Investigation of the Potential of Long Wave Radiation Heating to Reduce Energy Consumption for Greenhouse Heating

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Abstract

A parametric study has been carried out to quantify the contribution of each of the components of a greenhouse to the energy consumption during heating. The greenhouse, located in Western Greece, is heated by water pipes. Steady-state thermal balances are developed under general heating conditions and an approximate expression to estimate heating efficiency is introduced. The results confirm the dominant contribution of convective and radiative heat losses through the greenhouse cover. For the present case study the estimated heating efficiency coefficient does not exceed 17%. Thermal performance of the same greenhouse by assuming direct heating of the plants by long wave radiation is achieved by exploiting the general formulations of the thermal problem developed. A significant potential for increasing heating efficiency by involving long wave radiation heating is demonstrated. Improvement starts from 45% and may appreciably increase depending on the heating time assumed.

INTRODUCTION

Energy consumption for greenhouse heating represents a serious concern for greenhouse operators throughout the world (Bot, 2001). Conventionally, heating in a greenhouse occurs either by means of a piping system or by air heaters (Teitel et al., 1999; Bartzanas et al., 2005). Thus, the interior of the greenhouse is heated to the same or even slightly higher temperature than the value targeted for the plants. Several efforts have been undertaken to formulate the thermal behaviors of a greenhouse (Critten et al., 2002; Singh et al., 2006). The thermal behavior of a greenhouse is influenced by a variety of parameters including the structural features of the greenhouse (i.e. shape, dimensions, materials used), heating and ventilation systems, orientation, latitude and location, type of plantation as well as plantation and bare soil surface area, etc. To state the general thermal problem a set of non-linear equations are required to link heat exchanges between greenhouse air, plants, covers and floor, with heaters, sun, exterior air and sky.

To reduce energy consumption, some straightforward measures can be applied such as double glazing (Gupta et al., 2002), thermal screens (Ghosal et al., 2004), etc. The above measures contribute to overcome the basic cause for energy consumption in a greenhouse, which boil down to the unavoidable thermal losses.

An alternative for reducing energy consumption in greenhouse heating could emerge by the use of long wave radiation. By activating a long wave radiation heating source, plants and soil may receive heat directly. As air and cover temperatures remain relatively low, heat losses are significantly reduced. However the use of long wave radiation for greenhouse heating has been so far scarcely investigated. In (Blom and Ingratta, 1981), energy savings of 33-41% are reported by using a long wave radiation heating system, as compared to the conventional heating method. It is worth noting that long wave radiation heating has recently come to be considered as a welcome substitute for conventional heating in certain food processing applications (Galindo et al., 2005; Tanaka et al., 2007), because of its superiority in terms of reduced costs and increased product quality.

In the present work, the thermal performance of a greenhouse heated by water pipes is investigated theoretically and experimentally and the expected improvements by considering long wave radiation for direct heating of plants and soil are assessed.

CHARACTERISTICS OF THE CASE-STUDY GREENHOUSE

The greenhouse considered for the investigation is placed in the Technological Educational Institute (T.E.I) of Messologi in Western Greece and it consists of three structural units. It is equipped with a conventional heating system, which consists of a central boiler and a hot water pipe system. The structure is a metallic framework with glass cover. The total area of the greenhouse A_s is equal to 500 m^2, the area of the cover is $A_c = 815$ m^2 and the volume of the greenhouse is $V = 1700$ m^3. The number of air changes per hour, N, is equal to 1.5 h^{-1}; it refers to a new greenhouse construction with good maintenance. The cultivation consists of plants of lettuce and the greenhouse's floor can be considered as being completely covered by plants, thus the area of plant canopy A_p = 500 m^2.

The temperature data are collected at a meteorological station for a time period of 3 years, which is located next to the greenhouse and complies with the specifications of World Meteorological Organization (WMO). Processing of the meteorological data was performed using the statistical program SPSS 13. For the energy calculations of the greenhouse the average night temperature of the statistically most unfavorable month of the period examined was taken; it gives for the outside temperature T_o to the value of 7°C. The desirable temperature for the cultivation T_a is taken to be 14°C.

