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Temperature distribution analysis inside the strawberry flower head

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Abstract. Different studies by numerous researchers were carried out recently to describe different heat flux components of heat balance equations for radiation frost condition in plants. The aim of most of the papers was to present more simple and clear mathematical algebra to show the plant heat balance formulas. To achieve this aim several simplifications were made. Nevertheless there are studies reporting different flower damage rates during spring frost sessions that mentioned studies cannot explain. This leads us to the need to find the temperature distribution inside the flower to understand why during the similar energy flux conditions the flowers act against frost stress differently. It's easy to measure the flower surface temperature but rather difficult to measure temperature distribution inside the flower head due to very small flower head scale compared to sensor sizes. To help to overcome these difficulties the authors make simplification by substituting the strawberry flower head with spherical homogeneous body though it is clear that the flower head is not homogeneous because of varying flower structure. The aim of this study is to present mathematical formulas for temperature distribution calculation inside the spherical body in terms of heat transfer conditions characteristic to radiation frost. Transient numerical methods are implemented for different conditions in case of spherical body. This approach enables us to decide if suggested mathematical solution is usable for non-homogeneous body. Computer program was prepared to analyse the results.

Key words: radiation frost, temperature distribution, plant, transient numerical method.

INTRODUCTION

In this paper the plant under the observation is strawberry and the specific plant part is the flower. In spring time the plants may be endangered by night frost in any part of the World depending on weather conditions. 'Freezing is a major environmental stress, inflicting economy ic damage on crops and limiting the distribution of both wild and crop species' (Pearce, 2001). Despite the numerous studies in this field by several generations of researchers of both engineering and botanical experience this is still continuing to be a problem in our days. In this paper the authors handle this subject from general and thermal engineering points of view starting by how it was evolving historically. As the subject is of practical nature there is a long history of scientific publications developing different aspects of it. A number of authors (Businger, 1965; Gerber & Harrison, 1964; Barfield et al., 1981; Hamer, 1986; Perry, 1986; Perry, 1998) have tried to compose the radiation night-frost heat balance equation for the bud or flower taking into account different members of the heat balance. The second objective was to change the mathematical expressions so that these would be solved simply and swiftly. Martsolf (1992b) summarized previous results by night-frost general protection theory in his handbook 'Energy in Farm Production'. Heinemann et al. (1992) suggested the prototype of the computer program meant to support the farmer in his decision making process for night-frost protection strategy selection. One of the four program modules predicts the temperatures for the following night, using the night-frost statistics from previous years weather reports giving the user the possibility to define the 'night-frost windows'. The program allows also saving measurement data from the specific field, creating thus more exact statistical database. Despite the previous publications Martsolf (2000) tries once more to explain the differences of night-frost protection strategies because Ferguson & Isreal (1998) publish surprising results of questioning by which the citrus growers in America use commercial weather forecasts to get the information about possible night-frost threat.

The earlier research performed by (Gerber & Harrison, 1964; Businger, 1965; Barfield et al., 1981; Hamer, 1986; Perry, 1986; Perry, 1998; Hollender et al., 2012; Issa, 2012; Maughan et al., 2015) and the theory, according to which the damage in plants by night-frost is a result of the nucleation and ice growth (Pearce, 2001) still lacks the possibility to produce the information about the time when the ice crystals start forming in the specific part of the plant it is necessary to observe the temperature distribution in it.

The idea to supply the consumers with the computer program supporting the decision making process (Heinemann et al., 1992) is very good, but too general for real-time applications. The further development would have been needed, but it has not been done in these years.

The radiation night-frost phenomenon is observed as a rule at dusk or night time on a large area, so, to react on time and in a most appropriate way, the farmer has to know, what kind of thermal processes are going on at his field. That information could be produced by a thermal processes simulation computer program with the possibility to predict the temperature changes of the specific parts of the plants and the ambient environment.

One of the essential phases in development of such a program is creation of temperature calculation algorithm for most endangered parts of plants, which is the main purpose of this paper.

MATERIALS AND METHODS

General description of plant part as a model

In this paper the plant under the observation is strawberry and the specific plant part is the flower.

