GAS BASED INFRARED RADIANT HEATING IN GREENHOUSES. ASPECTS OF ENERGY USE AND PLANT DEVELOPMENT

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INTRODUCTION

Greenhouses have a large heating and lightning demand, especially in the cold Scandinavian climate. The annual heating demand is often around 500 kWh/m^2. Together with a high infiltration rate, greenhouses show characteristics suitable for infrared heating. The energy cost is also a significant part of the production cost. However, the crops are sensitive to the indoor climate.

A study including both energy as well as biological aspects was conducted during approximately two years. Identical crops were cultivated in a greenhouse with infrared heating and in a conventionally heated adjacent greenhouse. Comparisons were made on 10 crops. All biological steps from the sensitive root development to crops ready for sale to the consumer were studied. The energy aspects comprised both gas consumption and indoor climate. Special emphasis was put on the indoor climate study.

PLANT DESCRIPTION AND DATA ACQUISITION

A small part of a commercial greenhouse facility outside Malmö in southern Sweden was equipped with infrared heaters. In this facility plants are produced partly as rooted cuttings and partly as saleable adult plants. In figure 1 the layout of the greenhouses are shown.

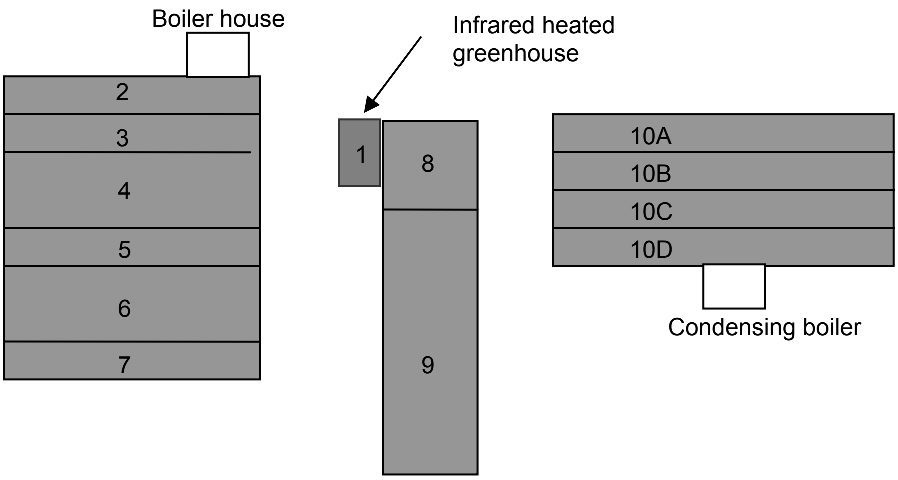

Figure 1: Layout of greenhouse facility where infrared heating was studied

Greenhouse 1 (285 m^2) has infrared radiant heating. Greenhouses 2–9 (11400 m^2) and 10A–10D (5000 m^2) were heated with conventional water pipes below the crop tables. Two conventional gas boilers (approx. 150°C flue gas temp.) supplied heat for greenhouses 2–9 and a single condensing boiler (approx. 50°C flue gas temp.) supplied heat to greenhouses 10A–10D. Normally, the heating systems in Swedish greenhouses are sized for 200–300 W/m^2 maximum heating demand. The infrared heating system was sized according to the same criterion.

The infrared heating system consists of low intensity infrared radiators. Above each table row an 18 meters long heating tube with a reflector is located. Each tube has two burners, one at the beginning and one approximately at the middle of the overall tube length. The radiant heaters have a steady-state efficiency of approximately 90%. These tubes (overhead heating) are used for crops where the roots have developed. Heating of cuttings where the roots were not sufficiently developed was done with radiation tubes below the crop tables. Before roots are developed the crops are very sensitive and if overhead heating are used at that time the crops may be destroyed if the water spraying is not working correctly. Combustion air is taken from outside.

The basic installation showed some weaknesses causing adjustments of for example the burner input, control system and reflector location. However, these weaknesses have helped the identification of key parameters.

