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# THEORETICAL MODELING OF TEMPERATURE PULSATIONS IN PLANT LEAF WHICH ARE CAUSED BY LEAF SWING WITH RESPECT TO THE SUN

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**Abstract.** The plant leaf temperature is a result of biological processes occurring in an organ of the plant and its energy exchange with the environment. The plant leaf temperature always differs from the ambient temperature except for the moments of transition from a positive to a negative (or vice versa) temperature gradient. It is determined that the plant leaf temperature continuously changes during the sunny time of the day. Temperature pulsations emerge in plant tissues when the leaf naturally changes its position with respect to the Sun (e.g. impacted by the wind) during the sunny period of the day. When a leaf position changes with respect to the source of radiation, a temperature change in the plant leaf also depends on local plant leaf thickness $\delta$, leaf position angle $\beta$, leaf oscillation frequency $f$ and a temperature difference between the leaf surface and the atmosphere. When changing its position with respect to the Sun during the sunny period of the day the plant leaf plate becomes a temperature mosaic. Changing the leaf tillt angle from 30° to 60° depending on leaf thickness $\delta$, it is estimated by mathematical modeling that during 6 s the temperature change in the plant leaf reaches 0,03–0,29 °C (when $\beta = 30°$) and 0,11–1,04 °C (when $\beta = 60°$) respectively. Temperature pulsations in the plant leaf entail local temperature gradients in the leaf plate as well as changes in the local balance of plant leaf energies. The anatomic framework of the plant leaf predetermines different local impulses of temperature changes in the plant leaf. The emerged temperature gradient generates heat fluxes in the plant leaf plate.

**Keywords:** plant leaf temperature, temperature pulsations, temperature gradient, energy balance.

## 1. Introduction

All biological processes occurring in the plant depend on the temperature of plant tissues and therefore the temperature of the plant and its environment gains special importance in theoretical and applied sciences of the environment and phytomedicine (Kerpauskas *et al.* 2006; Lafta 1995; Sirvydas *et al.* 2006a, b).

Processes in animate and inanimate nature are occurring under the influence of impulsive forces. Energy is required to maintain or create them. The Sun is the primary source of energy for vegetation supplying energy in a form of radiation energy, which predetermines the existence of the biosphere. Vegetation uses part of the absorbed radiation energy of the Sun to execute its vital functions by transforming it into chemical bonds – organic compounds. In a year, vegetation of the Earth assimilates around 640 bn tons of carbon dioxide and emits around 500 bn tons of free oxygen thus reducing environmental pollution (Baltrėnas *et al*. 2008; Gimbutytė, Venckus 2008) The plant transforms the remaining major portion (99–98%) of the absorbed solar energy into the simplest form of energy – heat. The plant uses energy, in a form of heat, for its vital processes as well as for the creation of the impulsive force and prolongation of biological processes in the plant's surroundings.

The thermal energy participates in many physiological processes of vegetation. The solar radiation energy transformed into heat in plants accounts for 96–98% of the total energy quantity participating in the plant energy exchange. It is regular that all energy forms used by the plant turn into the simplest form of energy, heat, in the final transformation.

Having converted into heat in plant leaves, the radiant energy from the Sun has to be released to the surrounding environment in the form of water vapour and heat or accumulated in plant tissues. Heat accumulation in plant tissues increases plant leaf temperature, which in turn changes the convective heat exchange of the plant organ with the environment. Due to a small mass and biologically limited maximal temperature of plant tissues, thin plant leaves (tissues) are not always able to use heat evolved in the plant leaf for the process of transpiration. Therefore, the radiant energy from the Sun, having tuned into thermal energy in the plant leaf, that is not expediently used in the plant is emitted to the surrounding environment as a metabolite. In the long run of its development the plant has accommodated to the natural conditions of a habitat to the maximum extent allowing use of all types of energy provided by the environment.

The maximum temperature of live plant tissues is limited. It's enough for plant tissues to be impetuously heated over a temperature of 58 °C as proteins coagulate in cells, cell membranes decompose and the heated tissues are exposed to the lethal termination (Stašauskaitė 1995; Ellwagner *et al.* 1973; Hege 1990; Levitt 1980).

The local temperature of the plant leaf depends on the local balance of plant leaf energies. The entire plant, like its every organ or part of the organ, contacts individually with the surrounding environment in terms of energy. Pariental layers of the plant's organs and surrounding as well as pulsations of the plant energy exchange processes show themselves and therefore individual organs of the plant or parts thereof experience different energy exchange with the environment, to say nothing of individual plants (Sirvydas *et al.* 2000; Kitaya *et al.* 2003). Consequently, the balance of energies in plant's every organ or part thereof may be different at the moment in question (depending on the intensity of the present energy factors). The influence of individual members of the plant energy balance is rather diverse (Sirvydas *et al.* 2000; Ilkun 1967). This is predetermined not only by biological processes within the plant (organ) but also by the plant's specific energy exchange with the environment of its habitat. When the wind is lowest, under natural environmental conditions plant leaves change their position with respect to the Sun. An oscillating plant leaf receives a variable amount of solar radiation energy, respectively. It is determined that the total quantity of radiant energy received during pulsations of the solar radiation energy is not dependent on the frequency of oscillation at the same interval of time (Sirvydas *et al.* 2009). Therefore, it is probable that at the time the plant leaf naturally changes its position with respect to the Sun the solar radiation energy pulsations should evoke local temperature pulsations in the plant leaf.

The aim of research is to determine pulsations of the plant leaf local temperature, which are caused by plant leaf oscillations with respect of the Sun.

## 2. The methods of research

The plant leaf local temperature is a result of biological processes occurring in the plant leaf and energy exchange with environment that is impacted by a number of factors. A theoretical analysis based on the method of balance of energies was employed to discuss temperature pulsations of the plant leaf during the sunny period of the day. According to the method of balance of energies, any moment of the plant's existence is subject to the equality between the energy received, accumulated and used for biological processes and transferred to the environment (in a form of heat and water vapour), i.e. $\sum Q = 0$ (Kerpauskas 2003; Čėsna *et al.* 2000; Herve *et al.* 2002; Ruseckas 2002; Incropera 2001).

