Experimental Investigation of the Energy Needs for a Conventionally and an Infrared (IR)-Heated Greenhouse

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Abstract

The potential advantages of heating greenhouses by infrared (IR) heaters, instead of conventional hot air, are examined experimentally. Measurements of indoor and outdoor conditions during a typical cold night and whole thermal period in Central Greece are taken in two experimental greenhouses using conventional and IR heating respectively. Data confirm that, the conventional system inside air and cover temperature remains always higher than the temperature targeted for the plants. On the contrary, with IR heating, inside air and cover temperatures are several degrees lower than the desired temperature sustained at the plantation level, and that this temperature difference increases proportionally to the drop in outside temperature. Since all thermal losses are almost proportional to the inside and outside temperature difference it is surmised that IR heating systems successfully implemented may present significant advantage over conventional heating setups. Direct measurements of energy consumption for the two test cases indicated 35-40% savings for infrared heated greenhouse. Besides, infrared heating contributed to improved total quality of the cultivated lettuce.

INTRODUCTION

Energy consumption for greenhouse heating represents a serious concern for greenhouse operators throughout the world (Bot, 2001) that is further aggravated by the present oil crisis. Conventionally, thermal energy is transmitted to the greenhouse either by circulation of hot water through a piping system or by air heaters (Teitel et al., 1999; Bartzanas et al., 2005). In both cases the heat distribution is enhanced by warm-air distribution systems as convective tubes and horizontal airflow (Nelson, 2003). In order for the plants to reach the required temperature by these methods, the interior of the greenhouse has to be heated to the same or even to a slightly higher temperature than the value targeted for the plants. This practice results in increased heat losses due to convection and radiation through the cover, and also due to ventilation and leakages through openings.

An alternative method of heating the plants in a greenhouse - originally proposed in the late 70s as a result of the first oil crisis (Youngsman, 1978; Itagi and Takahashi, 1978; Rotz and Heins, 1982) - is the use of low-intensity, infra-red (IR) radiation. The main potential advantage of IR heating is the direct heating of the plantation from the power source, with probably less heat losses to the surroundings. This concept of a “cold”
greenhouse overcomes the conventional one which demands to increase the inside air temperature in a greenhouse in order to deliver to the plants the necessary heat by convection. As a result, cover and inside air may ideally remain at significantly lower temperatures than the target value for the plants, with a concomitant reduction of energy losses.

Though IR heating has been advocated as having in principle the potential for improved energy performance (Hanan, 1998; Nelson, 2003), it has never been implemented to a significant scale. It is conjectured that the main obstacle hindering the method's potential from being realized is the radiative efficiency of the power source. For example, emission of IR radiation with peak intensity at 3 μm by a plain heated surface necessitates a temperature above 650°C. Such a hot surface inside the greenhouse will evidently suffer intense heat losses by natural convection to the surrounding air and by radiation to the cover, thus negating the ideal advantage of IR heating. Evidence pointing in this direction is a comparative study of the vertical temperature distribution in a conventional and an IR-heated greenhouse (Blom & Ingratta, 1981), which indicated no significant temperature differences and actually a worse thermal stratification in the latter.

Unlike conventional hot surfaces, modern IR heaters emit highly concentrated radiation while their outer surface is only mildly heated. Moreover IR heaters have fast response times and are suitable for modern automatic control implementation. The present wide availability of IR heaters in the market - combined with prospects of forthcoming improvements in radiant efficiency, with alternative operation the natural gas or someone renewable source or electricity and with the expected drop in prices due to mass production - justify revisiting the idea of IR heating of a greenhouse (Kavga et al., 2008). IR heating of greenhouses is also expected to contribute to improved product quality (Teitel et al., 2000) as preliminary qualitative observations indicate.

In the present study, the conditions under which IR heating may be energetically beneficial, are clarified and the possible improvement in the method when implemented with the use of modern IR heaters is investigated. The thermal performance of two experimental greenhouses heated by hot air and IR heating respectively is investigated experimentally and the energy savings by using infrared radiation for direct heating of plantation are assessed. To this end, a series of experiments in the small-scale greenhouses is performed.

**MATERIALS AND METHODS**

The experiments were performed in two pilot span greenhouses (Fig. 1 and 2) and involved systematic measurement and recording of the parameters that determine the interior microclimate. The exterior climatic conditions were also recorded by a properly equipped meteorological station. The cultivation tested was lettuce seed plants (*Lactuca sativa L.*), arranged with a density of 20 plants per square meter.

The greenhouses are constructed of an aluminium framework, with 3 mm thick glass sheet as covering material. Their dimensions are width 2.13 m, length 2.00m, eaves height 1.00m and total height up to the top 1.50m. The base area of the greenhouse \(A_p\) is equal to 4.26 m\(^2\), the area of the cover is \(A_c = 13.50 \text{ m}^2\) and the volume of the greenhouse is \(V = 7 \text{ m}^3\) respectively.