Measurements were made using both the data obtainable from the existing control system. One air temperature and relative humidity were collected from each greenhouse with either 2 or 4 minute sampling rate. Outdoor temperature and insolation were also collected.

RESULTS — INDOOR CLIMATE AND ENERGY USE

The leaf temperature is essential for the infrared heating. In conventional heating systems for greenhouses a temperature difference of approximately 0.5°C is assumed, and this can be used as input to the control system. The infrared heater control system in this case uses a direct measurement of a single point leaf temperature.

In this section, simplified calculations of leaf temperature in case of infrared radiation, tube surface temperature and tube radiation will be shown in order to give an introduction to factors important for infrared heating in greenhouses. Examples of measurement results of the greenhouse indoor climate in the test house and in the reference houses will be presented.

Calculation of leaf temperature

In order to evaluate the possible energy saving potential using infrared heating we must be able to calculate the difference between leaf and air temperature. There are several models describing the exchange of energy between the crop and the surroundings. A thermodynamic model is suitable in this case. A heat balance around a leaf yields the following equation for the leaf temperature T_{leaf}

$$T_{leaf} = T_{air} + \frac{\Phi \frac{r_i^h + r_e^h}{\rho_{air} c_p} - \frac{1}{\gamma}\left(p_{leaf}^* - p_{H_2O}\right)}{1 + \frac{\delta}{\lambda} + \frac{r_i^h}{r_e^h}}$$

A detailed description of the equation is found in for example [1] and [2]. Φ is the net radiation to the leaf, $r^h{}_i$ and $r^h{}_i$ are internal and external resistance for the leaves similar to heat conduction and heat transfer coefficient. ρ_{air} and c_p are density and specific heat for air. $p^*{}_{leaf}$ and p_{H2O} are saturation pressure at leaf temperature and water partial pressure in the greenhouse air respectively. δ is the slope for saturated water vapor pressure and γ is the psychrometric coefficient.

The calculated differences between leaf and air temperatures are shown in figure 2. The internal resistance $r^h{}_i$ was set to 200 sm^{-1} and the external resistance was calculated using heat transfer relationships given in [1] and [2].

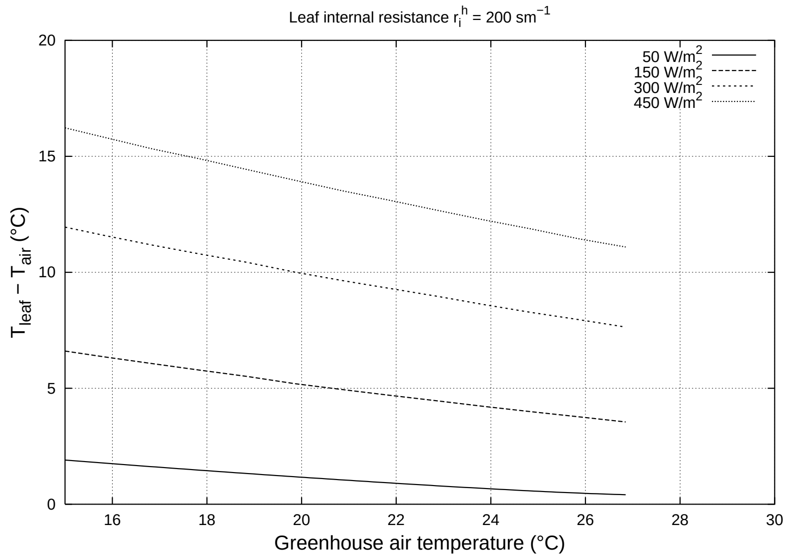

Figure 2: Difference between leaf and air temperature as function of indoor temperature and radiation intensity Φ

We clearly see that an increased net radiation also increases the temperature difference, but also that the difference decreases with increased air temperature. The lines for 150 and 300 W/m^2 are relatively close to the sizing criterion for traditional greenhouse heating systems. However, the total leaf area may exceed the floor area. Additional calculations show a larger temperature difference with an increased internal resistance r^h_{i}. Observe that these results are assuming a net heat transfer to the leaves, The opposite is possible, for example during the night, and for this reason climate curtains are used during the night time. We can conclude that infrared heating is a possible way to reduced air temperature while the leaf temperature can be kept at a desired level.