When analysing the dependence of plant leaf temperature pulsations on a single factor, i.e. leaf oscillations with respect of the Sun, the processes of energy metabolism occurring in the plant leaf are schematised.

## 3. Results of investigation

The plant organ's temperature is a result of biological processes occurring in the plant's organ and its energy exchange with the environment. During the sunny period of the day the plant leaf's temperature is continuously changing. The temperature change dynamics in any organ of the plant is described by the energy balance of the plant organ or any part thereof at a given moment that is in a permanent dynamic equilibrium during the sunny period of the day. A change in the plant organ's temperature as an expression of the dynamic energy balance shows itself through the thermal accumulative process of the plant leaf, which in turn evokes changes in the convective heat exchange with the environment. The plant's temperature can be determined by solving the equation of the plant's energy balance:

$$\pm Q_1 \pm Q_2 \pm Q_3 \pm Q_4 \pm Q_5 = 0, \qquad (1)$$

where $Q_1$ – flux of the Sun's radiation energy absorbed by the plant, J/s; $Q_2$ – heat flux that is transferred to or received from the environment during the convective heat exchange, J/s; $Q_3$ – heat flux used for transpiration and transferred to the environment in a form of water vapour, J/s; $Q_4$ – heat flux for photochemical reactions in an energy form or other exothermal and endothermic processes occurring in the plant, J/s; $Q_5$ – heat flux participating in the process of plant tissue thermal accumulation, J/s.

Plant organ's temperature $t$ is covered by two members of the plant's energy balance, i.e. convective heat exchange with the environment of the plant's organ $Q_2$ and energy balance's member evaluating the thermal accumulation of the plant's organ $Q_5$. The plant energy balance equation allows us, through the employment of calculations, analyse the pulsations of the local plant leaf tissue temperature that is entailed by plant leaf oscillations with respect to the Sun (Sirvydas *et al.* 2009).

In the majority of cases temperature pulsations in plant leaf tissues occur due to a sharp change in the plant leaf's position with respect to the Sun. This is often predetermined by a chaotic motion of the air due to which plant leaves change their position with respect to the source of the radiation energy. It is obvious that when the plant leaf's position angle β changes from its initial position A to position B (Fig. 1), a smaller quantity of the

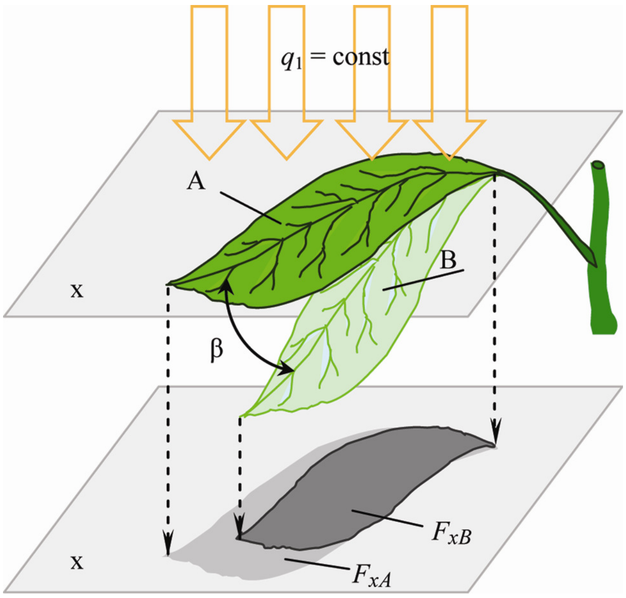


**Fig. 1.** Chart of a changing plant leaf position with respect to the Sun's radiation

radiation energy reaches the surface of the leaf. The decrease of this energy is directly dependent on size $x$ of the plant leaf surface area $F$ projection to the plane perpendicular to a ray fall direction.

With the aim of determining this decrease in the surface area projection, it is assumed that the density of the heat flux emitted by the radiation energy source $q_1 = const$ and the direction of a heat flux change is perpendicular to the plant leaf's plane. Upon a change of the plant leaf position by angle β (from position A to B), the projection of the plant would decrease by value $\Delta F_x$, i.e.:

$$\Delta F_x = F_{xA} - F_{xB} = F(1-\cos\beta) . \quad (2)$$

In case of such a decrease in the projection of the plant leaf surface area due to the change of the leaf position with respect to the radiation energy source, the quantity of heat that reaches the leaf surface when the leaf changes its position from A to B will decrease. Let's analyse a common case when not only the radiation energy flux quantity but also the heat quantity reaching the plant leaf is constant, i.e. $Q_1 = const$, and for a very short period of time $d\tau$, it is assumed that biological processes occurring within the plant leaf remain stable and therefore they use only a certain part of constant energy amount $Q_1$., i.e. $Q_4 = nQ_1$. Normally, the coefficient $n$ evaluating part of the absorbed radiation energy used for biological processes in the plant is in the range of 0.04–0.05 (Šlapakauskas 2006; Ількун 1967). In case of settled energy exchange of the plant $Q_5 = 0$, the remaining part of the absorbed radiation energy in the plant leaf would be used for transpiration and convective heat exchange. In this case the balance of energies equation would be as follows:

$$(1-n)Q_1 = Q_2 + Q_3 . \quad (3)$$

With the plant leaf position with respect to the Sun changing, the heat quantity that reaches the plant leaf will depend on the leaf position (Fig. 1). When the plant leaf area decreases by value $\Delta F_x$, which is reached by the radiation energy flux, the energy flux will decrease respectively by value $\Delta Q_1$ that will be expressed by the following dependence:

$$\Delta Q_1 = Q_{1A} - Q_{1B} = Q_1(1-\cos\beta) = q_1 F(1-\cos\beta) . \quad (4)$$

