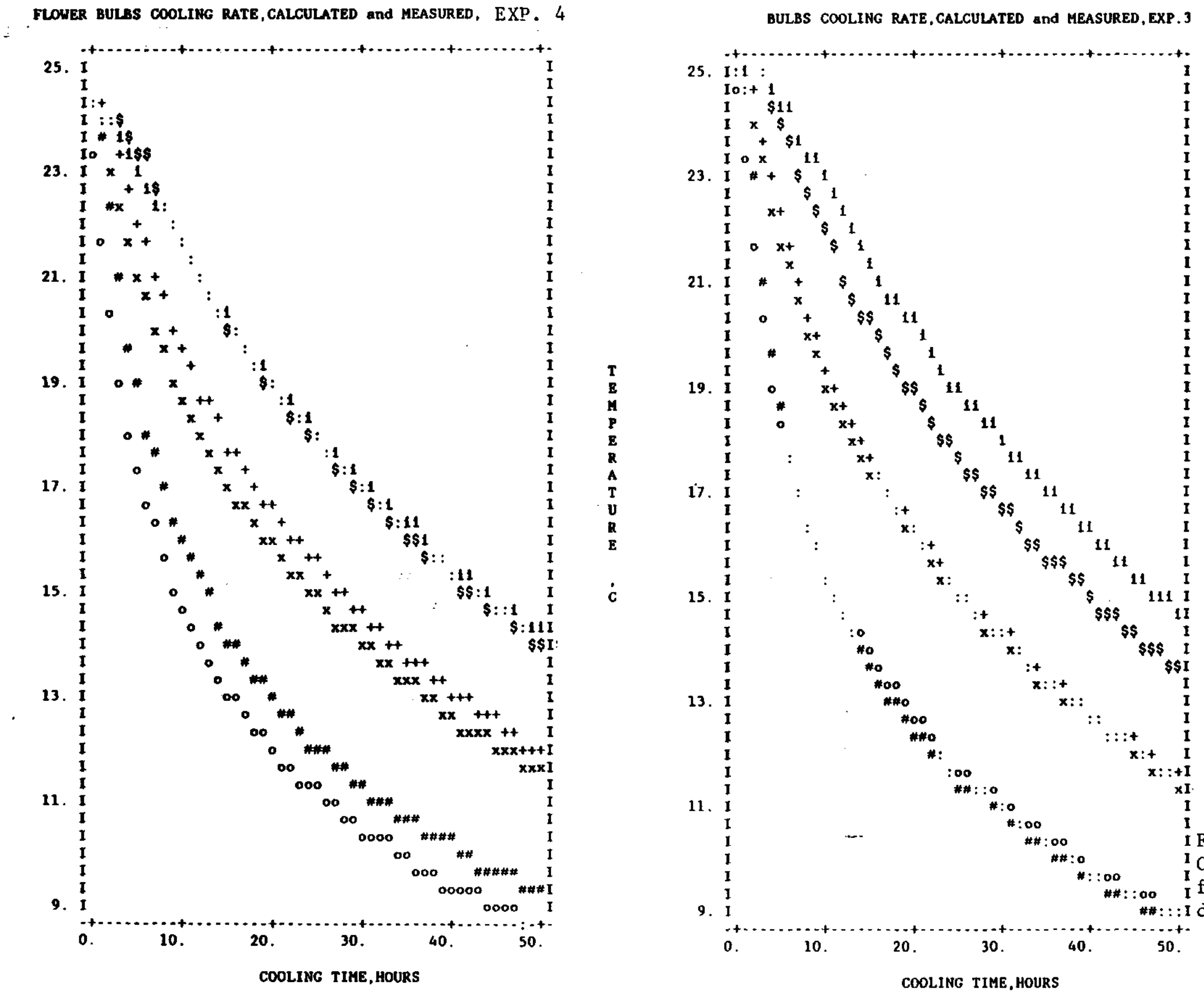




Legend exp. 2
o = measured at the first layer
x = measured at the second layer
i = measured at the third layer
c = measured at the fourth layer
# = calculated for the first layer
+ = calculated for the second layer
$ = calculated for the third layer
* = calculated for the fourth layer

