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The heat conductivity mechanism of the IR heating propagation for surfaces decontamination in protected ground

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Abstract. Modern greenhouses usually have flat concrete surfaces with communications for subsurface and above surface heating. It is proposed to disinfect surfaces with infrared radiation. We solve the corresponding heat equation. Field tests of the temperature field in protected ground have been performed to verify the mathematical model validity and to determine the empiric coefficients. The numerical investigation of the solution when the quantity of the Fourier series terms changes from 100 to 200 gives the heating time τ = 15 …16 min. Using these theoretical and experimental investigations one may conclude that the sufficient heating of a surface at the depth up to 5 cm needs a relatively long time of 15 …16 min and the surface will be strongly overheated during this time. We recommend using infrared heating for the decontamination purposes, but only in the case of thin layers of the ground or of the surface. The temperature necessary for the surface contamination and elimination of different pathogenic microorganisms, fungi, rots etc. emerging in the protected ground is achieved at a relatively small-time interval of 30…40 c. We think that the infrared radiation is a powerful and advanced method of sanitation of thin layers and surfaces.

1 Introduction

Today we have powerful technologies for growing fruits and vegetables in protected ground using soilless and substrate methods. Modern greenhouses usually have flat concrete surfaces with communications for subsurface and above-surface heating. The enclosing structures (frames and roof) are made of double or triple glass units, which–being properly installed–provide almost ideal microclimate and help to withstand significant wind and snow loads

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when operating greenhouses in the temperate climate of the northern hemisphere. Soilless and substrate growing methods and modern greenhouse facilities require decontamination of surfaces (floor and walls) in order to obtain healthy seedlings and a good harvest. Therefore, it is proposed to disinfect surfaces with infrared (IR) radiation [1-5].

2 Materials and methods

When the IR radiation interacts with the medium surface, it becomes partially reflected and partially penetrates into the substance being absorbed in it and transforming into heat. The transfer of the heat energy in a substance is determined by the heat conductivity processes. The heat transfer phenomenon emerges in the case of a direct contact of separate particles at different temperatures in a surface layer and can be explained by the elastic waves' propagation. The process is possible when the temperature is different at different points of the substance, so that the heat transfer being the result of the heat conductivity implies the temperature Tchange depending on the space coordinates (x, y, z,), as well as on the time τ.

To perform the theoretical analysis of the surface heating process, we assume the following:

- the treated material (the floor or the walls) is isotropic and homogeneous, that is, its properties are the same in any direction and the physical coefficients have negligibly small dependence on the temperature;
- the source of the heat, i.e., the surface doesn't depend on the temperature.

In this case the heat equation runs as follows:

$$\frac{\partial T}{\partial \tau} = a^2 \Delta T + f(x, y, z, \tau) \tag{1}$$

where T (x,y,z,τ) stands for the desired temperature field function, which depends on the space coordinates and the time τ;

Δ is the Laplace operator $\left(\Delta = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}\right)$;

$a^2 = k/c\rho$isthethermal diffusivity coefficient of the medium, m2/s; k – the heat conductivity coefficient, Wt/(m·K), c – the specific heat capacity of the substance, J/(kg·K); ρ – the density of the target substance of the surface, kg/m3;

$$f = \frac{q}{c\rho}, \tag{2}$$

q – the density of the inner heat sources distribution, Wt/m3.

In the one-dimensional case, when the IR-radiation heat salon its flow at the depth x, the equation (1) becomes:

$$\frac{\partial T}{\partial \tau} = a^2 \frac{\partial^2 T}{\partial x^2} + f(x, \tau). \tag{3}$$

The non-homogeneous heat equation (3) describes an idealized mechanism of heat distribution and is descriptive (phenomenological). One can understand how precise this equation describes a real physical interaction of an IR radiation with a surface only by comparing solutions of the equation with the results of experiment (of field tests).

The heat equation is a mathematical model of an entire class of heat conduction and heat transfer processes; however, this equation taken by itself says nothing about the process of heat transfer from the external to the internal plies of the surface. From the mathematical point of view it can be explained with the fact that the solution of a partial differential equation is not unique. In order to find a partial solution for a given special problem of a substance heating, one needs additional data. These additional conditions, necessary to determine a unique solution for a given heat transfer problem, are called uniqueness conditions.

The uniqueness conditions include:

- geometrical conditions for the shape and size of the body where the process of heat interchange takes place;
- conditions specifying the physical and thermophysical properties of the surface (the heat conductivity coefficient k, the specific heat capacity c, the densityρ), as well as the heat sources distribution law;
- boundary conditions specifying the thermal interaction with the environment and with the inferior layers at the very boundary of the surface;
- time conditions or initial conditions which define the temperature distribution at any point of the body at a given time considered as the zero time for the given problem.

Two last conditions are called the boundary conditions for the solution to (3).