With a leaf position with respect to the radiation energy source changing temperature in the leaf also changes by a certain value. $\Delta t$. In this case the lack of energy is compensated by the heat accumulated in the plant leaf $Q_5$, i.e. $\Delta Q_1 = Q_5$. With the aim to determine a change in the plant leaf temperature, the following equation of the balance of energies is applied for the process in question:

$$Q_1(1-\cos\beta) = Q_5 . \quad (5)$$

When analysing a temperature variation in the plant leaf caused by the change of its position, certain temperature changes are observed. There exists a certain difference in the initial plant leaf and environmental temperatures $t_0 - t_{apl}$ in the case of the settled energy change of the plant that is described by Eq. (3). When the leaf position with respect to the source of radiation changes by angle β, there emerges additional temperature change $\Delta t$ within time interval $d\tau$ and difference in temperatures $t_0 - t_{apl}$ that was at the presence of the settled plant energy balance decreases by value $\Delta t$ and equals $t_0 - \Delta t - t_{apl}$. Temperature change $\Delta t$ is a value showing temperature pulsations during plant leaf oscillations with respect to the Sun.

To find temperature change $\Delta t$, member $Q_1$ of Eq. (5) is expressed from Eq. (3):

$$Q_1 = \frac{Q_2 + Q_3}{1-n} . \quad (6)$$

When the leaf changes its position with respect to the Sun, the convective heat exchange between the environment and two surfaces of the plant leaf is expressed by the following equation of the Newton-Richmann law:

$$Q_2 = \alpha F(t_0 - \Delta t - t_{apl}) + \alpha F(t_0 - t_{apl}), \quad (7)$$

where α – plant leaf's heat transfer coefficient in J/(s·cm$^2$·K); $F$ – plant leaf area in cm$^2$.

When the plant leaf position with respect to the source of radiation changes, member $Q_3$, of the balance of energies Eq. (6), describing the quantity of heat used for transpiration and transferred to the environment in a form of water vapour, remains constant within the elementary period $d\tau$ and is expressed by the following equation:

$$Q_3 = wrF , \quad (8)$$

where $w$ – transpiration intensity g/(cm$^2$·s); $r$ – evaporation heat J/g.

Heat quantity $Q_5$ accumulated in the leaf and compensating for the lack of energy when the plant leaf changes its position with respect to the radiation energy source is described by the following equation:

$$Q_5 = \rho c V \frac{d(\Delta t)}{d\tau} , \quad (9)$$

where ρ – plant leaf density in g/cm$^3$; $c$ – specific thermal capacity of the plant leaf in J/(g·K); $V$– plant leaf volume in cm$^3$; $\Delta t$ – temperature change in the plant leaf in °C; τ – time in s.

Considering the fact that with the plant leaf position changing the quantity of the radiation energy reaching the leaf surface changes by value $\Delta Q_1$, expressions (6)–(9) are entered into equation of the balance of energies (5). The following equation of the balance of energies is obtained:

$$\frac{(1-\cos\beta)}{1-n}\left(\alpha F(2t_0 - 2t_{apl} - \Delta t) + wrF\right) = \rho c V \frac{d(\Delta t)}{d\tau} . \quad (10)$$

The following solution of the balance of energies Eq. (10) was received during further analysis for the calculation of plant leaf temperature change $\Delta t$:

$$\Delta t = \left(2(t_0 - t_{apl}) + \frac{wr}{\alpha}\right)\left(1 - \exp\left(\frac{-\alpha S}{\rho c \delta} \cdot \tau\right)\right), \quad (11)$$

where $S$ – member $\frac{1-\cos\beta}{1-n}$ of Eq. (10).

Taking account of the fact that plant leaf volume $V = F\delta$, the final expression of the temperature change in the plant leaf is obtained from Eq. (11):

$$\Delta t = \left(2\left(t_0 - t_{apl}\right) + \frac{wr}{\alpha}\right) \times \left(1 - \exp\left(\frac{\alpha(\cos\beta - 1)}{(1-n)\rho c\delta} \cdot \tau\right)\right). \quad (12)$$

Momentary temperature pulsations in the plant leaf may be of two types depending on the duration of the leaf's being in a certain position with respect to the Sun. The first case is when the plant leaf changes its position from A (Fig. 1) to B and remains in this position for a certain time $\tau$. Under real conditions it is probable (assumed) that this time interval is from 3 to 6 s. In this case temperature change $\Delta t$ is calculated according to Eq. (12). The second case is typical of periodic oscillation of the plant leaf at certain amplitude between the positions A and B (Fig. 1). The actual oscillation of the plant leaf can be described by the sine function assuming that the plant leaf oscillates in a semicircle trajectory, i.e. the change of angle β is expressed by the following equation:

$$\beta = \beta_A \sin(\pi f \tau + \varphi_0), \quad (13)$$

where: $\beta_A$ – leaf oscillation amplitude, rad; $f$ – leaf oscillation frequency, $s^{-1}$; $\tau$ – time, s; $\varphi_0$ – the initial phase of oscillation (assumed in calculations $\varphi_0 = 0$), rad.

In the afore–mentioned case of plant leaf oscillation, temperature change $\Delta t$ will express temperature pulsations in the plant leaf and will be calculated by entering the correction of oscillation of angle β (13) into Eq. (12):

$$\Delta t = \left(2\left(t_0 - t_{apl}\right) + \frac{wr}{\alpha}\right) \times \left(1 - \exp\left(\frac{\alpha\left(\cos\left(\beta_A \sin\left(\pi f \tau + \varphi_0\right)\right) - 1\right)}{(1-n)\rho c\delta} \cdot \tau\right)\right). \quad (14)$$

As Eqs (12) and (14) show, both plant leaf temperature change $\Delta t$ at a certain time and temperature pulsations depend on a number of parameters: initial difference in temperatures of the leaf surface and the environment $\left(t_0 - t_{apl}\right)$, a decrease in the absorbed solar radiation energy that is predetermined by the amplitude and frequency of the plant leaf oscillation angle β, plant leaf thickness δ, as well as the plant's transpiration intensity, heat of evaporation, the heat transfer coefficient, the density and specific heat of leaf's tissues.

