Danish Research Service for Plant and Soil Science
Research Centre for Horticulture,
Institute of Glasshouse Crops
Department of Horticultural Engineering,
DK-5792 Årslev

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Energy consumption and environmental parameters in different types of greenhouses
Seasons 15 august – 30 april 1983–84 and 1984–85

Energiforbrug og klimaforhold i forskellige væksthustyper
Perioderne 15. august–30. april 1983–84 og 1984–85

Marius G. Amsen and Otto F. Nielsen

Summary

This publication presents the mean values of energy consumption and a number of environmental parameters. The values shown are both the diurnal mean values, and separate day and night means. The diurnal mean values can be compared with other experiments in the same field, but the authors feel, that the diurnal values are not always very valuable when characteristic abilities of different types of greenhouses are described. For example the application of thermal screens totally alters the environmental behaviour of the greenhouse during the night. Therefore also values from day and night are shown separately. The experiments carried out in the experimental houses, not only compare three types of different insulated greenhouses, but also different control strategies in greenhouses of the same type.

The results show, that permanent insulation has a strong effect upon the energy consumption. There is no significant difference between twin walled PMMA and double glass. The general assumption, that greenhouses with permanent insulation are more humid (have a higher relative air humidity) is also confirmed in this experiment.

On the other hand the difference between the dew point temperature and the leaf temperature shows, that there is no higher risk of water condensation on the leaves.

Resumé

I denne beretning beskrives resultater af energiforbrug og klimaforhold i fem væksthuse af forskellige typer og med forskellige styringsstrategier eller indretninger. Anvendelse af gardiner om natten, især i væksthuse dækket med et lag glas, ændrer i høj grad klimaet. Et døgngennemsnit af måleværdier skjuler typiske klimaforskelle mellem væksthusene. Derfor er der i denne beretning foruden generelle værdier, som kan sammenlignes med undersøgelser af lignende karakter, også vist værdier for stabile perioder midt på dagen og midt om natten. Herved undgår man, at overgangsfænomener mellem dag og nat har indflydelse på måleværdier.

Generelt kan man konkludere, at anvendelse af kanalplader eller dobbeltglas har en stor effekt på varmeforbruget. Dette er ikke i overensstemmelse med de forrige forsøg, hvor væksthuset dækket med dobbelt glas havde et højere energiforbrug end væksthuset dækket med kanalplader. Men efter at væksthuset dækket med dobbeltglas er blevet tætnet, findes der ikke nogen større forskel mellem de to permanent isolerede væksthuse.

Den generelle opfattelse af, at der er en højere relativ luftfugtighed i permanent isolerede væksthuse, bekræftes af disse forsøg. Det har derimod ikke været muligt at påvise tydelige forskelle i energiforbrug som følge af, at bordenes overflade har været tør eller våd. Der findes heller ikke definitive forskelle i den relative luftfugtighed, når der ses på gennemsnitsværdier. En styring af den relative luftfugtighed baseret på en hævning af rumtemperaturen alene giver et øget energiforbrug og en luftfugtighed, der i kritiske perioder ligger omkring hygrostatens maksimum sætpunkt, 92% RH.

Det er en fordel at anvende rendeborde i forhold til lukkede borde, når vi betragter energiforbruget alene. Når vi ser på den relative luftfugtighed, viser denne også den laveste relative luftfugtighed.

Introduction

The effect of energy saving equipment or strategies in a greenhouse, will not only have an impact upon the energy consumption but also upon the environmental factors and consequently upon plant growth rates and quality.

The choice of greenhouse is therefore not only a question of energy saving but of biological response as well.

The experiments which started in Denmark in 1978 had therefore two main purposes. First to investigate what type of greenhouse that was preferable seen from a point of energy saving, and second to collect information on biological factors which might help to explain and predict a biological effect.

For these purposes the Ministry of Energy supported the building of an experimental unit, consisting of five experimental greenhouses of three different types.

The main point in the dispute between the growers in Denmark was, and still is, whether greenhouses with permanent insulation, are an attractive alternative for energy saving, bearing in mind plant growth rate and quality. In the traditional greenhouse clad with single glass, possibly equipped with thermal screens, the traditional growing routines, which have proved their value can still be applied.

The results of the first series of experiments (3) showed that for some species of pot plants permanent insulation is an attractive alternative. Furthermore the light reduction in two greenhouses clad with twin walled PMMA (acrylic) was less pronounced, as primary measurements had shown (1). This may explain why no severe reductions in plant growth were found. Due to an inadequate mounting system, the greenhouse clad with double glass was less tight and therefore had a remarkably higher energy consumption than the greenhouse clad with twin walled PMMA before 1983. The greenhouse has since been sealed.