Calculations of tube temperatures and radiation

A uniform temperature distribution is thus dependent on the radiation characteristics of the heaters. A simplified approach to calculate the steady-state surface temperatures and radiation output from a horizontal tube without a reflector was made to study the influence of burner input and overall excess air ratio λ_{tot}. This approach uses traditional heat transfer relationships and a description of such an approach is found in [3]. In figure 3 some calculation results are shown. It is clear that a high excess air ratio is favorable for an even temperature distribution along the tube.

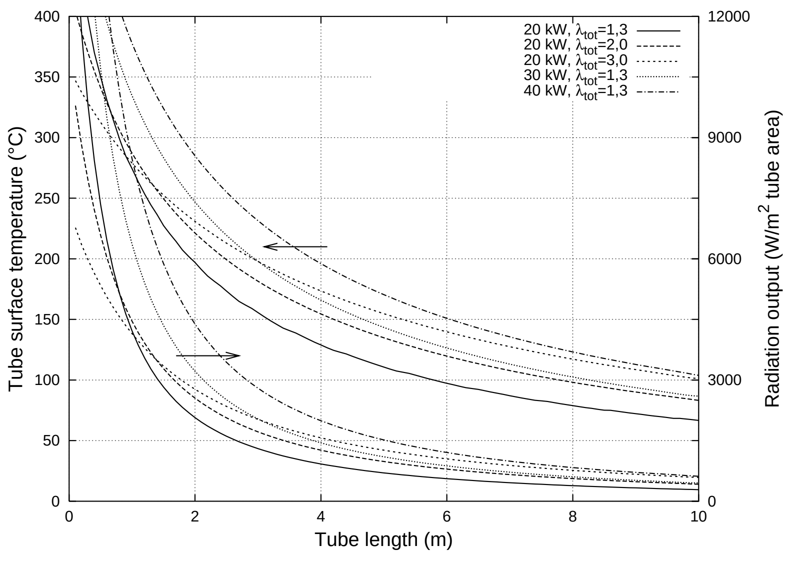

Figure 3: Surface temperature and radiation output for a horizontal radiating tube

Measurements of indoor climate

The different indoor climates with infrared heating and with conventional heating are illustrated in figure 4. The upper part of the figure shows the indoor climate, air temperature and relative humidity, with infrared heating during one month. From the large graph 24 hours and 2 hours are also shown for a chosen day. The lower part of the figure shows the corresponding values for reference house 5. It is clearly seen in the upper part of the figure that switching from heating from below the tables to overhead heating affects the indoor climate considerably. A closer look on data for selected days shows that the air temperature in the infrared heated house is 0.5–0.8°C lower than in the reference house. This difference increases to 1.8–2.0°C for days with overhead heating. The lower left graph for the infrared heated greenhouse clearly shows the on/off operation of the burners.

For a long period the collected indoor data for each greenhouse can be used to calculate the net heating demand. Adding the difference between indoor and outdoor temperatures for a longer period a measure of the net heating demand is obtained. For approximately 10 months during 2001 this was done and the result is shown in table 1 where the values are normalized with respect to the test house.

Greenhouse no.								
1 (IR)	2	3	4	5	6	7	8	9
1.000	1.172	1.092	1.112	1.164	0.991	1.274	1.020	1.122

Table 1: Normalized heat demand for the infrared heated greenhouse (IR) and the conventionally heated greenhouses 2–9

The average value is 1.118, i.e. 11.8% higher heating demand in the conventionally heated greenhouses. This value may be increased by for example using overhead heating only. It is thus estimated that infrared heating will decrease the heating demand by 15–20%. The actual gas consumption is dependent on the efficiency of heat generation. Boilers are kept warm the entire year. Stand-by and distribution losses are avoided when radiant heating is used. However, a boiler can have a higher full-load steady-state efficiency than a radiant heater. The difference in appliance efficiency is not further dealt with in this report.