The temperature changes and nucleation (ice crystals forming) assume the model where the cell solute temperature alteration of plant parts is observed in different aggregate states. The nucleation inside and between the cells is very complicated phenomenon because the cell solute temperature may often fell below 0 °C without the freezing which increases the ability of the plant to withstand the influence of chill (Pearce, 2001). The processes on the surface of the plant are also quite complicated as there may be found different nucleators, for example, INA (ice nucleation-active) bacteria species which produce a protein able to nucleate freezing (Warmund & English, 1998). There is no clear theory suggested describing the conditions, when the nucleation occurs and when not at the cell solute temperatures below 0 °C. Because of that in this paper for simplification purposes the process of temperature change is observed only until the beginning of nucleation. Suggested algorithms do not handle the aggregate state changes of the cell solute and temperature alteration after ice formation. Depending on the plant species and corresponding differences in cell solutes concentration the nucleation may occur at different temperatures: –0.6°C…–2.6 °C (Pearce 2001). In the model algorithm suggested here the temperature limit is chosen at 0 °C. In different research papers the thermal balance is analysed for different plant parts: the flower bud of the apple tree (Hamer, 1986), the plant leave (Businger, 1965), (Gerber & Harrison, 1964), (Barfield et al., 1981).

At the time when the strawberry flower may need frost protection its form may be different, depending on the stage of development. The authors presume the flower to be fully open as shown on Fig. 1.

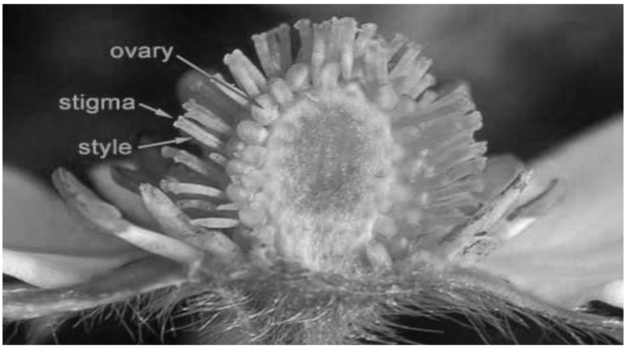

Figure 1. The cross-section of fully open strawberry flower.

The strawberry flower central part (receptacle) is practically entirely covered by spherical-shape ovaries (carpels) the number of which may vary between 100 and 400 depending on the species (Hollender et al., 2012). The ovaries have styles connected to them with the stigma at the end and are the most frost-endangered parts of the plant.

Defining as purpose the protection of the strawberry flowers from the night-frost it is necessary to provide the conditions that prevent the nucleation in the tissue of spherical-type ovaries.

Theory and modelling

Theory of spherically shaped body

In spring-time in case of radiation night-frost the surface layer temperature of the spherical-shape ovary of the flower changes first of all due to the radiative heat exchange. But for this theoretical approach it is not important, of what character are the heat flows influencing the surface layer, as much more important is to know how the temperature changes in time between the inside layers of the spherical ovary.

For more clear explanation of the essence of mathematical algorithm of the process the most frost-endangered part of the plant, the ovary, is looked at as a spherically shaped body, devided for analysis purposes to large number of spherical layers with homogenious density (Fig. 2), where layer counting starts outside-in from outer radius *R*. The total number of layers is *N*. Here it is important to notice that in further calculations r_{n-1} is the radius of the layer n–1, r_n is the radius of the current layer n and r_{n+1} is the radius of the layer n+1.

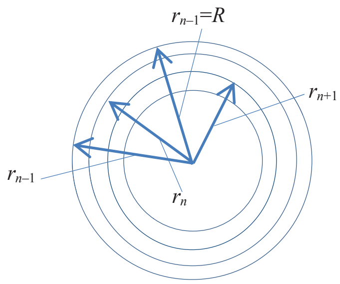

Figure 2. The description of the radiuses r_{n-1}, r_n and r_{n+1} of the body.

From these layers so small parts are chosen that it is possible to handle them as having not spherical but plain surfaces. Adjacent layers influencing each other are shown on Fig. 3.