As a result of the previous experiments (4) the greenhouses clad with single glass had their gables insulated with twin walled PMMA before the season 1983–84. The new series of experiments, which are reported in this paper, will not only compare insulation but also different equipment (benches) and environmental control routines.

The authors are convinced, and the results prove, that greater energy saving can be obtained in the greenhouses with permanent insulation.

While reading the report, one must bear in mind, that results are compared with a greenhouse with mobile insulation and clad with single glass, as the greenhouse clad with single glass from the previous series was not equipped with thermal screens. In Denmark thermal screens are not as common as desirable, and the greater amounts of energy can be saved as compared to common practice.

Methods

Research facilities

The experiments were carried out in five detached greenhouses, which differed in cladding or equipment. The greenhouses are east west orientated and placed in three rows, 16 meters apart and a gable distance of 7 m. The ground surface is 21.5 × 8 m (= 172 m²) (Fig. 1).

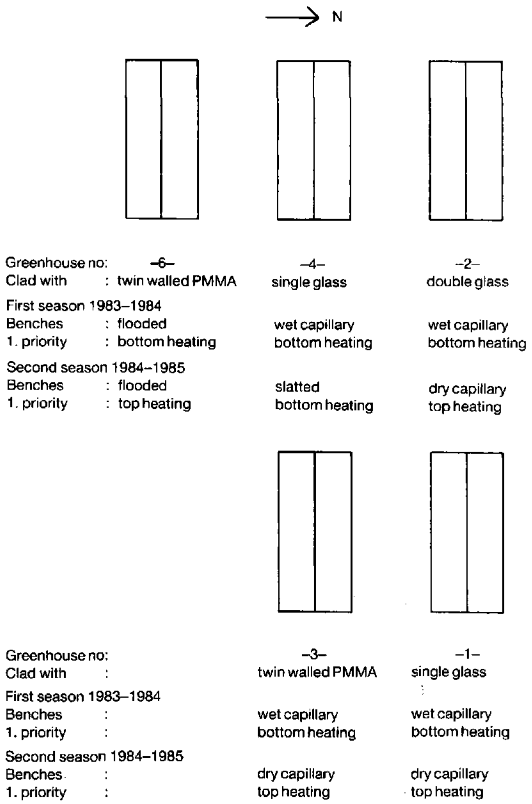

Fig. 1. Outline of the experimental site. Greenhouses: 21.5 × 8 m, 16 m apart and 7 m gable distance.

Insulation

Two greenhouses are clad with single glass (no. 1 and 4) and equipped with a thermal screen of aluminized PE film (peritherm) which is drawn at night.

Two greenhouses are clad with twin walled PMMA (no. 3 and 6). One greenhouse is clad with double glass (no. 2). All greenhouses are equipped with a shading screen of woven fabric which reduces light intensity by 40 per cent.

The shading screens are drawn simultaneously with the thermal screens, and activated at the hour nearest dawn or dusk.

Benches and irrigation

Three types of benches are used, which either differ in irrigation technique or in form. Four movable benches 18 × 1.6 m of the same type are installed in each greenhouse.

Wet capillary benches: lined with perforated polythene film to provide drainage and on top of this a capillary mat (vattex). Below the mat five capillary tubes per m² are evenly divided and supply the benches with a diluted nutrient solution. Water supply is activated by an evaporimeter which releases app. 1.2 mm whenever 1 mm is evaporated. The system provides a constant wet surface from which the plants currently are supplied by a hygroscopic process. The disadvantage of the system is, that evaporation from the wet surface generates a damp atmosphere and consumes energy, which does not contribute to the room temperature.

Dry capillary benches: In the second season the mat was covered with a perforated polythene film, to keep a dry surface and prohibit evaporation from the surface.

Flooded benches: The benches are flooded with a diluted nutrient solution. The water is allowed to raise app. 2 cm and after a quarter of an hour it is drained to a tank for renewed application after replenishment. The acidity and the nutrient concentration are readjusted at preset pH and conductivity values.

The advantage of the flooded benches is, that the surface is kept dry most of the time, which prevents energy loss by evaporation. The water supply is controlled by a clock which activates the system twice a day on average.