Legend exp. 1
o = measured at the third layer
x = measured at the fourth layer
i = measured at the sixth layer
c = measured at the seventh layer
# calculated for the thrid layer
+ calculated for the fourth layer
$ calculated for the sixth layer
* calculated for the seventh layer

Figure 6:
Comparison between the air surrounding different layers, cooling rate during the experiment 1 and 2.



Legend
o = measured at the first layer
x = measured at the second layer
i = measured at the third layer
# = calculated for the first layer
+ = calculated for the second layer
$ = calculated for the third layer

Figure 7:
Comparison between the bulbs, from the layers 1-3 cooling rate during the last two experiments.

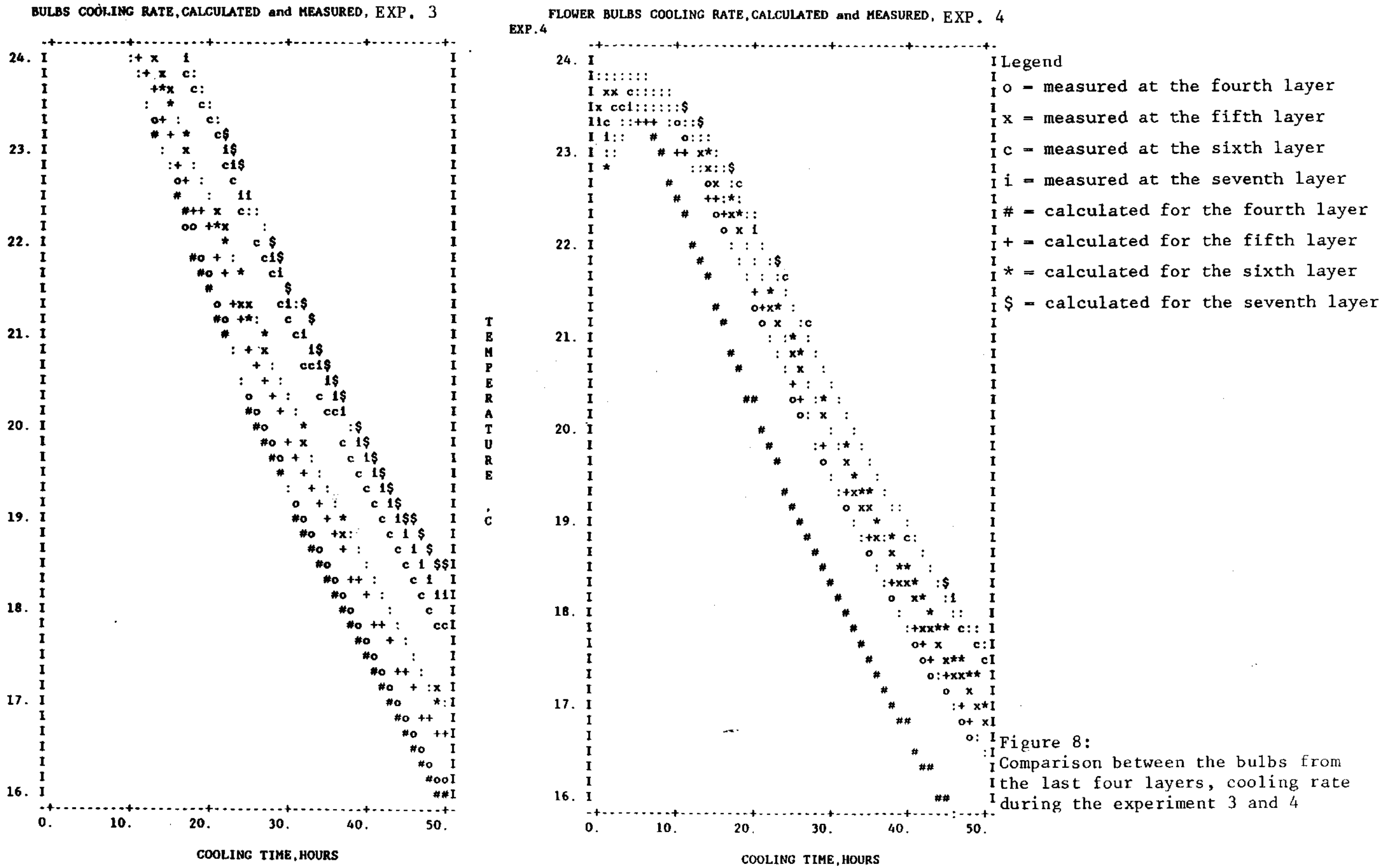
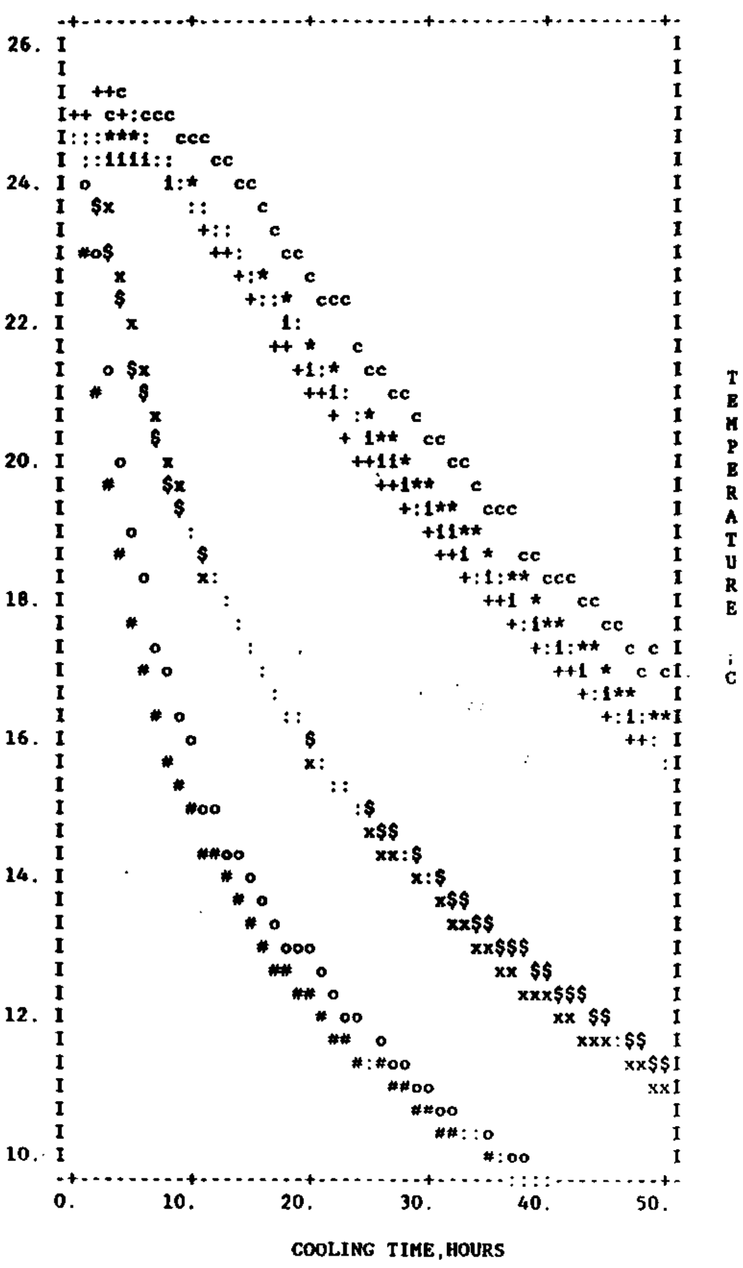
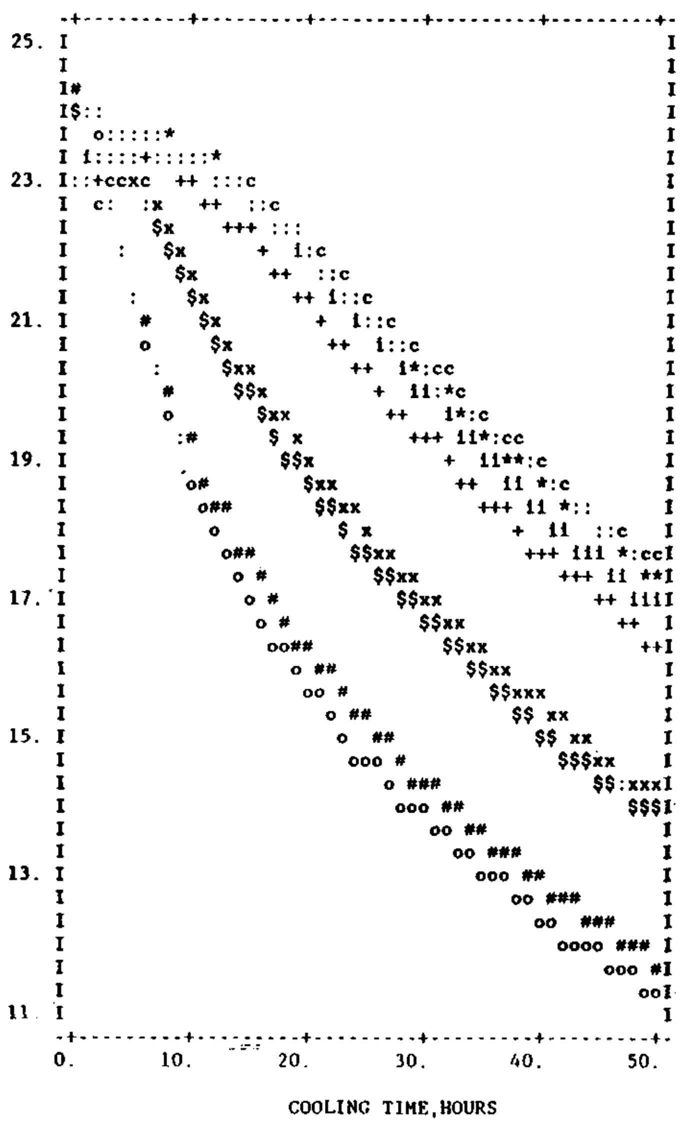