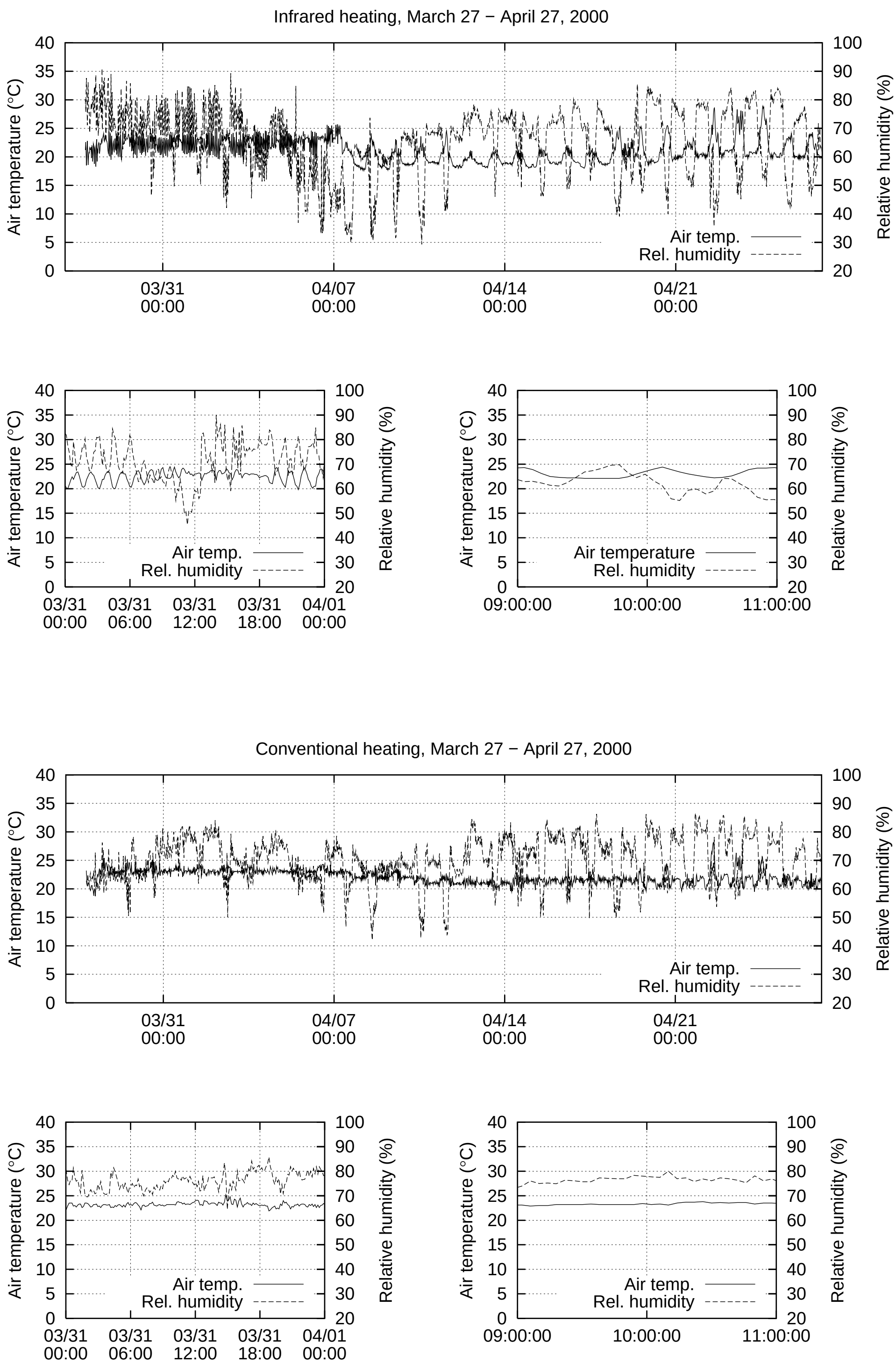

Figure 4: Indoor climate for the infrared heated greenhouse (upper part) and the conventionally heated reference house (lower part)

Local temperatures

Temperature distribution across the tables is not indicated by these single point temperature measurements. Temperature sensors located at 7 points in the test house collected data for evaluation of the temperature distribution for two measuring periods comprising approximately one month each. Thermography was also used to map the temperature of the entire area heated by a infrared heating tube.