For the theoretical analysis of the change of plant leaf temperature depending on a leaf position with respect to the source of the radiation energy, the following values of parameters were assumed for calculations: heat transfer coefficient $\alpha = 0.00125$ J/(s·cm²·K); specific thermal capacity of the plant leaf c = 3.58 J/(g·K); density $\rho = 0.9$ g/cm³; coefficient evaluating part of the absorbed radiation energy used for biological processes, n = 0.05; transpiration intensity $w = 2.5 \cdot 10^{-5}$ g/(cm²·s); heat of evaporation $r = 2500$ J/g.

The analysis of the parameters that predetermine temperature changes in the plant leaf was started from the impact of initial difference of temperatures between the leaf surface and the environment $\left(t_0 - t_{apl}\right)$ on value $\Delta t$. Upon assuming that the difference of temperatures $\left(t_0 - t_{apl}\right)$ varies in the range of 0 °C to 5 °C, $\Delta t$ values were calculated according to expressions (12) and (14) when the plant leaf remains in the same position with respect to the Sun at angle β for a certain period of time and when the leaf is oscillating at amplitude $\beta_A$ at a certain frequency. A plant leaf thickness of 0.2 mm was assumed for the calculations. With a plant leaf thickness decreasing a change in temperature is increasing proportionally.

In the first case calculations were made with the plant leaf changing its position with respect to the radiation source at angle β of 10°, 20°, 30° and 60° and remaining in these positions from 1 to 6 s. In the second case the plant leaf oscillation amplitude $\beta_A$ reaches 30° and 60°, and oscillation frequency $f$ equals 0.5 $s^{-1}$; 1 $s^{-1}$ and 2 $s^{-1}$.

One of the examples of calculation results of the impact of initial temperature difference $\left(t_0 - t_{apl}\right)$ on the plant leaf temperature change $\Delta t$ is the presented case when the plant leaf is at an angle of 30° with respect to the Sun for a certain period of time (Fig. 2).

The results obtained of the impact of initial temperature difference $\left(t_0 - t_{apl}\right)$ on plant leaf temperature change $\Delta t$ in the case of leaf oscillation amplitude of $\beta_A = 30°$ are presented in Fig. 3.

In different calculations, linear dependences of leaf temperature change on the initial difference in temperatures between the leaf surface and the environment $\Delta t = f(t_0 - t_{apl})$ were obtained. This allows us making an assumption that there is a direct correlation between values $\Delta t$ and $\left(t_0 - t_{apl}\right)$ regardless of plant leaf thickness δ, position with respect to the radiation source (angle β or amplitude $\beta_A$), duration of being in a certain position $\tau$ or oscillation frequency $f$. With the aim of determining this correlation, the marginal condition when the difference in temperatures $\left(t_0 - t_{apl}\right)$ is equal to zero, i.e. $\Delta t$ does not depend on the mentioned difference.

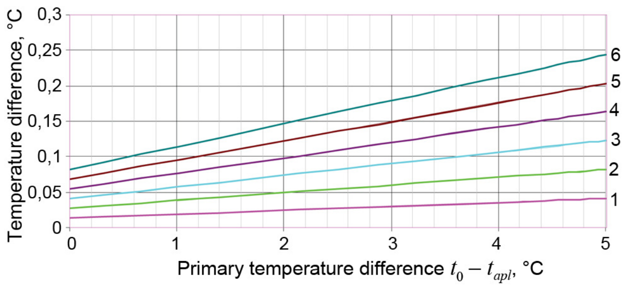


**Fig. 2.** The dependence of plant leaf temperature change $\Delta t$ on the initial difference in temperatures between the plant leaf surface and the environment when the plant leaf changes its position with respect to the radiation source at angle $\beta = 30°$. Plant leaf thickness is 0.2 mm. The duration of the changed leaf position with respect to the Sun: 1 – 1 s; 2 – 2 s; 3 – 3 s; 4 – 4 s; 5 – 5 s; 6 – 6 s

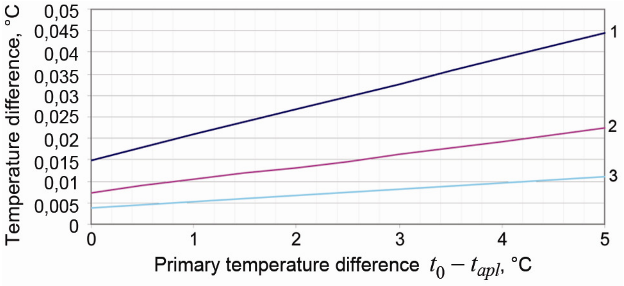


**Fig. 3.** The dependence of plant leaf temperature change $\Delta t$ on the initial difference in temperatures between the plant leaf and the surrounding environment when the plant leaf is oscillating with respect to the radiation source at amplitude $\beta_A = 30°$. Plant leaf thickness is 0.2 mm. Plant leaf oscillation frequency: 1 – 0.5 $s^{-1}$; 2 – 1 $s^{-1}$; 3 – 2 $s^{-1}$

In this case temperature difference $\Delta t$ is marked as $\Delta t_{rib}$ and according to expressions (12) and (14) is respectively equal to:

Value of temperature difference $\Delta t_{rib}$ is predetermined only by three variables: δ, β and τ (or *f*). Therefore, for the analysis of dependence $\Delta t = f(t_0 - t_{apl})$ it is assumed that $\Delta t_{rib}$ equals 100% and using this value the impact of temperate difference $t_0 - t_{apl}$ on $\Delta t$ value can be analysed.

$$\Delta t_{rib} = \frac{wr}{\alpha}\left(1 - \exp\left(\frac{\alpha(\cos\beta - 1)}{(1-n)\rho c\delta}\cdot\tau\right)\right), \quad (15)$$

$$\Delta t_{rib} = \frac{wr}{\alpha}\left(1 - \exp\left(\frac{\alpha(\cos(\beta_A \sin(\pi f\tau + \varphi_0)) - 1)}{(1-n)\rho c\delta}\cdot\tau\right)\right). \quad (16)$$