Slatted benches: 10 troughs, 10 cm wide, are evenly distributed per bench allowing an open space of 6 cm. Water and nutrients are supplied by inundation following the same principles as mentioned for flooded benches.

The advantage of the slatted benches is believed to be a constant movement of warm air from the bottom heating system. The air movement is assumed to have an effect on water evaporation from the leaves and to prevent fungal diseases. With this type of benches bottom heating is always set at first priority.

Heating system

All greenhouses are installed with an individually controlled top- and wall heating system and a bottom heating system. The standard capacity of the heating system is calculated to maintain a temperature difference between inside and outside of 30° in the greenhouses clad with single glass (greenhouse no. 1 and 4). In the greenhouses with permanent insulation (greenhouse no. 2 and 3) the heating system is reduced by 35 per cent. This reduction is obtained entirely by a reduction of the number of top and wall heating pipes.

In one of the greenhouses clad with twin walled PMMA (greenhouse no. 6), the heating system is extended to 170 per cent of the heating system in the greenhouse clad with single glass. This gives a possibility to test application of low temperature heat. Bench heating: All closed benches are equipped with a separate bench heating system, which is insulated from the surrounding air to ensure that all heat is used for heating the bench surface only.

Room temperature control

The room temperature is controlled by a thermostat, the sensor being placed in an aspirated screen. The thermostat controls the minimum room temperature by activating the vents, which have lee side priority. The top and wall heating system and the bottom heating system can be activated with different priorities or in alternating sequences.

Thermostat settings were minimum 18° for both day and night unless otherwise mentioned. The maximum room temperature setting was 28°.

Bench temperature control

The temperature in the pots is controlled by a thermostat and two sensors are placed in different pots. The pot temperature setpoint was minimum 20°.

Air humidity control

The air humidity is controlled by a hygrostat which activates heating and ventilation simultaneously. The sensor is placed in the aspirated screen.

The hygrostat activates the drying routine at 92 per cent relative air humidity and is deactivated at 88 per cent RH. This standard routine was changed in the greenhouse clad with double glass in the second season. The ventilation was omitted and the reduction of the relative air humidity only obtained by increasing the room temperature. This has the advantage that energy used for drying the air is not lost by ventilation but kept within the greenhouse.

Carbondioxide supply

All greenhouses are supplied with pure carbondioxyd, during daytime and as long as vents are closed. The level is measured by an infra-red gasanalyzer, and kept at a maximum CO_2 concentration of 800 cm^3/m^3.

The aspirated screen

The aspirated screen is an insulated metal box equipped with a fan which pulls the air at a speed of 1 m per second. It is placed 30 cm above the plant canopy in the middle of the greenhouse. Control sensors for room temperature and air humidity are placed in this box.

Data collecting

Different environmental factors are recorded currently, every ten minutes and hourly mean values are stored for analyzing. Dry and wet bulb temperatures are measured by a pt 100 thermo sensor placed in an aspirated screen. Mean values of room temperature, dewpoint temperature and relative air humidity are computed from these measurements.

Light intensity is measured by a solarimeter mounted on a revolving rod of 0.5 m placed over the top heating but below the shading screens. The revolving time is app. 3 minutes. Leaf temperature is measured as the radiant temperature of the plant canopy by an infra-red thermo sensor pointing at the plants at an angle of 20° and covering an area of app. 0.5 m^2.

Roof temperature is measured by an infra-red thermo sensor mounted 2 m below the roof and avoiding interference by heat radiation from the top heating system.

From a statistical point of view, the experiment suffers from restrictions, due to the fact that only one greenhouse per treatment is available. As a result of this the effect of greenhouse and locality cannot be separated.

Changing the heating priority in the second season, the effect of season, greenhouse and locality cannot be separated either. This should be taken into account when looking at the results.

The first experiment took place from 15 August 1983 until 30 April 1984 (first season) and was repeated with major alterations in the same period 1984–85 (second season).

The results from the energy measurements are shown in Table 1. The number on top of the table refers to the greenhouse in question. Percentages for all three heating systems in each greenhouse and the total energy consumption are shown. The percentages below the table show the energy consumption in relation to the experiment in question.

The environmental factors are shown in Table 2 and 3 and organized in the same way. The diurnal mean value may be of statistical value, but it does not always show a typical situation for the different greenhouses.

Therefore we have chosen to show mean values from six hours in the middle of the night and six hours in the middle of the day. The authors suppose that these are stable periods where transfer phenomena from day to night or from night to day do not interfere with the climatic conditions.