The local temperatures measured in the test house are illustrated in figure 5. It shows these local temperatures during March 1, 2001. The periodical shape corresponds to the burner on/off operation. The maximum difference between the highest and lowest measured temperature is approximately 2°C. Measurements in the reference house showed significantly lower differences.

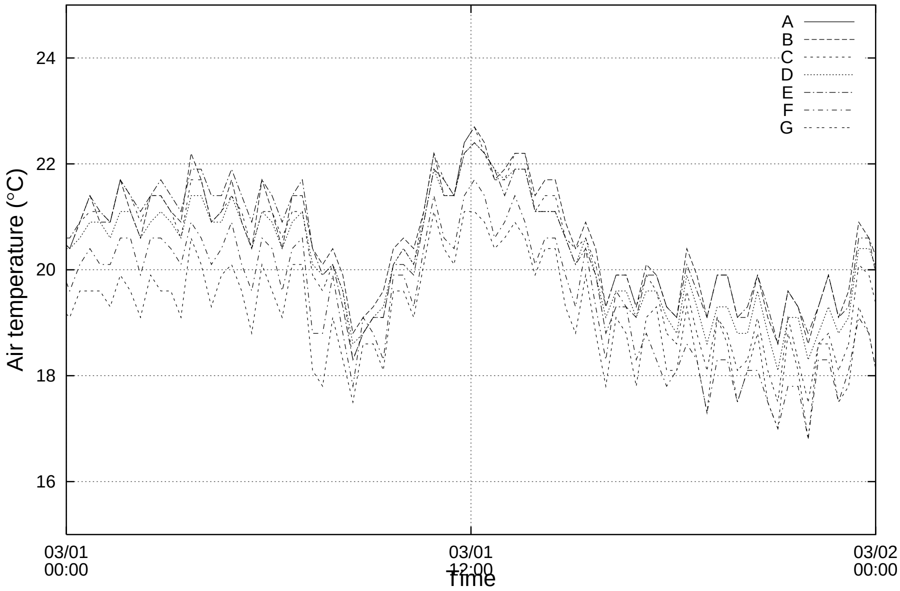

Figure 5: Measured local temperatures on the crop tables in the greenhouse with infrared radiant heating

Thermography

The thermography picture in figure 6 shows the instant temperature distribution on the crop table. At this time Poinsettias was cultivated and the measurements showed crop temperatures between 15.7°C and 19.8°C. Temperature differences in the reference house were considerably lower. The measured crop temperatures in the greenhouse correspond well according to the expected radiation distribution. It was also assumed that the relative humidity in the greenhouse air has a positive influence on the radiation distribution, i.e. a high relative humidity to some extent is leveling out the temperature differences on the crop tables.