THERMAL MODELING OF THE GREENHOUSE

A thermal analysis is performed in order to quantify the contribution of each component of the greenhouse to the required energy consumption, under general heating conditions. The heat transfer problem is formulated and solved under steady-state conditions for spatially uniform temperatures of cover T_c, inside air T_a and plants T_p. The plantation temperature T_p is assumed fixed at the target value and the unknowns are the temperatures of the cover T_c and of the inside air T_a.

The equations developed below are applicable to both heating alternatives which are considered in the present study, namely: (a) heating of the greenhouse interior by a water pipeline system, and (b) direct heating of the plantation and soil by long wave radiation. Three additive loss terms are considered: Term Q_1 is due to inevitable construction defects of the greenhouse that cause air leakage, as well as to the required ventilation through ventilation openings.

$$Q_1 = \frac{C_{p\alpha}\rho_\alpha NV}{3600}(T_a - T_o) \quad (W) \tag{1}$$

where, $C_{p\alpha}$ the specific heat of air (J/kg °C), ρ_α the density of air (kgr/m^3) and $T_\alpha - T_o$ the temperature difference between inside and outside air (°C).

Losses, Q_2, refer to combined convective and radiative losses from the greenhouse cover. The cover loses heat by convection to the outside air and by thermal radiation towards the sky.

$$Q_2 = h_{co}A_c(T_c - T_o) + \varepsilon_c A_c \sigma (T_c^4 - T_o^4) \tag{2}$$

where, h_{co} the convective heat transfer coefficient between cover and outside air (W/m^2 K), ε_c the emissivity of cover (-), σ the Stefan - Boltzmann constant (W/m^2 K^4) and $T_c - T_o$ the temperature difference between cover and outside air (°C). The sky temperature T_{sky} is always set equal to the mean monthly outside air temperature T_o.

The unknown temperature of the cover T_c is calculated by writing an energy balance, using the cover itself as the control volume. The cover exchanges heat by convection with the inside and outside air, and at the same time, it gains heat by radiation from the plants and loses heat by radiation towards the sky. A balance of these terms at steady-state leads to the following equation,

$$\frac{\sigma\varepsilon_p A_p(T_p^4 - T_c^4)}{1+(1-\varepsilon_c)\left(A_p\varepsilon_p / A_c\varepsilon_c\right)} + A_c h_{ac}(T_\alpha - T_c) - \varepsilon_c A_c \sigma(T_c^4 - T_o^4) - h_{co}A_c(T_c - T_o) = 0 \tag{3}$$

where, h_{ac} the convective heat transfer coefficient between inside ambient air and cover (W/m^2 K), ε_p the emissivity of plants (-) and $T_p - T_o$ the temperature difference between plantation and outside air (°C). The radiation exchange between plants and cover takes into account the grey nature of the surfaces and the geometric constraint.

Losses Q_3 refer to losses from the greenhouse floor and the floor temperature is taken equal to the temperature of the plantation T_p.

$$Q_3 = K_s A_s (T_p - T_o) \quad (W) \tag{4}$$

where, K_s the total heat transfer coefficient through the soil, (W/m^2 K).

To evaluate the quality of different heating schemes a heating efficiency coefficient n, may be formulated:

$$n = \frac{Q_{p,t}}{Q_{total}} \tag{5}$$

In eq. (5), $Q_{p,t}$ stands for the amount of energy absorbed by the plants of an initially cold greenhouse in order to reach the desired temperature and Q_{total} is the total amount of energy provided by the heating system during the entire transient heating period. Rigorous evaluation of Q_{total} would necessitate integration of a system of ordinary differential equations in time. However, a conservative estimate is provided by approximating thermal losses by their maximum value, which is attained under steady-state conditions. Thus, Q_{total}, may be calculated from the following expression,

$$Q_{total} = (Q_1 + Q_2 + Q_3)\Delta t + Q_{a,t} + Q_{p,t} \tag{6}$$

where Q_1 to Q_3 are the steady values of the various thermal losses and $Q_{a,t}$, $Q_{p,t}$ the energy needed to heat the inside air and plants. The energy stored in the greenhouse components during heating can be evaluated simply by considering the mass, m (Kg) and specific heat of each component, C_p (J/kg °C). The major contributions come from the plant canopy and the interior air, and are given by the expressions,

$$Q_{p,t} = m_p C_{pp}(T_p - T_o) \text{ (7a)}$$

$$Q_{\alpha,t} = m_a C_{p\alpha}(T_\alpha - T_o) \quad \text{(7b)}$$

Finally, Δt, stands for the duration of heating period, which in this study is taken equal to $\Delta t = 1h$. It approximates well the time interval observed experimentally from the actual operation of the greenhouse under consideration. Furthermore, this choice is justified by the computed characteristic time of thermal response of the plantation.