Based on The Law of Conservation of Energy we can describe the heat balance equation for the layer n (Fig. 3) as

$$m_n \cdot c_n \cdot dt_n = k_n \cdot F_{n-1} \cdot (t_{n-1} - t_n) \cdot d\tau - k_n \cdot F_n \cdot (t_n - t_{n+1}) \cdot d\tau \,, \tag{1}$$

where: n is the number of the layer; m_n – layer mass, kg; c_n – specific heat capacity of layer material, J (kg °C)$^{-1}$; dt_n – layer temperature change, °C; k_n – heat transfer coefficient of the layer, W·(m^2·°C)$^{-1}$; F_n – spherical surface area, m^2, separating layers n and n+1; F_{n-1} – spherical surface area, m^2, separating layers n–1 and n; t_{n-1} – layer n–1 temperature, °C; t_{n+1}– layer n+1 temperature, °C; t_n – layer n temperature, °C; $d\tau$ – time step, s.

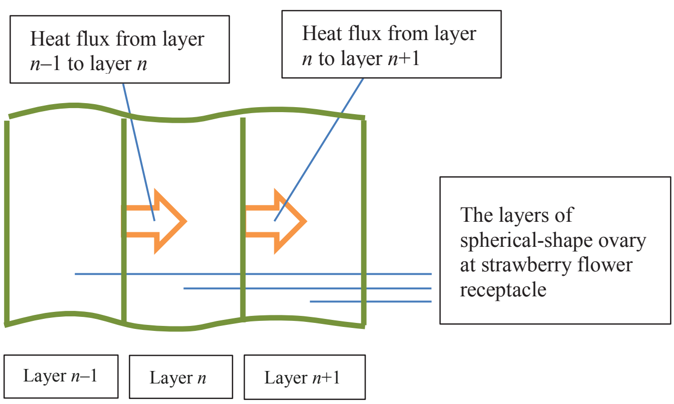

Figure 3. The heat-flows model of spherical-shape ovary layers at strawberry flower receptacle.

The layer mass definition expression looks like

$$m_n = \rho_n \cdot V_n \,, \tag{2}$$

where: ρ_n is the density of the layer, kg m^{-3}; V_n – the volume of the layer, m^3.

The heat transfer coefficient for the layer is:

$$k_n = \frac{\lambda_n}{\delta_n} \,, \tag{3}$$

where: δ_n is the thickness of the layer, m; λ_n – thermal conductivity of the layer material, W·(m·°C)$^{-1}$.

As we noticed earlier that spherical surfaces are replaced with plain surfaces we can declare

$$F_{n-1} = F_n \,. \tag{4}$$

Transforming the formula (1) in appropriate way we get

$$\frac{m_n \cdot c_n}{k_n \cdot F_n} \cdot \frac{dt_n}{d\tau} = t_{n-1} - 2t_n + t_{n+1} \,. \tag{5}$$

In the expression (5) let

$$T_n = \frac{m_n \cdot c_n}{k_n \cdot F_n} \,, \tag{6}$$

where T_n is the heating or cooling time constant of the layer, s.

The differential equation for temperature t_n change is

$$T_n \cdot \frac{dt_n}{d\tau} + 2t_n - t_{n-1} - t_{n+1} = 0 \,. \tag{7}$$

As the functions $t_{n-1} = f(t_n)$ and $t_{n+1} = f(t_n)$ are not defined, we shall not try to find the analytical solutions for the differential equation but concentrate on numerical methods.

To define the equation (7) term

$$\frac{dt_n}{d\tau} = \frac{t_{n,j+1} - t_{n,j}}{d\tau} \,, \tag{8}$$

we have to introduce the index j to formula (7), characterising the time dependence, which also enables the definition of calculation time interval length

$$d\tau = \tau_{j+1} - \tau_j \,. \tag{9}$$

Substituting the term in differential equation (7) by expression (8) we get

$$T_n \cdot \frac{t_{n,j+1} - t_{n,j}}{d\tau} + 2t_{n,j} - t_{n-1,j} - t_{n+1,j} = 0 \,. \tag{10}$$

After alteration

$$\frac{T_n}{d\tau} \cdot t_{n,j+1} = \frac{T_n}{d\tau} \cdot t_{n,j} - 2t_{n,j} + t_{n-1,j} + t_{n+1,j} \,. \tag{11}$$