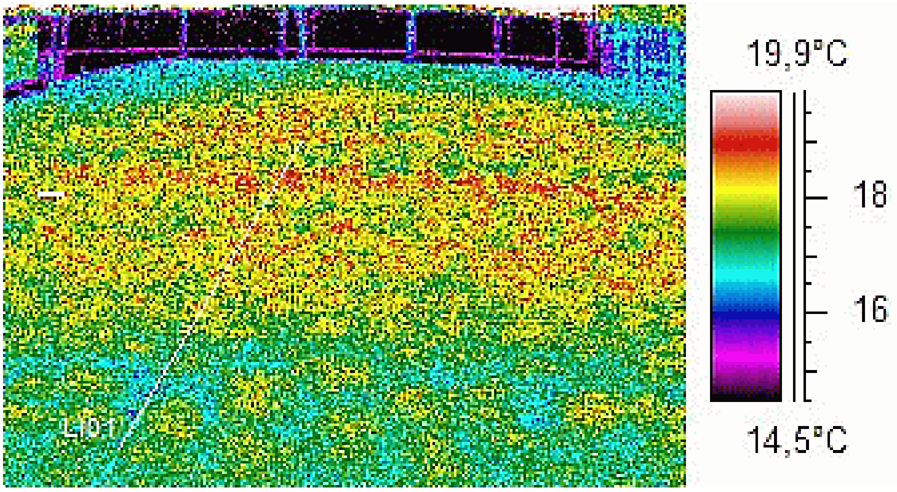

Figure 6: Thermography picture showing the temperature distribution when overhead infrared heating was used.

RESULTS — BIOLOGICAL ASPECTS

Previous section clearly showed that infrared heating has the potential of reduced heating demand in greenhouses but a less uniform climate than in conventionally heated greenhouses is obtained. Does this affect the crop development?

The crops and cultivation were chosen in order to evaluate infrared heating (test house) both in early growth of cuttings, especially the sensitive root development and growth of almost finished crops. The overall impression from the crop development and growth in the test house was a later development due to uneven temperature distribution. However, these differences disappeared when the plants were ready for sale to the end consumer. Some cultivations also showed increased plant quality when infrared heating was used. 20 samples from four locations in the test house and one location in the reference house were collected and assessed with respect to root development, plant height and width, overall impression etc. When cuttings were studied the 20 samples from each location were further cultivated at the Swedish Agricultural University to evaluate and assess the finished crop. The following text will describe results and findings from some of the tested cultivations.

Calibrachoa Cerv. 'Trailing Million Bells Blue' — Million Bells

Calibrachoa Cerv. 'Trailing Million Bells Blue' is a plant that is sensitive to temperature and can be used as a good indicator of a not uniform greenhouse climate. It is also sensitive during the root development period. Not surprisingly, differences were found, especially close to the crop table edges in the test house. Parts of the plants were equal to the plants from the reference house. Some of the crops in the test house did not develop roots and died. After the entire growth period the differences between plants from the test house and the reference house were not significant.

Argyranthemum frutescens — Boston Daisy

Argyranthemum frutescens is a patient plant that accepts wide temperature variations. Two weeks after potting of *Argyranthemum frutescens* (L.) Sch.Bib 'Dana' cuttings the roots were well developed in both greenhouses. Single plants were at that time already larger in the reference house than in the infrared heated test house. In the reference house the plants grew faster and became both higher and wider. This can be considered as a disadvantage and substances for reducing the growth had to be sprayed in the reference house. This was not necessary in the test house. Flowers developed earlier in the reference house but at the time for crop assessment more flowers had developed in the test house. In addition to this, plants in the infrared heated greenhouse were better shaped and more compact, which increased the overall impression and quality.

Eurphorbia pulcherrima — Poinsettia

Several cultivations of Poinsettias were studied. An interesting case was the cultivation of *Eurphorbia pulcherrima* Willd. Ex Klotsch 'Sonora' when the outdoor temperature was low. The crop is a miniature

Poinsettia and is not water sprayed during the latter part of the cultivation. This, and the low water content in the outside air during the cold period in this case, often below 0ºC, further reduced the relative humidity. The smoothing effect of air humidity assumed from the thermography results was thus not present. Leaf temperature in the test house was found to have a variation of 5ºC in some cases. A clear correlation was found between crop growth and local radiation intensity. The difference in growth caused a sales time spanning several days which has to be considered a disadvantage since the greenhouse could not be emptied at the same time. Figure 7 shows the crops in the test house. A comparison with the thermography picture in figure 6 shows a clear correlation in variation in crop development and in the radiation pattern. Crops from the reference house were later in the growth but they showed a more uniform growth and a better visual impression.

Figure 7: Photograph of *Euphorbia pulcherrima* Willd. Ex Klotsch 'Sonora' showing differences in crop growth

The differences between the locations in the infrared heated greenhouse and the reference house are clearly seen in figure 8.