COMPUTATION OF THE ENERGY NEEDS OF THE GREENHOUSE

In order to produce indicative figures for the case-study greenhouse, the following temperatures are set at the respective values: (i) The desirable temperature for the growth of the considered cultivation is taken as $T_p = 14\,^0C$. (ii) The temperature of the environment outside the greenhouse is taken from the statistically most unfavorable weather conditions for this geographical area as $T_o = 7\,^0C$.

The conversion efficiency coefficient n_h for the heater is taken to be 0.85 equal, if the amount of energy produced is exploited to operate a water pipes or a long wave radiation heating system. Finally the thermal properties of plant mass are equal to those of water, due to the high content of water in the plant. It should be noticed that the present model may be readily applied also to other case studies by adopting different sets of data.

Estimation of the Energy Needs Using a Water Pipes Heating System

In the case of heating by means of water pipes, the greenhouse interior is uniformly heated and the plants receive energy mainly by convection from the inside air. As a result, $T_\alpha = T_p$. Substituting in eq. (3), it remains the cover temperature, T_c, as the single unknown. Instead of solving this equation numerically and then returning to eq. (2)

to calculate the thermal losses, Q_2, one may in this case derive an analytical approximation by linearizing the radiative contributions. Thus, eqn (2) may be written as:

$$\frac{Q_2}{A_c\left(h_{co}+\varepsilon_c\lambda_1\right)}=T_c-T_o$$

where $\lambda_1=\sigma(T_c^2+T_o^2)(T_c+T_o)$ (2α)

Adding eqs (2) and (3), it gives:

$$Q_2 = h_{\alpha c}A_c(T_p-T_c)+\frac{\varepsilon_p A_p\sigma(T_p^4-T_c^4)}{1+(1-\varepsilon_c)\left(A_p\varepsilon_p/A_c\varepsilon_c\right)} \quad (8)$$

In eqn (8) it has been also made use of the substitution $T_\alpha=T_p$. Equation (8) may be similarly linearized to give

$$\frac{Q_2}{A_c\left[h_{\alpha c}+\varepsilon_p\left(A_p/A_c\right)\lambda_2\right]}=T_p-T_c \quad (8\alpha)$$

where $\lambda_2=\sigma(T_p^2+T_c^2)(T_p+T_c)/\left[1+(1-\varepsilon_c)\left(A_p\varepsilon_p/A_c\varepsilon_c\right)\right]$

The temperature summation terms λ_1, λ_2 are approximated by the constant *λ=5.01781 W/m²K.* This numerical value is equal to the algebraic mean of λ_1 and λ_2, when the unknown T_c is set equal to the mean value between the desirable internal temperature in the greenhouse, $T_p=14\,^0C$, and the external ambient temperature, $T_o=7\,^0C$. Adding eqs (2a) and (8a), the unknown T_c is eliminated and the following expression for the heat losses from the cover in terms of the total temperature difference (T_p-T_o) is derived:

$$Q_2=\frac{1}{\dfrac{1}{h_{ca}+\varepsilon_p\left(A_p/A_c\right)\lambda}+\dfrac{1}{h_{co}+\varepsilon_c\lambda}}A_c(T_p-T_o)=K_cA_c(T_p-T_o) \quad (9)$$

In eqn (9) the total heat transfer coefficient through the cover K_c, has been defined as

$$K_c=\frac{1}{\dfrac{1}{h_{ac}+\varepsilon_p\left(A_p/A_c\right)\lambda}+\dfrac{1}{h_{co}+\varepsilon_c\lambda}} \quad (10)$$

it incorporates both, the convective and radiative contributions.

Using equations (1) and (4) and the above equation (9), the contribution of each greenhouse component to the required energy consumption during heating has been calculated. All values used in the calculations are summarized in Table 1. The results are displayed (Fig. 1), where the values give the contribution of each component in terms of absolute energy amounts. The same values are given as percentage of the required energy consumption during heating. As expected, losses through the cover are the most significant. It represents 77.3% of the total energy consumption required during heating. However, ventilation and soil losses are also not negligible. Using the ratio $h_{co}/\left(h_{co}+\varepsilon_c\lambda\right)$ appearing in eq. (2a), the contribution of convection and radiation to the total cover losses are determined to 81.6 % for the convective contribution and 18.4 % for the radiative contribution respectively.