Extracting the term $t_{n,j+1}$, we get

$$t_{n,j+1} = \frac{d\tau}{T_n} \cdot t_{n-1,j} + t_{n,j} - 2 \cdot \frac{d\tau}{T_n} \cdot t_{n,j} + \frac{d\tau}{T_n} \cdot t_{n+1,j} \,, \tag{12}$$

and finally,

$$t_{n,j+1} = \frac{d\tau}{T_n} \cdot t_{n-1,j} + \left(1 - 2 \cdot \frac{d\tau}{T_n}\right) \cdot t_{n,j} + \frac{d\tau}{T_n} \cdot t_{n+1,j} \,. \tag{13}$$

The calculation method here is based on the equality of time constant T_n for all layers. In this case looking at the terms in equation (13), we can see that if the values in ratio $\frac{d\tau}{T_n}$ are chosen so, that

$$\frac{d\tau}{T_n} = \frac{1}{2} \,, \tag{14}$$

then expression (13) is reduced to arithmetic mean

$$t_{n,j+1} = \frac{t_{n-1,j} + t_{n+1,j}}{2} \,. \tag{15}$$

That is the n-layer temperature at the next time-step (j+1) equals to the mean temperature of the previous layer (n–1) and next layer (n+1) temperatures at given time-step j.

Expression (15) describes the situation, where temperature change dt_n has maximal possible increase

$$dt_n = t_{n,j+1} - t_{n,j} \,. \tag{16}$$

In case of

$$\frac{d\tau}{T_n} > \frac{1}{2}, \tag{17}$$

the multiplier of $t_{n,j}$ in expression (13) becomes negative. In this circumstances the equation (3) describes the situation when the heat energy has to move from the body with lower temperature to the body with higher temperature which is conflictng with heat exchange laws. From that we can conclude that the term $\frac{d\tau}{T_n}$ in expression (13) should always be

$$\frac{d\tau}{T_n} \leq \frac{1}{2}. \tag{18}$$

The condition (18) becomes important when the temperature change in time is beeing sought.

The real body of spherical shape in our case is divided into layers so that the time constant is equal for all layers excluding the last, innermost one. The heat-balance for that layer differs from the equation (1):

$$m_n \cdot c_n \cdot dt_n = k_n \cdot F_{n-1} \cdot (t_{n-1} - t_n) \cdot d\tau . \tag{19}$$

After mathematical alterations similar to formulas (5) – (13) we get the differential equation

$$T_n \cdot \frac{dt_n}{d\tau} + t_n - t_{n-1} = 0 . \tag{20}$$

Defining the term $t_{n,j+1}$ for the core layer, we get

$$t_{n,j+1} = \frac{d\tau}{T_n} \cdot t_{n-1,j} + \left(1 - \frac{d\tau}{T_n}\right) \cdot t_{n,j} . \tag{21}$$

The second special case is the surface layer of the sphere, the heat balance conditions for which are described by following expression:

$$m_n \cdot c_n \cdot dt_n = k_{n-1} \cdot F_{n-1} \cdot (t_{n-1} - t_n) \cdot d\tau - k_n \cdot F_n \cdot (t_n - t_{n+1}) \cdot d\tau . \tag{22}$$

This result is similar to the equation (1) but the essence of the terms k_{n-1} and t_{n-1} here should be described in more detail. As in this paper we are describing an algorithm for defining the temperature change of the inner layers of the spherical body, the ambient environment is looked at as a solid body with an initial temperature $t_{n-1} = t_0 = 0\,°\text{C}$, which stays constant during the whole process. The heat-exchange between the environment and the surface layer *n* of the sphere is considered to be conductive.

In case of spherical body we have to take into account some conditions:

$$F_{n-1} \neq F_n \,, \tag{23}$$

$$\lambda_n = const,\ n = 1..N \,, \tag{24}$$

where N is a number of layers for which the body is divided.