In order to make a comparison between $\Delta t$ change results depending on the difference in temperatures $t_0 - t_{apl}$ when the plant leaf is in different positions with respect to the radiation source for different periods of time or is oscillating, a percentage increase in $\Delta t$ when the difference $t_0 - t_{apl}$ changes by one degree each time was calculated in both cases addressed. The obtained result shows that an increase in the difference of temperatures between the plant leaf and the environment by one degree (1 °C) predetermines a 40% increase in plant leaf temperature change $\Delta t$ regardless of plant leaf thickness δ, leaf position angle β, duration of being in a certain position τ or oscillation frequency *f*. In summary of the obtained results, the following dependence of plant leaf temperature change $\Delta t$ on the initial difference in temperatures between the leaf surface and the environment $t_0 - t_{apl}$ can be written down:

$$\Delta t = \Delta t_{rib}\left(1 + 0{,}4(t_0 - t_{apl})\right). \quad (17)$$

As mentioned above, the change of plant leaf temperature with plant leaf position with respect to the radiation source changing also depends on plant leaf thickness δ, leaf position angle β, duration of being in a certain position τ or oscillation frequency *f*, but expression (17) points to a considerable impact that the difference in temperatures between the leaf surface and the environment $t_0 - t_{apl}$ has on value $\Delta t$.

Another important parameter of the plant leaf is its thickness δ. The leaf thickness is different at different growth periods. Young leaves of European beech (*Fagus sylvatica*) may be 0.117 mm thick, whereas the thickness of mature leaves reach 0.210 mm (Šlapakauskas 2006). Depending of a plant type and leaf structure, there may be cases when leaf thickness *δ* equals 1 mm. With plant leaf position with respect to the radiation source changing, the change in leaf temperature also depends on leaf thickness *δ* (see expressions (12) and (14)). Considering leaf thicknesses during different growth phases, different leaf thicknesses, i.e. 0.1 mm to 1 mm, were assumed for the calculations of leaf temperature changes. Changes in plant leaf temperature were calculated in the two cases addressed.

In the first case, expression (12) was used in the calculations when the plant leaf changes its position with respect to the Sun and remains in this position for a certain period of time. A typical calculation example of the change of plant leaf temperature is the calculation of temperature change $\Delta t$ value when the angle of plant leaf position with respect to the radiation source β is *30° and 60°* which remain for a maximum of 6 seconds (Fig. 4).

As Fig. 4 shows, when angle β is *30°* or *60°*, depending on leaf thickness, significant differences in temperature change are recorded at the same angle β. When leaf thickness δ is from 0.1 to 1 mm a temperature change within 6 s reaches 0.03–0.29 °C (when β = *30°*) and 0.11–1.04 °C (when β = 60°*)*, respectively. The biggest leaf temperature change is when leaf thickness is the smallest. However, a non-linear dependence of a temperature change on a leaf thickness is observed.

In order to analyse and generalise this dependence it is assumed that a temperature change of 0.1 mm thick leaf corresponds to 100%. With leaf thickness increasing a temperature change is respectively decreasing: a temperature change in a leaf of 0.2 mm thickness is nearly 50%, in 0.3 mm – 66%, 0.5 mm – 80%, whereas in 1 mm – 89% smaller than in a 0.1 mm thick leaf. Mathematically, a percentage decrease in temperature change with plant leaf thickness increasing can be expressed as the following dependence:

$$\Delta t_{\%} = 10.324\delta^{-0.9884}, \quad (18)$$

where $\Delta t_{\%}$ – decrease in temperature change, %; δ – plant leaf thickness, mm.

Graphic (18) expression of this dependence is presented in Fig. 5.

The analysis of the second case that is typical of plant leaf's periodic oscillation at certain amplitude between position A and B (Fig. 1) shows that temperature pulsations are analogous to periodic pulsations of the solar radiation energy in the plant leaf. When plant leaf oscillation is described by the sine function and the leaf oscillates in a semicircle trajectory, the calculation results of the dependencies of temperature change in the plant leaf on leaf thickness according to Eq. (14) are given in Figs 6 and 7. The calculations were made when plant leaf oscillation amplitude $\beta_A$ reaches 30° and 60°, and