The energy amounts $Q_{a,t}$ and $Q_{p,t}$ needed to heat inside air and plants are calculated from eqs (7a) and (7b) to 15.5 MJ and 55 MJ, respectively. By using eqn (6) the total amount of energy required to heat the initially cold greenhouse is derived to

$Q_{total} = 324.17\ MJ$ and the thermal efficiency coefficient for heating period of the greenhouse is calculated from eq. (5) as 17.0 %. It is worth noting that although case specific, this value is not expected to differ appreciable for other cultivations as well as other locations with comparable climatic conditions.

Estimation of the Expected Improvements by Assuming Infrared Radiation System

An alternative to increase the thermal efficiency of the greenhouse could emerge by the direct heating of plants and soil using long wave radiation. With this mode of heat transfer, the air temperature T_a is expected to be significantly different than that of the plants, and its calculation at steady-state requires another equation. As such, the energy balance around a control volume that contains only the inside air will be taken. The air exchanges heat by convection with the plants canopy and the inside surface of the cover and also exchanges mass with the exterior (air renewal by leakages and ventilation).The balance of these contributions at steady-state is expressed by the equation

$$A_p h_{ap}(T_p - T_\alpha) - A_c h_{ac}(T_\alpha - T_c) - nV0.36(T_\alpha - T_o) = 0 \qquad (11)$$

Equations (3) and (11) need to be solved simultaneously to determine the two unknown temperatures, T_α and T_c. This task may be accomplished either numerically or analytically by a symbolic mathematics software. For the present case study the Mathematica® software tool has been used. By taking again $T_p = 14\,^0C$ and $T_o = 7\,^0C$ the values derived for air and cover are $T_\alpha = 10.2\,^0C$ and $T_c = 8.3\,^0C$ respectively. It is worth noting that the air equilibrates at a temperature significantly lower than that of the plants, and that the cover remains even colder. These changes are expected to influence favorably the heat losses of the greenhouse. Indeed, each contribution is re-calculated from eqs (1), (2) and (4), and the results are compared to those corresponding to conventional heating (Fig. 2). With the exception of the conductive losses through the soil (which remain by definition identical) all other thermal losses are appreciably reduced in the case of infrared heating. The total result is a 45-50 % economy in energy needs during steady-state operation. It is worth mentioning that heat losses from cover, although appreciably reduced in absolute values as compared to water pipes heating, are still representing the most significant contribution to the total energy losses and reach 73.7% of it (Fig. 2). Hence, searching for alternative cover material solutions would remain an urgent need also by using long wave radiation heating systems.

Using the eqs (5) and (6) and taking again a heating time equal to 1h, the values calculated for total thermal load Q_{total} and thermal efficiency coefficient n are $Q_{total} = 222.24\ MJ$ and $n = Q_{p,t}/Q_{total} = 24.7\%$, respectively. These values evidently underline the significant potential of the long wave radiation heating systems for achieving appreciable reduction of the energy needs to heat the greenhouse. It should be noted that the assumption of same heating time by the use of direct long wave radiation as for heating with water pipes clearly represents an unfavourable heating time scenario for the case of long wave radiation heating as an essential benefit of long wave radiation is the potential for dramatic reduction in heating time. This reduction is achieved by increasing the intensity of radiation sources and is probably only limited by the receiving ability of the plants. Experimental results presented in (Teitel et al., 2000) indicated that direct heating of tomato and pepper within only a few seconds by using a microwave system, did not cause visible injury to leaves, flowers and fruits. At any case, a tenfold decrease appears feasible. Thus, the present analysis concludes with an estimate of possible gains in efficiency stemming from the reduction of heating time, and results are shown (Fig. 3) for times ranging from 5 min up to 60 min. Comparison of these results with the efficiency n=17.0 % achieved by water pipes heating indicates improvements starting from 46% and reaching up to 280% for the shortest heating time assumed.