Then the mathematical modifications of formula (1) differ from ones described above:

$$m_n \cdot c_n \cdot \frac{dt_n}{d\tau} = k_n \cdot F_{n-1} \cdot t_{n-1} - k_n \cdot F_{n-1} \cdot t_n - k_n \cdot F_n \cdot t_n + k_n \cdot F_n \cdot t_{n+1} \,. \tag{25}$$

Opening the term dt_n, we get

$$\frac{m_n \cdot c_n}{d\tau} \cdot t_{n,j+1} - \frac{m_n \cdot c_n}{d\tau} \cdot t_{n,j} = k_n \cdot F_{n-1} \cdot t_{n-1,j} - k_n \cdot F_{n-1} \cdot t_{n,j} - \\ - k_n \cdot F_n \cdot t_{n,j} + k_n \cdot F_n \cdot t_{n+1,j} \,, \tag{26}$$

and extracting the variable $t_{n,j+1}$, we have

$$t_{n,j+1} = \frac{k_n \cdot F_{n-1} \cdot d\tau}{m_n \cdot c_n} \cdot t_{n-1,j} + t_{n,j} - \frac{k_n \cdot F_{n-1} \cdot d\tau}{m_n \cdot c_n} \cdot t_{n,j} - \\ - \frac{k_n \cdot F_n \cdot d\tau}{m_n \cdot c_n} \cdot t_{n,j} + \frac{k_n \cdot F_n \cdot d\tau}{m_n \cdot c_n} \cdot t_{n+1,j} \,. \tag{27}$$

After grouping by $t_{n-1,j}$, $t_{n,j}$, $t_{n+1,j}$ we get

$$t_{n,j+1} = \frac{k_n \cdot F_{n-1} \cdot d\tau}{m_n \cdot c_n} \cdot t_{n-1,j} + t_{n,j} \left(1 - \frac{k_n \cdot F_{n-1} \cdot d\tau}{m_n \cdot c_n} - \frac{k_n \cdot F_n \cdot d\tau}{m_n \cdot c_n} \right) + \\ + \frac{k_n \cdot F_n \cdot d\tau}{m_n \cdot c_n} \cdot t_{n+1,j} \,. \tag{28}$$

Writing the formula (13) as

$$t_{n,j+1} = \frac{d\tau}{T_n} \cdot t_{n-1,j} + t_{n,j} \left(1 - \frac{d\tau}{T_n} - \frac{d\tau}{T_n} \right) + \frac{d\tau}{T_n} \cdot t_{n+1,j} \tag{29}$$

we see, that expressions (28) and (29) have similar structure. Therefore, we have to find an answer to the question: can the parameters of the body layers correspond to the next relationship

$$\frac{k_n \cdot F_{n-1} \cdot d\tau}{m_n \cdot c_n} = \frac{k_n \cdot F_n \cdot d\tau}{m_n \cdot c_n} = \frac{1}{2} . \tag{30}$$

We can see that this relationship is not correct as

$$r_{n-1} \neq r_n , \tag{31}$$

where: r_{n-1} is the radius of the layer n–1, m; r_n is the radius of the layer n, m (Fig. 2).

In equation (29) the condition $\left(1 - \frac{k_n \cdot F_{n-1} \cdot d\tau}{m_n \cdot c_n} - \frac{k_n \cdot F_n \cdot d\tau}{m_n \cdot c_n}\right) = 0$, necessary for determining the arithmetical mean likewise in formula (15), is fulfilled when

$$\frac{k_n \cdot F_{n-1} \cdot d\tau}{m_n \cdot c_n} + \frac{k_n \cdot F_n \cdot d\tau}{m_n \cdot c_n} = 1 . \tag{32}$$

In this case from

$$\frac{k_n \cdot F_{n-1} \cdot d\tau + k_n \cdot F_n \cdot d\tau}{m_n \cdot c_n} = 1 \tag{33}$$

we get

$$k_n \cdot F_{n-1} \cdot d\tau + k_n \cdot F_n \cdot d\tau = m_n \cdot c_n . \tag{34}$$

After substituting surface area in (34) we have

$$4 \cdot \pi \cdot k_n \cdot d\tau \cdot \left(r_{n-1}^2 + r_n^2\right) = m_n \cdot c_n \tag{35}$$

and then replacing heat transfer coefficient and mass as follows

$$\frac{4 \cdot \pi \cdot \frac{\lambda_n}{r_{n-1} - r_n} \cdot d\tau \cdot \left(r_{n-1}^2 + r_n^2\right)}{\frac{4}{3} \cdot \pi \cdot \left(r_{n-1}^3 - r_n^3\right)} = \rho_n \cdot c_n \tag{36}$$

we get finally

$$\frac{r_{n-1}^2 + r_n^2}{\left(r_{n-1} - r_n\right)\left(r_{n-1}^3 - r_n^3\right)} = \frac{\rho_n \cdot c_n}{3 \cdot \lambda_n \cdot d\tau} . \tag{37}$$