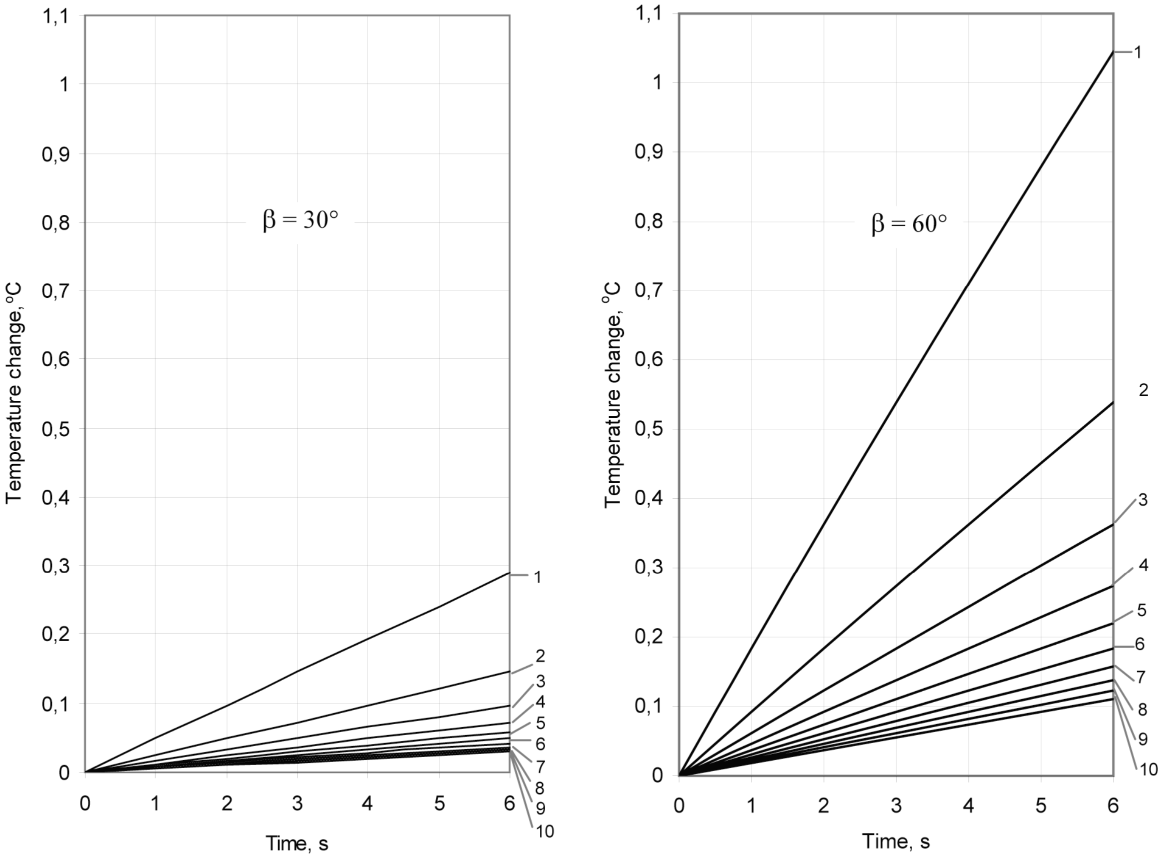


**Fig. 4.** The dependence of plant leaf temperature change $\Delta t$ on time, when β = 30° and β = 60°, and plant leaf thicknesses of: 1 – 0.1 mm; 2 – 0.2 mm; 3 – 0.3 mm; 4 – 0.4 mm; 5 – 0.5 mm; 6 – 0.6 mm; 7 – 0.7 mm; 8 – 0.8 mm; 9 – 0.9 mm; 10 – 1 mm

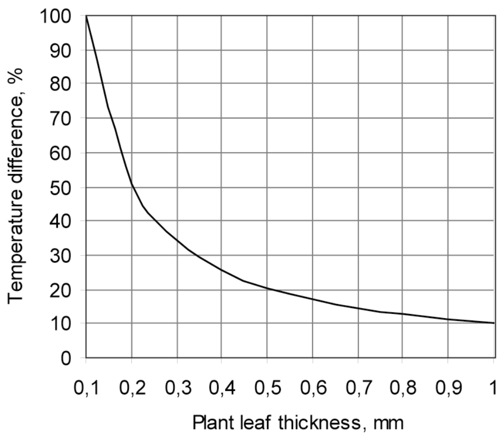


**Fig. 5.** The dependence of temperature change on plant leaf thickness in percent

oscillation frequency $f$ is 0.5 $s^{-1}$; 1 $s^{-1}$ and 2 $s^{-1}$. The initial assumed difference of temperature between the plant leaf surface and the environment is 2 °C. Depending on leaf oscillation frequency when leaf oscillation amplitude $\beta_A = 30°$ *(*Fig. 6) and $\beta_A = 60°$ *(*Fig. 7) temperature pulsations of similar duration are obtained; however, in case of a bigger amplitude of leaf oscillation bigger temperature changes are recorded in the leaf. When the plant leaf oscillates at a frequency $f = 0.5$ $s^{-1}$, a temperature change in the plant leaf 0.1 mm thick reaches up to 0.053 °C, when $\beta_A = 30°$ *(*Fig. 6a) and up to 0.2 °C when $\beta_A = 60°$ (Fig. 7a). It is typical that lower temperature pulsations are obtained when plant leaf thickness is bigger. When oscillation frequency is 0.5 $s^{-1}$, 10 times lower temperature changes are recorded in the plant leaf of 1 mm thickness compared to the plant leaf of 0.1 mm thickness, i.e. they reach up to 0.0053 °C, when $\beta_A = 30°$ *(*Fig. 6b) and up to 0.02 °C, when $\beta_A = 60°$ *(*Fig. 7b).

The data given in Figs 6 and 7 show that the pulsations of the Sun's radiation energy with plant leaf naturally changing its position with respect to the Sun during the sunny period of the day also evoke local temperature pulsations in the plant leaf.

The data given in Fig. 8 show that the maximal local temperature reached in the plant leaf plate at the time of temperature impulse depends on a local thickness of the plant leaf when other conditions are the same. Venation of the plants in medium-wet habitats (mesophites) and the anatomic framework of the leaf evoke a local change in the thickness of their transverse section. Taking account of this it is obtained a local change in the plant leaf thickness predetermines local temperature pulsations in the leaf. Therefore, when changing its position with respect to the Sun during the sunny period of the day under natural environment the plant leaf plate becomes a temperature mosaic. Data on the values of local temperature pulsations in the plant leaf plate are given in Figs 6, 7 and 8.