CONCLUSIONS

A parametric study has been undertaken to quantify the contribution of each of the components of a greenhouse located in Western Greece and heated by water pipes system to the energy consumption during heating. For the calculations, conductive, convective and radiative resistances have been identified and appropriate energy balances have been formulated for temporally steady and spatially uniform (but not necessarily equal with each other) temperatures of cover, inside air and plants. Also, a preliminary, conservative estimate of thermal efficiency during heating has been developed.

Using the thermal model developed, thermal performance of the case-study greenhouse has been examined; it gives for the thermal efficiency coefficient the unacceptably low value of 17%. As the results of the calculation represent actual figures of a thermal model formulated under general conditions they can be considered as representative also for other cultivations and other locations with similar climatic conditions. Combined convective and radiative losses from the cover represent nearly 80% of the overall thermal losses of the greenhouse during heating and are predominantly responsible for the unacceptably low thermal efficiency of the greenhouse, and thus their reduction is of primary concern.

A significant improvement of the heating efficiency could emerge by the direct heating of plants and soil by the means of long wave radiation. By assuming for direct long wave radiation heating the same heating time as by using water pipes, which clearly represents the most unfavourable scenario by the use of long wave radiation, it results to a heating efficiency increase of about 45% as compared to the derived heating efficiency when using water pipes heating.

Literature Cited

Bartzanas, T., Tchamitchian, M. and Kittas, C. 2005. Influence of the Heating Method on Greenhouse Microclimate and Energy Consumption. Biosystems Eng. 91:487-499.

Bot, G. 2001. Developments in indoor sustainable plant production with emphasis on energy saving. Computers and Electronics in Agriculture 30:151-165.

Critten, D.L. and Bailey, B.J. 2002. A review of greenhouse engineering developments during the 1990s, Agricultural and forest Meteorology 112:1-22.

Galindo, F.G., Toledo, R. and Sjoholm, I. Tissue damage in heated carrot slices. Comparing mild hot water blanching and infrared radiation. J. Food Eng. 67:381-385.

Ghosal, M.K. and Tiwari, G.N. 2004. Mathematical modeling for greenhouse heating by using thermal curtain and geothermal energy. Solar Energy 76:603-613.

Gupta, M.J. and Chandra, P. 2002. Effect of greenhouse design parameters on conservation of energy for greenhouse environmental control. Energy 27:777-794.

Singh,,G., Singh, P.P., Lubana, P.P.S. and Singh, K.G. 2006. Formulation and validation of a mathematical model of the microclimate of a greenhouse. Renewable Energy 31(10):1541-1560.

Tanaka, F., Verboven, P., Scheerlinck, N., Morita, K., Iwasaki, K. and Nicolai, B. 2007. Investigation of far infrared radiation heating as an alternative technique for surface decontamination of strawberry. J. Food Eng. 79(2):445-452.

Teitel, M., Segal, L., Shklyar, A. and Barak, M. 1999. A comparison between pipe and air heating methods for greenhouses. J. Agric. Eng. Research 72:259-273.

Teitel M., Shklyar A., Elad Y., Dikhtyar V. and Jerby, E. 2002. Development of a microwave system for greenhouse heating. Acta Hort. 534:189-195.

Tables

Table 1. Input parameters used for the computations.

$m_p = 1875\,kg$	$A_c = 815\ m^2$	$T_p = 287.16K$	$Cp_p = 4190\,J/kg\,^0C$
$m_\alpha = 2210\,kg$	$A_p = 500\ m^2$	$T_o = 280.16K$	$\rho_a = 1.3\ kg/m^3$
$h_{ap} = 8.5W/m^2\,K$	$V = 1700\ m^3$	$\varepsilon_p = 0.9$	$\sigma = 5.662 \cdot 10^{-8}\ W/m^2\,K^4$
$h_{ac} = 8.5W/m^2\,K$	$N = 1.5\ h^{-1}$	$\varepsilon_c = 0.9$	$\lambda = 5.01781\,W/m^2K$
$h_{co} = 20W/m^2\,K$	$n_h = 0.85$	$Cp_a = 1004\ J/kg\,^0C$	$K_s = 1.85\ W/m^2K$