Figure 8: Samples of *Euphorbia pulcherrima* Willd. Ex Klotsch ‘Sonora’. The three rows to the left in the picture show crops from different locations in the infrared heated greenhouse and the rightmost row shows crops from the reference house.

Pelargonum x hortorum — Geranium

Pelargonum x hortorum L.H. Bailey 'Grand Prix' were studied at two occasions and 'Rokoko' at one occasion. During one of these studies the local air temperatures on the crop tables were measured, see also the text on indoor climate. Comparing these measured temperatures and the visible roots show a clear relationship between temperature and root development indicating the importance of a uniform indoor climate.

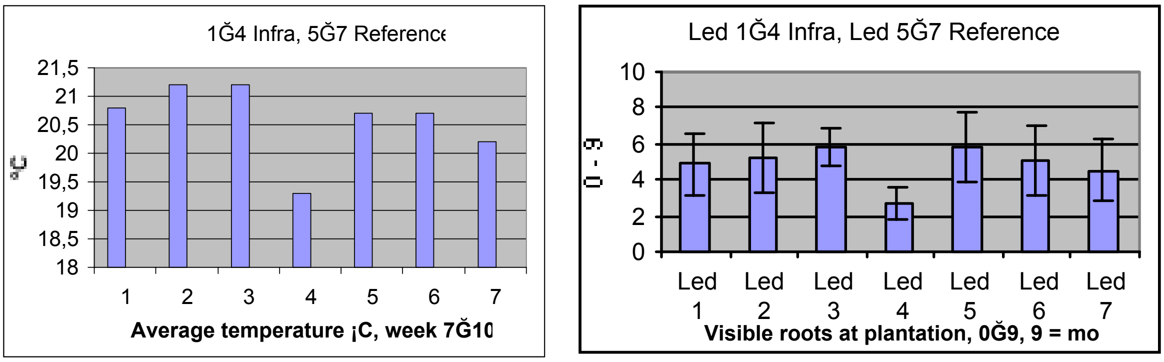

Figure 9: Measured average temperature for *Pelargonum x hortorum* L.H. Bailey 'Grand Prix' and the root development showing a clear correlation. Measurements in both the infrared heated house (1–4) and in the reference house (5–7)

DISCUSSION AND CONCLUSIONS

Infrared heating in greenhouses reduces the heat demand due to a reduced air temperature. The temperature reduction is largest when overhead heating is used. In the test greenhouse the air temperature could be reduced by approximately 2ºC. Comparing greenhouse air temperatures in the test house and in the reference houses showed a reduced heating demand of slightly above 10%. This value could probably be increased to 15–20% if overhead heating only is used. However, this requires that the crops already have the roots developed.

Infrared heating is likely to cause temperature differences at various locations in the greenhouse. Conventional greenhouse heating does not cause as such large temperature differences, and this was verified by air temperature measurements at several locations during extended periods. Thermography showed the instant temperature distribution on the crop tables.

Due to the temperature differences in the infrared heated greenhouse the crops developed not as uniform as in conventionally heated reference houses. However, these differences were often diminished when the plants reached the time for sale to the consumer. Examples of improved quality using infrared radiant heating were also found.

The temperature differences can easily be reduced using a good heating system design. Heaters located in parallel with overlapping radiation fields are recommended. The operating parameters of the burners do also affect the temperature distribution on the crop tables. The location of the leaf temperature sensor will also affect the heater operation. Finally, the greenhouse geometry, i.e. length, width and height, has to be suitable to permit for example overlapping radiation fields. The infrared heating system in this study was sized according to normal Swedish design rules, 200–300 W/m^2. There has been no indication of this being neither wrong nor optimal.

Infrared radiant heating in greenhouses has been shown to work well with a potential of reduced energy use. The technique is best suited for crops where roots are already developed. Increased product quality can be obtained but each plant sort has to be investigated and evaluated.

ACKNOWLEDGEMENTS

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