In the expression (37) the function of the term r_n exists in implicit form. To resolve the problem the computer program is written for searching the suitable values of r_n. The term r_{n-1} acts as a constant, because it is always already defined before r_n (at the first run $r_{n-1} = R$, where R is the radius of sphere). The members on the right side of equation

(37) are constants that express the physical parameters of the body and the process time $d\tau$. Giving different values to the radius r_n we search such value for it in case of which the equality (37) is valid with sufficient accuracy.

The equation (37) is suitable also for the body with layers of different physical properties that is nonhomogeneous body. It is possible to describe the density ρ_n, specific heat capacity c_n and thermal conductivity λ_n for each layer *n*. These calculated r_n values take into account physical parameters of nonhomogeneous body and the condition (37).

Special cases

The temperature change in the core layer of the sphere can be found from the heat-balance equation (19).

After mathematical modifications shown in (5) – (13) we get

$$t_{n,j+1} = t_{n,j} \cdot \left(1 - \frac{k_n \cdot F_{n-1} \cdot d\tau}{m_n \cdot c_n}\right) + \frac{k_n \cdot F_{n-1} \cdot d\tau}{m_n \cdot c_n} \cdot t_{n-1,j} \,. \qquad (38)$$

More complicated is temperature change definition for the surface layer of the sphere. Very thin surface layer is allocated for that, which participate in the radiative, convective and sensible heate-exchange. The mathematics describing these three heat-exchange types is of complex nature and has been handled by many authors: (Gerber & Harrison, 1964; Businger, 1965; Barfield et al., 1981; Hamer, 1986; Perry, 1986; Perry, 1998; Martsolf, 1992b). Taking into account the scope of this paper, we do not elaborate on these heat-exchange processes and in such case, the form of equation (1), suitable for surface layer temperature change definition, similarly to the equation (28) takes the specific form

$$t_{n,j+1} = \frac{k_n \cdot F_{n-1} \cdot d\tau}{m_n \cdot c_n} \cdot t_{vk,j} + t_{n,j}\left(1 - \frac{k_n \cdot F_{n-1} \cdot d\tau}{m_n \cdot c_n} - \frac{k_n \cdot F_n \cdot d\tau}{m_n \cdot c_n}\right) + \\ + \frac{k_n \cdot F_n \cdot d\tau}{m_n \cdot c_n} \cdot t_{n+1,j} \,, \qquad (39)$$

where t_{vk} is the surface temperature of the sphere, °C.

Thus, the mathematical algorithm describing temperature change inside the strawberry flower spherically shaped ovary, devided to $n = 1 \ldots N$ layers, can be described for different layers by following system of equations:

$$
\begin{cases}
n = 1: \\
t_{n,j+1} = \frac{k_n \cdot F_{n-1} \cdot d\tau}{m_n \cdot c_n} \cdot t_{vk,j} + t_{n,j} \left(1 - \frac{k_n \cdot F_{n-1} \cdot d\tau}{m_n \cdot c_n} - \frac{k_n \cdot F_n \cdot d\tau}{m_n \cdot c_n} \right) + \frac{k_n \cdot F_n \cdot d\tau}{m_n \cdot c_n} \cdot t_{n+1,j}, \\
1 > n > N: \\
t_{n,j+1} = \frac{k_n \cdot F_{n-1} \cdot d\tau}{m_n \cdot c_n} \cdot t_{n-1,j} + t_{n,j} \left(1 - \frac{k_n \cdot F_{n-1} \cdot d\tau}{m_n \cdot c_n} - \frac{k_n \cdot F_n \cdot d\tau}{m_n \cdot c_n} \right) + \frac{k_n \cdot F_n \cdot d\tau}{m_n \cdot c_n} \cdot t_{n+1,j}, \\
n = N: \\
t_{n,j+1} = \frac{k_n \cdot F_{n-1} \cdot d\tau}{m_n \cdot c_n} \cdot t_{n-1,j} + t_{n,j} \cdot \left(1 - \frac{k_n \cdot F_{n-1} \cdot d\tau}{m_n \cdot c_n} \right).
\end{cases} \quad (40)
$$

RESULTS AND DISCUSSION

To implement the algorithm, described by equations (40) the spherical body (in our case with strawberry flower ovary properties) has to be divided previously to virtual layers. Example results of such division defining the number of virtual layers depending on time-step length, which was performed using the equation (37), are shown in Table 1. To implement the algorithm, the computer program was composed.