Figure 8:
Comparison between the bulbs from
the last four layers, cooling rate
during the experiment 3 and 4


CALCULATED and MEASURED AIR TEMP.EXP.3


CALCULATED and MEASURED AIR TEMP.EXP.4

Legend exp. 4
o = measured at the second layer
x = measured at the third layer
i = measured at the fifth layer
c = measured at the seventh layer
# = calculated for the second layer
$ = calculated for the third layer
+ = calculated for the fifth layer
* = calculated for the seventh layer

Legend exp. 3
o = measured at the first layer
x = measured at the second layer
i = measured at the fourth layer
c = measured at the seventh layer
# = calculated for the first layer
$ = calculated for the second layer
+ = calculated for the fourth layer
* = calculated for the seventh layer

Figure 9:
Comparison between the air surrounding different layers cooling rate during experiment 3 and 4.

```
T                CORRELATION BETWEEN E and U,  EXPER.1 FLOWER BULBS
H
E           -+---------+---------+---------+---------+---------+-
R       0.45 I                                                  I
M            I                                              +   I
A            I                                                 +I
L            I                                                : I
             I                                                  I
C            I                                                : I
O       0.40 I                                                 +I
N            I                                                  I
D            I                                         ++   + ::I
U            I                                   + + +          I
C            I                                  : +             I
             I                     +  +   + + + +    +          I
.       0.35 I        + + + +  + +                              I
W           -+---------+---------+---------+---------+---------+-
/           18.       19.       20.       21.       22.       23.
mK
                                TEMP DIFFERENCE,C
```

```
T                CORRELATION BETWEEN E and U,  EXPER.2 FLOWER BULBS
H
E           -+---------+---------+---------+---------+---------+-
R       0.45 I                                                + I
M            I                                                  I
A            I                                                ++I
L            I                                                + I
             I                                            +  :  I
C            I                                         : +      I
O       0.40 I                                    : +  +        I
N            I           +    + ++++ +  ++  ++ : +              I
D            I   +  +  +:+ + +  +                               I
U            I                                                  I
C            I                                                  I
             I                                                  I
.       0.35 I                                                  I
W           -+---------+---------+---------+---------+---------+-
/           17.       18.       19.       20.       21.       22.
m
K                                TEMP DIFFERENCE,C
```

Figure 10:
Correlation between the effective thermal conductivity E and the temperature difference U, for the first two experiments

```
T                CORRELATION BETWEEN E and U,  EXPER.3 FLOWER BULBS
H
E            -+---------+---------+---------+---------+---------+-
R       0.40 I                                                   I
M            I                                                   I
A            I                                                   I
L            I                                                   I
             I                                               + + I
C            I                                            + ++   I
O       0.35 I                                      +  ++        I
N            I                                +++  ++  +         I
D            I                +  ++ + ++ +++ +                   I
U            I       +++++ :+ + +   +                            I
C            I                                                   I
             I                                                   I
.       0.30 I                                                   I
W            -+---------+---------+---------+---------+---------+-
/           16.       17.       18.       19.       20.       21.
m

                                 TEMP DIFFERENCE,C
```

```
T                CORRELATION BETWEEN E and U,  EXPER.4 FLOWER BULBS
H
E            -+---------+---------+---------+---------+---------+-
R       0.40 I                                                   I
M            I                                              +    I
A            I                                             +     I
L            I                                             +     I
             I                                             +     I
C            I                                           +       I
O       0.35 I                                         + +       I
N            I                                       ++          I
D            I                                   ++++            I
U            I                                +++                I
C            I                       +++ +++++                   I
             I                 ++: ++                            I
.       0.30 I         +++: +:+                                  I
W            -+---------::--------+---------+---------+---------+-
/           16.       17.       18.       19.       20.       21.
m

                                 TEMP DIFFERENCE,C
```

Figure 11:
Correlation between the effective thermal conductivity E and the temperature difference U for the last two experiments