The experimental greenhouses are equipped with heating, and ventilation systems. More specifically, two alternative heating systems are available: (i) a conventional one, consisting of an air heater with two power levels (1-2 kW) and a small fan that promotes air mixing and alleviates development of stratification (Fig. 1), and (ii) an IR heating
system consisting of four lamps with blown-bulb reflectors (total power 1 kW, beam angle 60°) placed at the greenhouse corners and at an elevation of 1 m above the plants. (Fig. 1 and 2). Ventilation is accomplished by natural draft through two vents (door and roof window), and also by a forced flow of 68 m3/h imposed by a ventilator.

The microclimate of the inside environment is monitored and controlled with appropriate sensors including a silicon type pyranometer (400-1000nm), a thermopile type pyranometer (300-3000nm), a photosynthetic active radiometer (400-700nm), a temperature and relative humidity probe, and a number of thermocouples distributed throughout the greenhouse. In particular throughout the greenhouse base, Cu-Ni thermocouples of 0.5 mm diameter are used, while on the glass cover Cu-Ni thermocouples of 0.2 mm diameter are used because of their faster response and better spatial sensitivity. The meteorological station recording the outdoor environmental conditions is equipped with a data logger with two relay analogue multiplexer units and a number of sensors including a silicon type pyranometer (400-1000nm), a temperature and relative humidity probe, a rain gauge, a pyrgeometer that embodies a sky temperature sensor and an anemometer with threshold sensitivity 0.25 m/sec. All the above instruments and sensors have been meticulously calibrated.

The parameters of central interest to the present study are the temperatures of the plants, of the inside and outside air, and of the glass cover, the inside and outside relative humidity, as well as the outdoor wind speed and the temperature of the sky. The duration of the heating systems operation is also recorded and is subsequently used for the calculation of the energy consumption. As their values generally change with time, the data are scanned per minute, and 10-minute averages are computed and recorded on a 24 h basis at the station’s data logger. Attention is focused on greenhouse performance during the night, when the heating system is automatically turned on. Overall night-time mean values are also computed from the respective time-series, based on the interval between the steep temperature changes at sunrise and sunset.

Preliminary measurements have indicated that the plant temperature is spatially almost uniform throughout the greenhouses base (the plant canopy). Thus, it is represented by a reference temperature, Tref, taken at the centre of the base, which also serves as the reference variable for the thermal control of the greenhouse. For the present cultivation, the reference temperature is set to the value Tref = 15±1°C, i.e. the heating systems turn on when Tref drops below 14°C and off when Tref exceeds 16°C. The cover temperature has been found to vary weakly with location, and thus an average of the relevant thermocouples data is reported. Finally, the outdoor temperature, Tout, and wind speed, WS, are measured at a height of 2.50 m above ground, and the inside air temperature, Ta, is measured at the centre of the greenhouse and at 1.20 m above ground level and 0.3 m below the top of the roof. During daytime, greenhouse overheating is avoided by automatic operation of the ventilation system as soon as Ta rises above 22°C. The operation of the ventilation system is discontinued when Ta drops below 18°C, the wind speed rises above 6 m/sec and when it is raining. Finally the energy consumption in the greenhouses is recorded again, by two electronic watt meters (kWh) respectively.

The IR lamps that are used are made of hard glass with high mechanical strength and resistance to thermal shocks (water splashes). The temperature of the external lamps’ surfaces during operation is about 90-100°C. The lamps emit a high proportion of infrared light and a low proportion of visible light. Their positioning at the four corners of the greenhouse and at a distance of 1 m from ground has been selected to achieve a more or less uniform distribution of the energy flux at the plants level. An important characteristic
of the IR lamps with respect to the present study is their radiative efficiency, $\eta$, i.e. the percentage of electrical energy consumed that is delivered as thermal radiation. Surface integration of the data shown in figure 2, gives the value $\eta=60\%$. The remaining 40\% of the input energy is predominantly lost by convection to the surrounding air.

**EXPERIMENTAL RESULTS**

Experimental results collected during a period of 40 days of the experimental greenhouses operation are presented in the following. Typical results of the night time temperature variations of inside air and cover are presented, characterizing each mode of operation. Furthermore the mean nightly values for the above period of hot air and IR heating operation are presented and the relative merits of IR heating are outlined. Finally total energy losses between hot air and IR heating systems are calculated and compared.