Figures

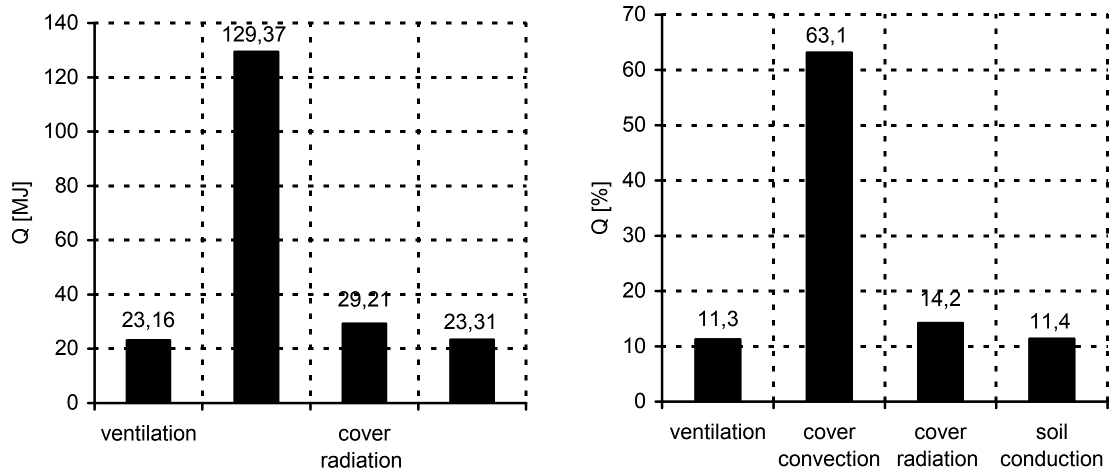

Fig. 1. Contribution of each greenhouse component to the energy balance in MJ and in percentage of the total energy consumption.

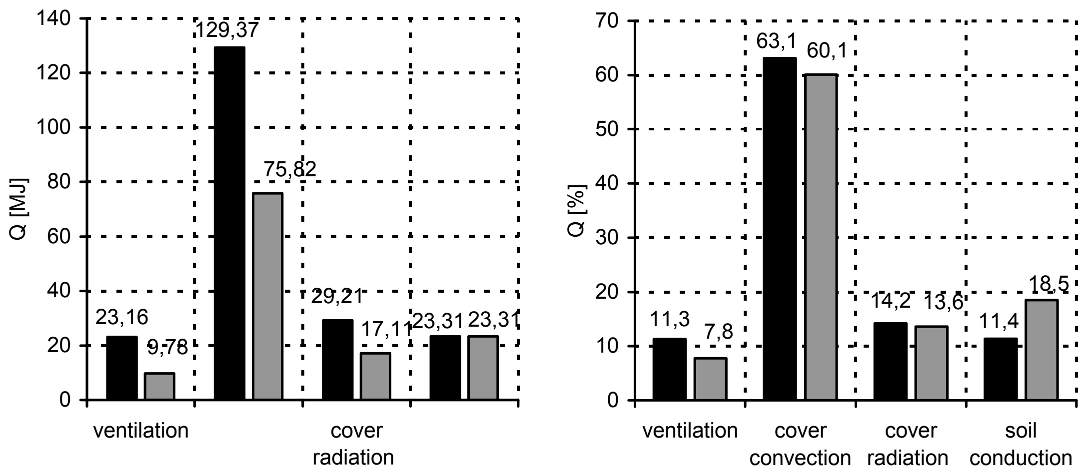

Fig. 2. Comparison between conventional and in MJ and long wave radiation heating in percent of the total energy consumption.

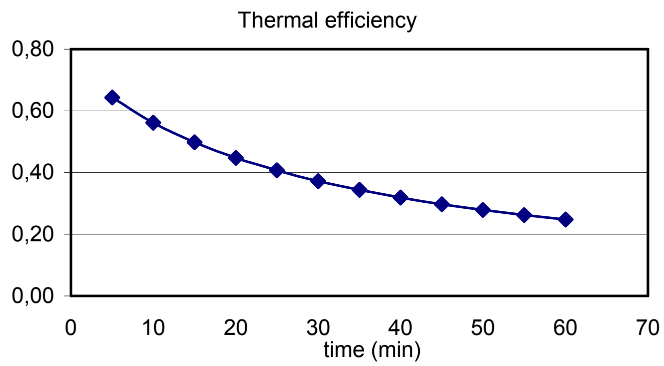

Fig. 3. Relation between thermal efficiency coefficient and heating time for the case of long wave radiation heating.