Table 1. Energy consumption.

Greenhouse no.	1	2	3	4	6
			first season 1983–84		
Heating system					
Top-wall %	29	27	24	25	9
Bottom %	51	55	55	51	72
Bench %	20	19	21	23	19
Total w/m^2	100.5	76.4	80.6	111.0	77.2
Insulation %	100	76	80		
Night temp. %	100			110	
Irrigation system %			100		96
			second season 1984–85		
Top-wall %	70	82	81	18	87
Bottom %	5	4	3	82	0
Bench %	25	14	16	–	13
Total w/m^2	113.1	94.9	85.5	95.1	85.1
Insulation %	100		76		
Humidity control %		111	100		
Benches %	100			84	
Irrigation system %			100		100

Results

Insulation

Experiments

First season 1983–84, greenhouse no. 1, 2 and 3. Bottom heating first priority. Wet capillary benches.

1. Single glass, thermal screens, standard heating system.
2. Double glass, reduced heating system.
3. Twin walled PMMA, reduced heating system.

Energy consumption

As may be seen in Table 1, the impact of permanent insulation on the total energy consumption is indisputably the best. In the greenhouses with permanent insulation only little difference is observed between the two materials, glass and PMMA. The heat reduction is observed for all three heating systems, top, bench and bottom as the relative energy consumption between the heating systems is not affected.

Environmental factors

As may be seen in Table 2, the impact of the permanent insulation on the room temperature during the day time is persistent and only little difference is seen between glass and PMMA. The same is the case for the leaf temperature.

The higher dewpoint temperature both during the day and the night shows that the water vapor content in the air is higher in the permanent insulated greenhouses.

Experiments, second season 1984–85

Greenhouse no. 1 and 3.

Top and wall heating first priority. Dry capillary benches.

1. Single glass and thermal screens, standard heating system.
3. Twin walled PMMA, reduced heating system.

Table 2. Temperatures, °C, and relative air humidity %. First season 1983–84.

Greenhouse no.	1	2	3	4	6
Insulation	X	X	X		
Night temp. red.	X			X	
Irrigation system			X		X
			diurnal		
Room	19.2	19.7	19.6	19.2	19.4
Top heating	33	32	31	29	22
Roof	14.7	–	17.5	14.8	16.5
Leaf	18.9	19.3	19.3	19.1	18.5
Dew point	15.4	17.3	16.7	15.2	15.7
Air humidity %	79	86	84	78	80
			day 10 – 16 hours		
Room	21.0	22.1	21.9	22.3	21.7
Top heating	36	30	29	38	25
Roof	14.3	–	19.0	15.2	18.6
Leaf	20.9	21.8	21.7	21.7	21.3
Dew point	17.0	19.4	18.8	17.5	18.2
Air humidity %	79	85	83	75	81
			night 21 – 03 hours		
Room	18.2	18.3	18.3	17.3	18.1
Top heating	28	32	31	19	20
Roof	16.3	–	17.3	15.5	15.9
Leaf	18.0	17.9	18.1	17.6	17.0
Dew point	14.6	16.2	15.6	13.8	14.4
Air humidity %	80	87	84	81	79

Energy consumption

As may be seen in Table 1, the effect of the twin walled PMMA is of the same order as in the first season. The change from first priority on the bottom heating to first priority on top heating does not make a great difference on the insulating effect of the permanent insulation.

It is interesting to notice that bottom heating has only taken a very little part of the total energy consumption in the second season. This indicates that the top and wall heating system has been sufficient to heat the greenhouse most of the time.

Environmental factors

As may be seen in Table 3, the room temperature is higher in the greenhouse clad with twin walled PMMA, in the day time. This is due to an increased greenhouse effect, which reduces the demand of heat and consequently the temperature of the top heating system in spite of a reduced top heating system.

The opposite happens during the night, due to the fact that the thermal screen has better insulating abillities than the twin walled PMMA. We now observe a higher temperature in the top heating system.

The connection between the temperature of the top heating system and the leaf temperature can be clearly observed in day time.

Discussion

For both seasons we see a pronounced effect on the energy consumption for greenhouses with permanent insulation. The change in heat priority has no influence on this.

The general assumption that the air humidity is higher in greenhouses with permanent insulation is also confirmed in our experiments. There seems to be a connection between the dew point temperature and the roof temperature as both temperatures are higher in the greenhouses with permanent insulation. From this we may con-

Table 3. Temperature, °C, and relative air humidity %. Second season 1984–85.