**Night-time temperature variation**

Results from both experimental greenhouses during a typical fall night (mean nightly value 3.16 $^\circ$C, mean sky temperature 259.72 K and 0.38m/sec wind speed) and the variations of outdoor, indoor and reference temperatures of inside air and cover are presented in figures 3 and 4. It is confirmed that the reference temperature, $T_{ref}$, is successfully kept in both cases at the desired value 15±1 $^\circ$C. Moreover, figure 3 indicates that, stratification is alleviated thanks to the fan presence, and the internal air temperature $T_a$ always remains at a slightly higher value than that of the plants. The most important observation is that the inside air $T_a$ of the infrared heated greenhouse remains always cooler than the plants, providing an initial indication in favour of the IR-heating concept (Fig. 4). In figure 5 the energy consumption during the aforementioned night is depicted, clearly indicating the lower heating demands of the IR greenhouse. The overall energy savings during this night is graphically depicted in figure 6, reaching 40\%.

**40 night’s temperature variation**

Similar trends are observed in figures 7 and 8 where mean temperatures values of outdoor, indoor and reference temperatures of inside air and cover are depicted. The corresponding meteorological conditions including outside air, the inside and outside relative humidity, as well as the outdoor wind speed and the temperature of the sky are presented in figures 9 and 10, along with relative humidity of outside air as well as inside each greenhouse presented in figure 10.

**Effect of outside temperature**

The merit of IR heating is related to the ability of the system to sustain the desired temperature of plantation while maintaining the greenhouse air at a significantly lower temperature. Data presently used to compare the two heating systems are the 40 nights averages night-time temperatures. More specifically, we plot in figure 11 the difference between the internal air and the outside air temperatures, indicative of the overall greenhouse heat losses, as a function of the difference between the reference and the outside air temperatures. Points correspond to IR heating and reveal an almost linear relationship, indicating that thermal losses increase proportionally to the drop in outside temperature. The relevant results for hot air heating are represented by the diagonal line in the plot, given that the internal air is at best maintained at the plantation temperature. Finally, in figure 12 the energy consumption during the 40 night’s thermal period also is
depicted, clearly indicating the lower heating demands of the IR greenhouse. The overall energy savings during this time period is graphically depicted in figure 13, reaching 40%.

**Product quality**
As shown in table 1, lettuce plants biomass yield (fresh weight) was increased reaching 15% under infrared direct heating of the plants than conventional hot air heating respectively. In addition physiological parameters (photosynthetic rate, transpiration rate and CO₂ conductivity) have shown statistically significant increased rates when infrared heaters instead of air heaters were used.

**CONCLUSIONS**
Measurements of indoor and outdoor conditions during several cold nights in Central Greece were obtained in two experimental greenhouses using conventional and infrared heating respectively.

Greenhouse operation with hot air heating has resulted in inside air temperatures equal to or higher than the target value for the plants, whereas operation with IR heating has demonstrated that the inside air is maintained several degrees cooler. The temperature difference between inside air and plants during IR heating was found to increase linearly with the drop in outdoor temperature, pointing to the potential interest of this alternative for colder climates.

Energy savings of the order of 40% have been obtained with IR heating, whereas the quality of the plants (lettuce) has been considerably improved.

**Literature Cited**
Tables

Table 1. Yield of lettuce plants (fresh weight) grown into experimental greenhouses under infrared or air heating, but at the same leaf temperature, after 40 days crop season (late winter).

<table>
<thead>
<tr>
<th>Heating method</th>
<th>F. W. (gr/plant)</th>
<th>Photosynthetic rate (μmol m² s⁻¹)</th>
<th>Transpiration rate (mmol m² s⁻¹)</th>
<th>Stomatal conductance of CO₂ (mol m² s⁻¹)</th>
<th>Leaf temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infrared heaters</td>
<td>382.8 ± 4.1</td>
<td>16.8 ± 2.3</td>
<td>3.54 ± 0.1</td>
<td>0.37 ± 0.02</td>
<td>15</td>
</tr>
<tr>
<td>Hot air heating</td>
<td>334.5 ± 3.8</td>
<td>12.6 ± 1.2</td>
<td>2.91 ± 0.3</td>
<td>0.26 ± 0.03</td>
<td>15</td>
</tr>
</tbody>
</table>

Figures

Fig 1: The experimental conventionally heated greenhouse and the meteorological station

Fig 2: The experimental infrared heated greenhouse and radiative heat flux distribution of the lamps
Fig 3: Night time temperature variations of inside air and cover by using hot air heating during the typical night.

Fig 4: Night time temperature variations of inside air and cover by using infrared heaters during the typical night.

Fig 5: Energy consumption during the typical night.

Fig 6: IR energy savings in percentage of total hot air heating energy consumption during the typical night.

Fig 7: Night time temperature variations of inside air and cover by using hot air heating.

Fig 8: Night time temperature variations of inside air and cover by using IR heating.
Fig 9: Night time temperature variations of outside and sky temperatures and wind speed

Fig 10: Night time variations of outside and inside relative humidity (RH) for both test cases

Fig 11: Temperature differences indicative of the overall heating losses for hot air and infrared radiation heating

Fig 12: Average night energy consumption during the 40 nights thermal period

Fig 13: IR energy savings in percentage of total hot air heating energy consumption during the 40 nights