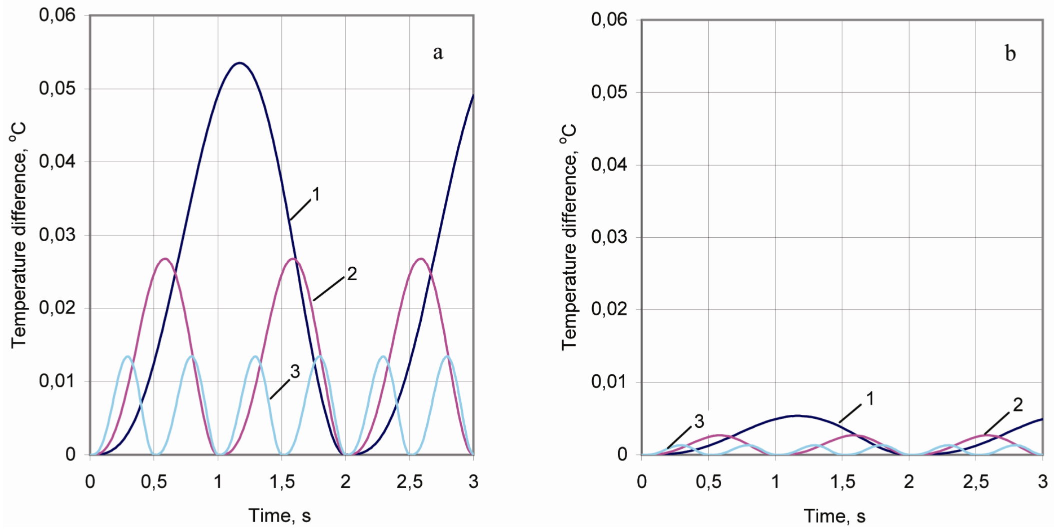


**Fig. 6.** The dependence of temperature pulsations in plant leaf plates of different thickness on the frequency of plant leaf oscillation when leaf oscillation amplitude $\beta_A = 30°$ in a – leaf plate part whose thickness is 0.1 mm; in b – leaf plate part whose thickness is 1 mm; plant leaf oscillation frequency: curve 1 – 0.5 $s^{-1}$; curve 2 – 1 $s^{-1}$; curve 3 – 2 $s^{-1}$

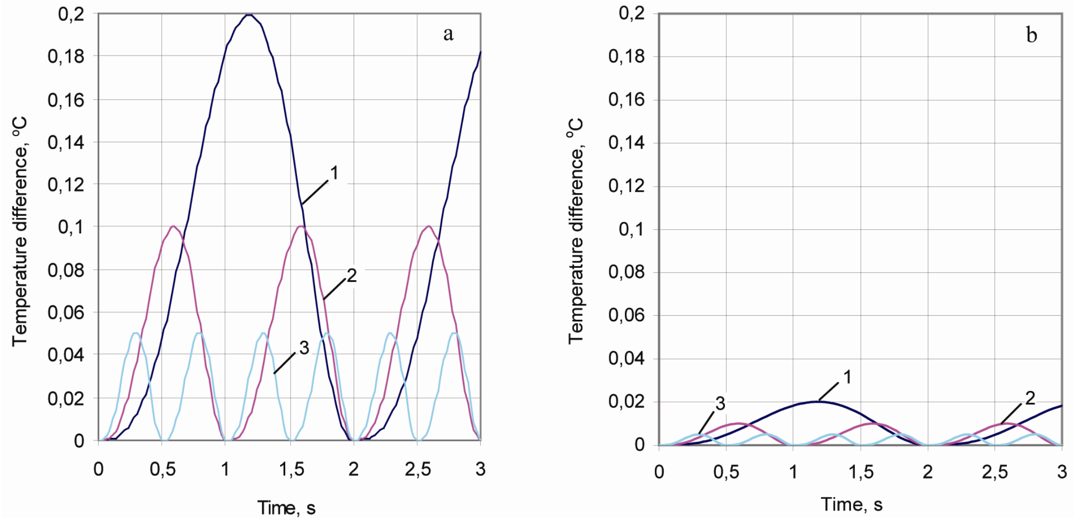


**Fig. 7.** The dependence of temperature pulsations in plant leaf plates of different thickness on the frequency of plant leaf oscillation when leaf oscillation amplitude $\beta_A = 60°$ in a – leaf plate part whose thickness is 0.1 mm; in b – leaf plate part whose thickness is 1mm; plant leaf oscillation frequency: curve 1 – 0.5 $s^{-1}$; curve 2 – 1 $s^{-1}$; curve 3 – 2 $s^{-1}$.

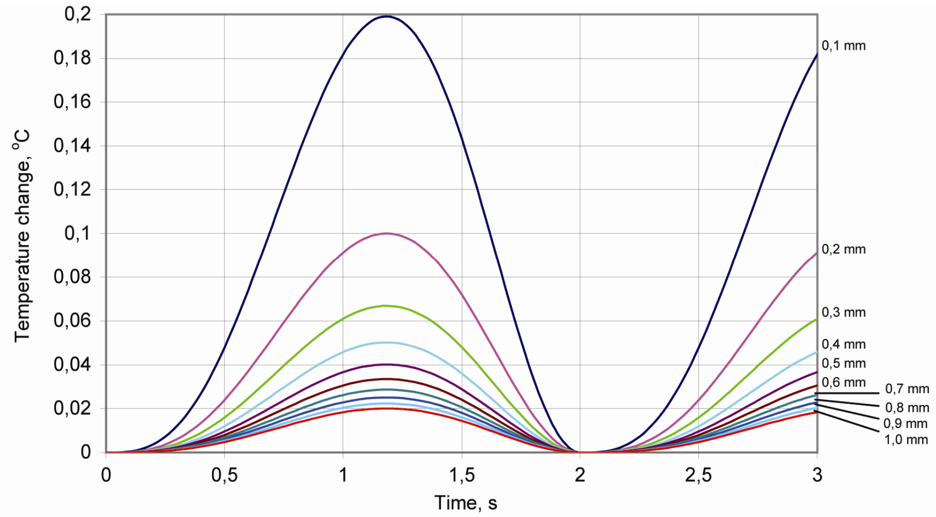


**Fig. 8.** Local temperature pulsations in the plant leaf depending on leaf plate thickness when plant leaf oscillation frequency is 0.5 $s^{-1}$ and amplitude $\beta_A = 60°$

The plant leaf venation and anatomic framework predetermine change in plant leaf thickness. As the data given above show, during the sunny period of the day the plant leaf plate is a pulsating temperature mosaic when it changes its position with respect to the Sun, which is changing depending on the thickness of the leaf transverse section (mass of leaf area unit). Therefore, different thicknesses of the plant leaf plate (e.g. $\delta_1$ and $\delta_2$) different temperature changes, $\Delta t_1$ and $\Delta t_2$, caused by the pulsations of the Sun's radiation energy form within the entire surface of the plant leaf. Uneven temperature changes in the plant leaf predetermine heat fluxes in the plant leaf tissues that are described by temperature gradient (*gradt*). On the basis of the assumption that $\Delta t_2 > \Delta t_1$ and expression (12), temperature difference $\Delta t_\delta$ between plant leaf segments of different thickness $\delta_1$ and $\delta_2$ may be expressed as follows:

$$\Delta t_\delta = \Delta t_2 - \Delta t_1 = \left(2\left(t_0 - t_{apl}\right) + \frac{wr}{\alpha}\right) \times \left(\exp\left(\frac{\alpha(\cos\beta - 1)}{(1-n)\rho c\delta_1}\cdot\tau\right) - \exp\left(\frac{\alpha(\cos\beta - 1)}{(1-n)\rho c\delta_2}\cdot\tau\right)\right). \quad (19)$$

Thus, a conclusion can be made that depending on the change of the plant leaf plate thickness an analogous temperature mosaic of the plant leaf tissues is obtained. The Pulsations of the Sun's radiation energy in the plant leaf plate tissues evoke local temperature pulsations which generate heat fluxes in the plant leaf plate that are impacted by temperature gradient *gradt.* The heat flux direction in plant leaf tissues is in the direction of temperature equilibration.