Greenhouse no.	1	2	3	4	6
Insulation	X		X		
Humidity control		X	X		
Benches	X			X	
Irrigation system			X		X
			diurnal		
Room	19.0	20.1	19.4	18.9	19.3
Top heating	52	57	55	25	40
Roof	15.9	17.7	17.4	14.7	16.8
Leaf	19.6	19.1	19.2	17.9	19.1
Dew point	15.0	17.7	16.6	13.4	16.1
Air humidity %	78	87	84	71	82
			day 10 – 16 hours		
Room	20.6	22.3	21.4	20.6	21.4
Top heating	48	45	42	27	35
Roof	13.8	17.2	17.6	13.7	17.8
Leaf	22.2	20.9	20.8	19.7	21.2
Dew point	16.2	19.3	18.0	15.3	18.3
Air humidity %	77	84	82	73	83
			night 21 – 03 hours		
Room	18.1	18.9	18.3	18.1	18.1
Top heating	51	63	62	21	43
Roof	18.5	18.5	18.1	16.6	16.8
Leaf	18.0	18.3	18.5	16.9	18.1
Dew point	14.6	16.9	15.9	12.4	14.8
Air humidity %	80	88	86	70	81

clude that water condensation on the cold glass plays an important role in the air humidity level.

A warmer wall and the first priority on the top heating system has an effect on the plant canopy temperature.

The difference between the leaf temperature and the dew point temperature indicates when water condensation on the leaves may be expected.

Night temperature reduction

Experiments, first season 1983–84

Greenhouse no. 1 and 4, single glass and thermal screens. Same average diurnal temperature.

1. Day/night temperatures 18°/18°.
4. Day/night temperatures 20°/17°.

Energy consumption

As may be seen in Table 1, a reduction of night temperature and an increase in day time to maintain the same average temperature, costs 10 per cent more energy in a greenhouse with mobile insulation. This is presumably due to the fact that the highest room temperature is kept in those periods where the thermal screens are not in position.

Environmental factors

As may be seen in Table 2, both treatments have had equal average room temperature regimes. The impact of room and roof temperatures is repeated on the leaf temperature day and night. It is important to notice that though the relative air humidity is equal at night in the treatment with changing temperatures the water vapor content, indicated by the dew point temperature, is lower.

Discussion

Night temperature reduction does not have the effect on heatsaving as is normally believed in greenhouse nurseries. This is of course due to the enormous effect of the thermal screen on the energy consumption. Increasing temperature during day time in the uninsulated greenhouse costs much more in energy than can be saved by a lower temperature when the thermal screen are in position during the night.

From this it might be better to increase temperatures during the night and reduce temperatures during the day, but of course only when this can be done without harming plant growth or delaying plant development.

Air humidity control

Experiments, second season 1984–1985

Greenhouse no. 2 and 3. Hygrostat setpoint 92 per cent relative air humidity. Top and wall heating first priority.

2. Double glass,
   air humidity control by heating only.
3. Twin walled PMMA,
   air humidity control by heating and ventilation.

Energy consumption

As may be seen in Table 1, omitting the ventilation in the air humidity control, did not save energy. The authors are convinced that the difference in cladding (double glass versus twin walled PMMA) does not affect the result of the experiment.

The ventilation rate during the night reveals, that air humidity control, has only been necessary during the months of September and October.

While looking at the energy consumption for these two months we find an increase of 32 per cent.

Environmental factors

As may be seen in Table 3, the air humidity control by heating only shows as expected a higher room temperature during the day. The effect of the control mode on the relative air humidity is suppressed by the fact that both room and dew point temperature increase at the same ratio.

As both roof and top heating temperatures are of the same order, leaf temperature is the same in both treatments.

Discussion

Drying air by heating only, did not have the expected effect on the energy consumption. Whenever a demand for air drying exsists, the relative air humidity is kept very close to the maximum value, 92 per cent, while omitting ventilation.

The higher dew point temperature and consequently a higher water vapor pressure in the air indicates that water evaporation from the leaves might have been restricted.

Benches

Experiments, second season 1984–1985

Greenhouse no. 1 and 4, single glass and thermal screens.

1. Dry capillary benches, bench heating.
   Top heating first priority.
4. Slatted benches, no bench heating.
   Bottom heating first priority.

Energy consumption

As may be seen in Table 1, the difference between the application of slatted benches combined with the first priority on bottom heating has a tremendous effect on the energy consumption as compared to dry capillary benches with the first priority on the top and wall heating.