Table 1. The numerical results for body division to spherical layers (body radius R = 0.5 mm, number of spherical layers N, calculation time-step $d\tau$, density ρ_n = 400 kg m^{-3}, specific heat capacity c_n = 3,800 J·kg^{-1}·K^{-1}, thermal conductivity λ_n = 0.8 W·m^{-1}·K^{-1})

Time-step	Number	Outside radius r of layer n, mm				
$d\tau$ length, s	of layers N	1	2	3	4	5
0.01	5	0.5	0.3969	0.2936	0.1894	0.0818
0.05	2	0.5	0.2636			
0.10	2	0.5	0.1476			
0.50	1	0.5				

On Fig. 4 the change of temperatures in the body is shown with starting temperature 5° C and final temperature 0 °C. In reality, so rapid temperature changes are possible at some specific conditions, e.g. sunset or the change of atmospheric radiation heat flux depending on the cloudiness.

As the results of the modelling show that the temperature change is very fast process it could be useful to specify more precisely the physical properties of the strawberry flower ovary – the density, specific heat capacity and thermal conductivity. But in any case, as the internal temperatures change is much faster process than the speed of change of the heat fluxes producing this temperature alteration it will not have great influence.

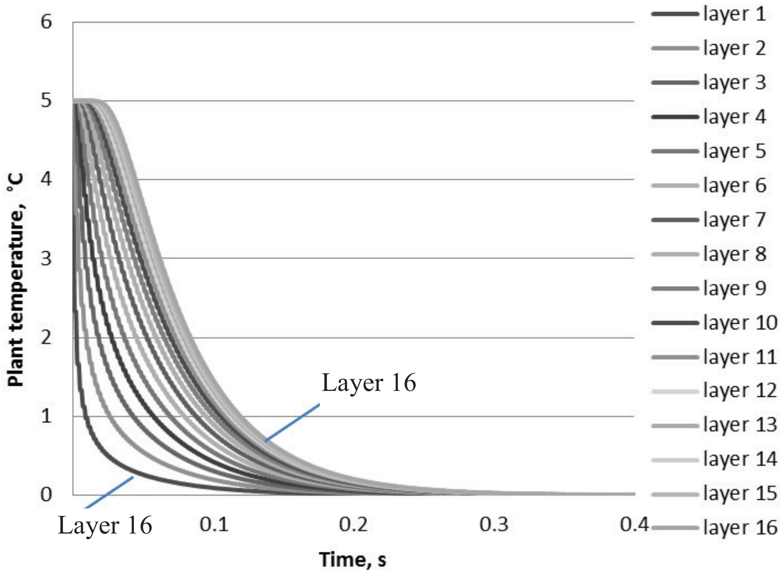

Figure 4. The calculated temperature change of different layers of strawberry flower ovary.

Choosing different time intervals in equation (37) we get different number of layers. If the interval is so long that the number of layers is small (2…5), the condition of the expression (32) is fulfilled with comparatively large error. Because of that it is important to select the time interval so short, that the number of layers would be larger than 15. The analysis of model errors due to the calculation method needs further investigation.

CONCLUSIONS

The strawberry flower freezing or the ice crystals forming in the ovaries covering the flower receptacle is thermally very quick process. If this process is really so fast, then it is difficult to understand, how the strawberry flowers can survive in the night-frost conditions in spring. As a result of this analysis the phenomenon of 'super cooling' of cells solute needs more attention at radiative night-frost. Mathematical algorithm for the heat transfer analysis inside the ovaries is now available.