## 4. Conclusions

1. According to the calculating data the plant leaf plate becomes a temperature mosaic when changing its position with respect to the Sun during the sunny period of the day.
2. Temperature pulsations emerge in plant tissues when the leaf naturally changes its position with respect to the Sun (e.g. impacted by the wind) during the sunny period of the day.
3. When a leaf position changes with respect to the source of radiation, a temperature change in the plant leaf also depends on local plant leaf thickness $\delta$, leaf position angle $\beta$, leaf oscillation frequency $f$ and a temperature difference between the leaf surface and the atmosphere.
4. Temperature pulsations in the plant leaf entail local temperature gradients in the leaf plate as well as changes in the local balance of plant leaf energies.
5. The anatomic framework of the plant leaf predetermines different local impulses of temperature changes in the plant leaf. The emerged temperature gradient generates heat fluxes in the plant leaf plate.

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**LOKALIŲ AUGALO TEMPERATŪROS PULSACIJŲ, KURIAS SUKELIA LAPO SVYRAVIMAI SAULĖS ATŽVILGIU, TEORINIS MODELIAVIMAS**

**A. P. Sirvydas, V. Kučinskas, P. Kerpauskas, J. Nadzeikienė**

Santrauka

Augalo organo temperatūra yra augalo organe vykstančių biologinių procesų ir jo energinės apykaitos su aplinka rezultatas. Augalo lapo temperatūra, išskyrus perėjimo momentus iš teigiamo į neigiamą (arba atvirkščiai) temperatūros gradientą, visuomet skiriasi nuo aplinkos temperatūros. Nustatyta, kad saulėtu paros metu augalo lapo temperatūra nuolat kinta. Saulėtu paros metu natūraliai keičiantis augalo lapo padėčiai Saulės atžvilgiu (pvz., dėl vėjo poveikio) lapo audiniuose kyla temperatūros pulsacijos. Temperatūros pokytis augalo lape, kintant lapo padėčiai spinduliavimo šaltinio atžvilgiu, priklauso ir nuo lokalaus augalo lapo storio δ, lapo padėties kampo β, lapo svyravimo dažnio *f* ir temperatūrų skirtumo tarp lapo paviršiaus ir aplinkos. Augalo lapo plokštelė, saulėtu paros metu keisdama padėtį Saulės atžvilgiu, tampa temperatūrine mozaika. Kintant lapo posvyrio kampui nuo 30° iki 60°, matematiškai modeliuojant nustatyta, per 6 s temperatūros pokytis augalo lape priklausomai nuo lapo storio δ (0,11 mm) atitinkamai siekia 0,03–0,29 °C (kai β = 30°) ir 0,11–1,04 C (kai β = 60°). Dėl temperatūros pulsacijų augalo lape susidaro lokalieji temperatūros gradientai lapo plokštelėje, atsiranda pokyčių lokaliame augalo lapo energijų balanse. Dėl augalo lapo anatominės sandaros augalo lape susidaro lokalūs temperatūros pokyčio impulsai. Temperatūros gradientas augalo lapo plokštelėje sukuria šilumos srautus.

**Reikšminiai žodžiai:** augalo lapo temperatūra, temperatūros pulsacijos, temperatūros gradientas, energijų balansas.

**ТЕОРЕТИЧЕСКОЕ МОДЕЛИРОВАНИЕ ЛОКАЛЬНЫХ ПУЛЬСАЦИЙ ТЕМПЕРАТУРЫ, ВЫЗЫВАЕМЫХ КОЛЕБАНИЕМ ЛИСТА РАСТЕНИЯ ОТНОСИТЕЛЬНО СОЛНЦА**

**А. П. Сирвидас, В. Кучинскас, П. Керпаускас, Ю. Надзейкене**

Резюме

Температура органа растения является результатом биологических процессов в нем и его энергетического обмена с окружающей средой. Температура листа растения, за исключением моментов перехода от положительного к отрицательному (или наоборот) градиенту температуры, всегда отличается от температуры окружающей среды. Установлено, что в солнечные часы дня при натуральном изменении положения листа по отношению к Солнцу температура листа постоянно меняется. В солнечные часы дня при натуральном изменении положения листа относительно Солнца (например, под влиянием ветра) в тканях листа возникают температурные пульсации. Температурные изменения в листе растения зависят от локальной толщины листа δ, угла положения листа β, частоты колебаний листа *f* и разницы между температурой листа и окружающей среды. В солнечные часы дня пластинка листа растения под влиянием ветра меняет положение относительно Солнца и становится пульсирующей температурной мозаикой. Математическим моделированием установлено, что изменение угла положения листа β от 30° до 60° в зависимости от толщины листа δ (0,1–1 мм) в течение 6 с вызывает температурные изменения соответственно 0,03–0,29 °C (при β = 30°) и 0,11–1,04 °C (при β = 60°). Пульсации температуры в листе растения вызывают локальные градиенты температуры, а также изменения в локальном энергетическом балансе листа растения. Анатомическая структура листа растения является причиной, вызывающей локальные изменения температуры, что создает тепловые потоки в пластинке листа растения под влиянием температурного градиента.

**Ключевые слова:** температура листа растения, температурные пульсации, температурный градиент, энергетический баланс.

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