## PROGRAMME FOR CALCULATING THE BULBS COOLING RATE
## (SECOND EXPERIMENT)

```
open' F1.dat';channel=2;width=350
units [nvalues=50]
READ [CHANNEL=2]J,T0,I1,T1,I2,T2,I3,T3,I4,T4,I5,T5,I6,T6,I7,\
T7,Tp,Tt,Ta,Q
SCALAR [VALUE=0.47] KF
SCALAR [VALUE=0.022] MI
SCALAR [VALUE=1.98] AI
SCALAR [VALUE=1.050] CF
SCALAR [VALUE=0.57] H
SCALAR [VALUE=34]  AS
SCALAR [VALUE=3.8] X
SCALAR [VALUE=0.00185] QR
CALCULATE L1=X/2
CALCULATE P=(KF*AI)/(MI*CF*X*1000)
CALCULATE P1=(KF*AI)/(MI*CF*L1*1000)
CALCULATE N=(H*AS)/(MI*CF*1000)
CALCULATE R=QR/(MI*CF)
CALCULATE O1=(P*T2)+T1*(1-P-P1-N)+(P1*T0)+(N*I1)+R
CALCULATE O2=(P*T3)+T2*(1-P-P-N)+(P*T1)+(N*I2)+R
CALCULATE O3=(P*T4)+T3*(1-P-P-N)+(P*T2)+(N*I3)+R
CALCULATE O4=(P*T5)+T4*(1-P-P-N)+(P*T3)+(N*I4)+R
CALCULATE O5=(P*T6)+T5*(1-P-P-N)+(P*T4)+(N*I5)+R
CALCULATE O6=(P*T7)+T6*(1-P-P-N)+(P*T5)+(N*I6)+R
CALCULATE O7=(P1*Tt)+T7*(1-P1-P-N)+(P*T6)+(N*I7)+R
CALCULATE Z=J+1
TEXT T;VALUES=' BULBS COOLING RATE,CALCULATED and MEASURED,\
         EXP.2'
GRAPH [TITLE=T;YTITLE='TEMPERATURE ,C';\
XTITLE='COOLING TIME,HOURS';YLOWER=9;YUPPER=25 ;XLOWER=0;\
XUPPER=50;NROWS=49;NCOLUMNS=51];\
Y=T1,T2,T3,O1,O2,O3;X=J,J,J,Z,Z,Z;\
METHOD=POINT,POINT,POINT,POINT,POINT,POINT ;\
SYMBOL='o','x','i','#','+','$'
STOP
```

## PROGRAMME FOR CALCULATING THE AIR COOLING RATE

(FIRST EXPERIMENT)

```
open' F.dat';channel=2;width=350
units [nvalues=50]
READ [CHANNEL=2]J,T0,I1,T1,I2,T2,I3,T3,I4,T4,I5,T5,I6,T6,I7,\
T7,Tp,Tt,Ta,Q
SCALAR [VALUE=0.031] K 1
SCALAR [VALUE=0.04] MI
SCALAR [VALUE=2.8] A
SCALAR [VALUE=0.293] C1
SCALAR [VALUE=0.57] H
SCALAR [VALUE=34] S
SCALAR [VALUE=3.8] L
SCALAR [VALUE=694] L1
SCALAR [VALUE=0.000102] W
CALCULATE L2=L/2
CALCULATE P=(K1*A)/(MI*C1*L*1000)
CALCULATE P1=(K1*A)/(MI*CF*L2*1000)
CALCULATE N=(H*AS)/(MI*C1*1000)
CALCULATE V=(L1*W*S)/(MI*C1*1000)
CALCULATE O1=(P*I2)+I1*(1-P-P1-N)+(P1*T0)+(N*T1)+V
CALCULATE O2=(P*I3)+I2*(1-P-P-N)+(P*I1)+(N*T2)+V
CALCULATE O3=(P*I4)+I3*(1-P-P-N)+(P*I2)+(N*T3)+V
CALCULATE O4=(P*I5)+I4*(1-P-P-N)+(P*I3)+(N*T4)+V
CALCULATE O5=(P*I6)+I5*(1-P-P-N)+(P*I4)+(N*T5)+V
CALCULATE O6=(P*I7)+I6*(1-P-P-N)+(P*I5)+(N*T6)+V
CALCULATE O7=(P1*Tt)+I7*(1-P1-P-N)+(PI*I6)+(N*T7)+V
CALCULATE Z=J+1
TEXT T;VALUES=' CALCULATED and MEASURED AIR TEMP. EXP.1'
GRAPH [TITLE=T;YTITLE='TEMPERATURE ,C';\
XTITLE='COOLING TIME,HOURS';YLOWER=19;YUPPER=27 ;XLOWER=0;\
XUPPER=50;NROWS=49;NCOLUMNS=51];\
Y=I3,I4,I6,I7,O3,O4,O6,O7;X=J,J,J,J,Z,Z,Z,Z;\
METHOD=POINT,POINT,POINT,POINT,POINT,POINT ,POINT,POINT;\
SYMBOL='o','x','i','c','#','$','+','*'
STOP
```