One knows ([1]) that the solution to (3) can be written as the following sum:

$$T(x,\tau) = U(x,\tau) + V(x,\tau), \tag{4}$$

Where U(x,τ) stands for the solution of the homogeneous equation

$$\frac{\partial U}{\partial \tau} = a^2 \frac{\partial^2 U}{\partial x^2} \tag{5}$$

with the boundary conditions for the ply of the substance having the width h:

$$U(x,0) = U_0(x) \neq 0,\ U(0,\tau) = U_1(\tau) \neq 0,\ U(h,\tau) = U_2(\tau) \neq 0, \tag{6}$$

and V(x,τ) satisfies the non-homogeneous equation

$$\frac{\partial V}{\partial \tau} = a^2 \frac{\partial^2 V}{\partial x^2} + f(x,\tau) \tag{7}$$

with the zero boundary conditions

$$V(x,0) = 0,\ V(0,\tau) = 0,\ U(h,\tau) = 0. \tag{8}$$

A powerful solution technique for the heat equation is the separation of variables method (Fourier method). For example, if $x \in [0;h]$ one can write the Fourier series using only sines.

In this case, the solution to (7) runs as follows:

$$V(x,\tau) = \sum_{n=1}^{\infty}\left(\int_0^{\tau} e^{\omega_n^2(\tau-\xi)} \cdot \varphi_n(\xi)d\xi\right) sin\left(\frac{n\pi}{h}x\right), \tag{9}$$

where$\omega_n = \frac{n\pi a}{h}$;

$$\varphi_n(\tau) = \frac{2}{h}\int_0^h f(x,\tau) \cdot sin\left(\frac{n\pi}{h}x\right) dx. \tag{10}$$

When the heat supply is constant: f(x,τ) = F = const (K/s), (10) gives us:

$$\varphi_n = \frac{2F}{n\pi}\big(1 - cos(n\pi)\big), \tag{11}$$

and (9) becomes:

$$V(x,\tau) = \frac{2Fh^2}{a^2}\sum_{n=1}^{\infty}\frac{\big(1-cos(n\pi)\big)\left(e^{\omega_n^2\tau}-1\right)}{(n\pi)^3} sin\left(\frac{n\pi}{h}x\right). \tag{12}$$

The Fourier method gives us the solution to (5) with the boundary conditions (6) as:

$$U(x,\tau) = \sum_{n=1}^{\infty} U_n(\tau) \cdot sin\left(\frac{n\pi}{h}x\right), \tag{13}$$

where

$$U_n(\tau) = e^{-\omega_n^2\tau}\left(\frac{2}{h}\int_0^h U_0(x) \cdot sin\left(\frac{n\pi}{h}x\right) dx + \frac{2n\pi a^2}{h^2}\int_0^{\tau} e^{\omega_n^2\tau}\big(U_1(\xi) - (-1)^n \cdot U_2(\xi)\big)d\xi\right). \tag{14}$$

When the boundary conditions are isothermal, that is, when the temperature of the boundary points of the investigated layer of the surface is kept constant

U1 = T1 = const, U2 = T2 = const,

and the initial temperature of the layer is supposed to be the same in the entire layer of the depth h:

U0 = T0 = const, which is true under the protected ground conditions, the expression (14) takes the following form:

$$U_n(\tau) = \frac{2}{n\pi}\Big((-1)^n \cdot T_2 - T_1 + T_0\big(1 - cos(n\pi)\big)\Big) e^{-\omega_n^2\tau}. \tag{15}$$

Here T1is the surface temperature, T2is the temperature of the lower boundary of the substance, and T0is the medium temperature (inside the green-house).

Then the heat equation solution is given by:

$$T(x,\tau) = 2\sum_{n=1}^{\infty}\left(\frac{\left(((-1)^n \cdot T_2 - T_1)\left(1-e^{-\omega_n^2\tau}\right) + T_0\left(1-cos(n\pi)\right)e^{-\omega_n^2\tau}\right)}{n\pi} + \frac{Fh^2}{a^2} \frac{\left(1-cos(n\pi)\right)\left(e^{\omega_n^2\tau}-1\right)}{(n\pi)^3}\right) sin\left(\frac{n\pi}{h}x\right). \quad (16)$$

Moreover, one can add to (16) a constant term or a term linearly depending on x; for example, the solution may have the form:

$$T(x,\tau) = T_1 + \frac{T_2-T_1}{h}\cdot x + 2\sum_{n=1}^{\infty}\left(\frac{\left(((-1)^n \cdot T_2 - T_1)\left(1-e^{-\omega_n^2\tau}\right) + T_0\left(1-cos(n\pi)\right)e^{-\omega_n^2\tau}\right)}{n\pi} + \frac{Fh^2}{a^2} \cdot \frac{\left(1-cos(n\pi)\right)\left(e^{\omega_n^2\tau}-1\right)}{(n\pi)^3}\right) sin\left(\frac{n\pi}{h}x\right). \quad (17)$$

3 Results and discussion

Field tests of the temperature field in protected ground have been performed to verify the mathematical model validity and to determine the empiric coefficients (Figures 1 and 2).