Further analysis of temperature distribution inside the ovary of strawberry flower is needed in the situation, when the surface layer of the ovary participate in real radiative, convective and sensible heate-exchange. The results of analysis presented in this paper enable us to suggest a new point of view on the night-frost problem. Instead of asking, when the flower will freeze, we should rather have to ask, is it really possible, that the flower will not freeze at night-frost?

REFERENCES

Barfield, B.J., Walton, L.R. & Lacey, R.E. 1981. Prediction of sprinkler rates for night-time radiation frost. *Agricultural and forest meteorology* **24**, 1–9.

Businger, J.A. 1965. Frost protection with irrigation. *Agricultural and forest meteorology*, ISSN 0168–1923. Vol. **1** (1964)–30/1983).

Chesness J.L., Kidder E.H. & Dhanak A.M. 1968. Heat and Mass Transfer Study of Freeze Protection of a Leaf Model Subjected to water sprinkling. *Transactions of the ASAE* **11**(1), 0028–0033.

Ferguson, J.J. & Isreal G.D. 1998. Citrus cold protection: A 1996 Survey. *Proc. Fla. State Hort. Soc.*, **111**,117–121.

Finnikov, K.A., Minakov, A.V., Dekterev, A.A., Gavrilov, A.A., Korzun, A.M., Voinikov, V.K. & Kolesnichenko, A.V. 2010. Mathematical modeling of heat transfer between the plant seedling and the environment during a radiation frost. *Journal of Stress Physiology & Biochemistry* **6**(4), 2010, 108–125.

Gerber, J.F. & Harrison, D.S. 1964. Sprinkler irrigation for cold protection of Citrus. *Transactions of the ASAE*, pp. 464–468.

Hamer, P.J.C. 1986. The heat balance of apple buds and blossom. Part III. The water requirements for evaporative cooling by overhead sprinkler irrigation. *Agricultural and Forest Meteorology* **37**, 175–188.

Heinemann, P.H., Morrow, C.T., Martsolf, J.D. & Crassweller, R.M. 1992. A decision support program for design and management of frost protection systems. In: Watson, D.G., Zazueta, F.S. & Bottcher A.B. (ed.). Computers in Agricultural Extension Programs. *Proc. Of 4th International Conf.*, 28–31 Jan., Orlando, Fla., ASAE Publ. 1–92, pp. 135–140.

Heinemann, P.H. & Morrow, C.T. 1986. An Artificial Apple Bud for Frost Temperature Sensing. *Transactions of the ASAE* **29**(5), 1338–1341.

Hollender, C.A., Geretz, A.C., Slovin, J.P. & Liu, Z.C. 2012. Flower and early frukt development in a diplomid strawberry, Fragaria vesca. PLANTA. Volume **235**(6), 1123–1139.

Issa, R.J. 2012. Numerical Heat Transfer Model for Frost Protection of Citrus Fruits by Water from a Spraying System. *Thermal Science*, **16**(1), 31–42.

Martsolf, J.D. 2000. Diversity of frost protection methodology. *Proc. Fla. State hort. Soc.*, **113**, 133–137.

Martsolf, J.D. 1992a. Cold Protection Mechanisms. Proc. Fla. State hort. Soc., **105**, 91–94.

Martsolf, J.D. 1992b. Energy Requirements for Frost Protection of Horticultural Crops. Chapter 15. Pp. 221–241. In: Fluck, R.C. (ed.). *Energy in Farm Production* **6**, 219–239.

Maughan, T.L., Black, B.L. & Drost, D. 2015. Critical temperature for sub-lethal cold injury of strawberry leaves. *Scientia Horticulturae* **183**, 8–12.

Pearce, R.S. 2001. Plant freezing and damage. *Annals of Botany* **87**, 417–424.

Perry, K.B. 1998. Basics of frost and freeze protection for horticultural crops. *HortTecnology*, January-March 1998, **8**, 10–15.

Perry, K.B. 1986. FROSTPRO, a model of overhead irrigation rates for frost/freeze protection of apple orchards. *HortScience* **21**(4), 1060–1061.

Warmund, M.R. & English, J.T. 1998. Ice Nucleation, Freezing Injury, and Colonization of ‘Totem’ Strawberry Flowers with Ice-nucleation-active (INA) Bacteria. J. Amer. *Soc. Hort. Sci.*, **123**(2), 234–238.