Environmental factors

As may be seen in Table 3, the application of slatted benches combined with the bottom heating at first priority has a pronounced effect on all environmental parameters apart from the room temperature.

The lower temperature of the top heating can be recognized in the lower leaf temperature. The lower dew point temperature in connection with an unchanged room temperature gives a lower relative air humidity, especially during the night.

Discussion

The combination of slatted benches and first priority on the bottom heating has a very benificial effect on the energy consumption. The fact that all heat to the leaves is transported by air results, as may be expected, in a lower leaf temperature than room temperature.

There is a greater difference between leaf and dew point temperature. This indicates a lower risk of water condensation on the leaves and better possibilities of water evaporation from the plants.

One must be well aware of the fact that this is obtained as a combined effect of bench type, irrigation system and heating priority.

Irrigation system

Experiments, first season 1983–84

Greenhouse no. 3 and 6, clad with twin walled PMMA. First priority bottom heating system.

3. Wet capillary benches.
   Reduced heating system.
6. Flooded benches.
   Extended heating system.

Energy consumption

As may be seen in Table 1, there is only a minor effect of the dry surfaces on the flooded benches in the greenhouses with permanent insulation.

However the authors should like to stress the point that the lowest energy consumption is observed in the greenhouse with the highest energy release from the bottom heating system, and we feel that this may be an explanation for the difference (see also »Benches«).

Environmental factors

As may be seen in Table 2, the environmental parameters show that the impact of the extended heating system might have been of greater importance than the effect of the wet surface of the benches. Roof temperatures are very much lower in the greenhouse with the flooded benches especially at night. The same holds for the top heating temperatures.

Consequently the leaf temperature during the night is also lower. This is typical of a heating system with high energy release from the bottom heating system.

We observed a distinctly higher water vapor content in the air at night, where the wet benches are applied. This is repeated in the relative air humidity of the air.

Experiments, second season 1984–1985
Greenhouse no. 3 and 6, clad with twin walled PMMA. First priority on top heating system.

3. Dry capillary benches.
   Reduced heating system.
6. Flooded benches.
   Extended heating system.

Energy consumption
As may bee seen in Table 1, the heat consumption in the second season is equal in both greenhouses.

The change in heating priority from first priority on the bottom heating to first priority on the top and wall heating might also have had an effect on this result.

Environmental factors
The extended heating system resulted, especially at night in a pronounced lower temperature of the top heating system.

Consequently the roof temperature is lower as well. This again resulted in a slighter lower leaf temperature.

Discussion
As compared to the observations in the first season the change in heating priority from bottom heating towards top heating, has had a typical effect in the greenhouse with the extended heating system.

The change from wet capillary benches to dry capillary benches as compared to flooded benches has also had an effect on the energy consumption.

The difference between the two irrigation systems on the climatic parameters is in our opinion, more due to the heating system than to the difference in irrigation technique.

Conclusion

Insulation
For both seasons we see a pronounced reduction of the energy consumption of greenhouses with permanent insulation. The change in heat priority does not inflict on this. The general assumption that the air humidity is higher in greenhouses with permanent insulation is also confirmed in our experiments.

Night temperature
Increasing temperature during day time in the uninsulated greenhouse, does cost much more in energy than can be saved by keeping a lower temperature when the thermal screens are in position during the night in spite of equal diurnal room temperatures.

Air humidity
Drying air by heating only did not show the expected reduction in energy consumption. The relative air humidity, when omitting ventilation, is kept very close to the maximum value, 92 per cent, whenever a demand for air drying exsists.

Benches
The combination of slatted bences and first priority on the bottom heating has a very benificial effect on the energy consumption. One must be well aware of the fact that this is obtained as a combined effect of bench type, irrigation system and heating priority.

Irrigation system
Flooded benches in a greenhouse with permanent insulation saved energy as compared to wet capillary benches. However covering the capillary mat with perforated polythene film reduced energy consumption, so both systems showed the same energy consumption in the second season.

Heating priority
Whenever a system with high energy release from the bottom heating system is compared with a system with high energy release from the top heating system, we find a reduction in energy consumption.

The results in this paper show only major values obtained during the two seasons. A more detailed knowledge of the dynamic variation of energy consumption and environmental factors may be of interest. For this purpose the authors have published a separate report in which variations and progress of environmental parameters and energy consumption in the five greenhouses in the two seasons 1983–84 and 1984–85 are shown (2, 5).

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