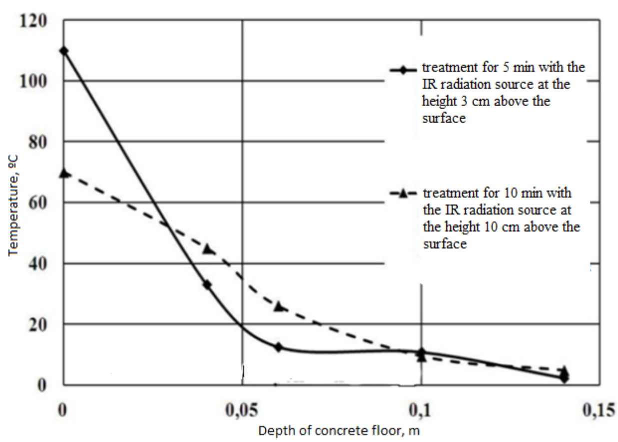

Fig. 1. The temperature change depending on the depth of the concrete floor due to the IR radiation.

The numerical investigation of (17) with the parameters obtained from experiment gives us the average value F = 0.02 K/c for the inner heat sources distribution density coefficient (it is constant for the temperature depends on time almost linearly, Figure 2) and a2 = 0.9·10-9m2/cfor the thermal diffusivity coefficient. The result fits with the reference data ([2]).

To make calculation, we take the following values:

$$T_1 = 70^o \ldots 100^o\ C;\ T_2 = T_0 = 15^o \ldots 18^o\ C;\ F = 0.02\ K/c;\ a^2 = 0.9 \cdot 10^{-9} m^2/c. \quad (18)$$

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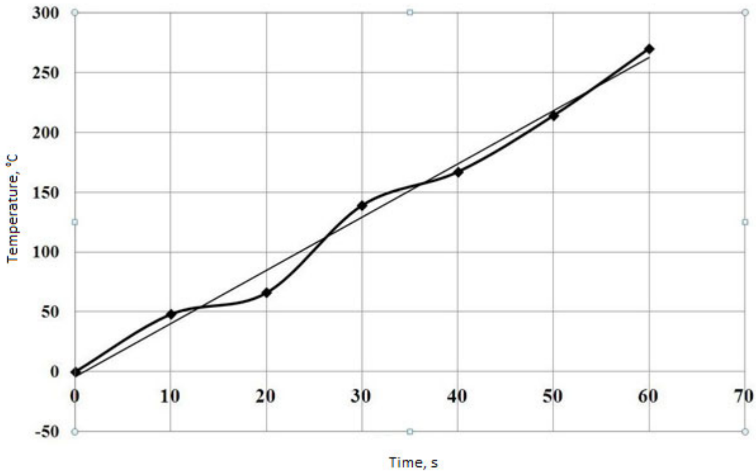

Fig. 2. The concrete floor temperature change over time due to the IR heating.

Figure 3 gives the temperature change over time at the depth h = 0.14 m.

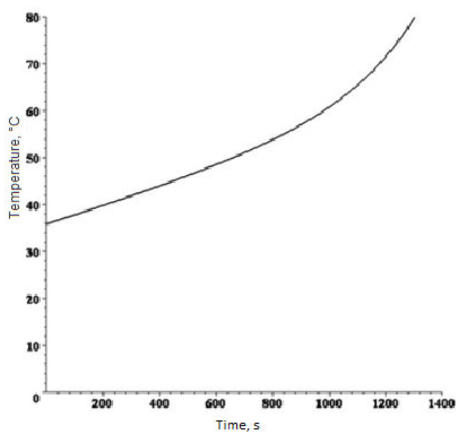

Fig. 3. The concrete floor temperature change over time at the depth h = 0.14 m.

The time necessary for the temperature at the depth of 0.14 m to achieve 70º C (with T1 = 100º C; T2 = T0 = 15º C; F = 0.02 K/c; a2 = 0.9·10-9m2/c) is equal toτ = 913.5 c = 15.2 min.

The numerical investigation of (17) under (18) when the quantity of the series terms changes from 100 to 200 gives the heating timeτ = 15 …16 min.

4 Conclusions

Using these theoretical and experimental investigations one may conclude that the sufficient heating of a concrete floor at the depth up to15 cm needs a relatively long time of 15 …16 min and the surface will be strongly overheated during this time.

That's why we recommend to use the IR heating for the decontamination purposes, but only in the case of thin layers of the ground (substrate) or of the surface. The temperature necessary for the surface (concrete floor, walls) contamination and elimination of different pathogenic microorganisms, fungi, rots etc. emerging in the protected ground is achieved at

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a relatively small-time interval of 30…40 c. That's why we think that the IR radiation is a powerful and advanced method of sanitation of thin layers and surfaces.

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