SOLAR ENERGY CONVERSION IN PLANT LEAF STOMATA AS LEAF TEMPERATURE CHANGES

T. Ūksas, R. Čingienė, V. Kučinskas, A. Sirvydas

Aleksandras Stulginskis University, Lithuania

Abstract

The Sun provides energy to the Earth in the form of rays which is used by plants for biomass development. Biomass developed by plants can only release such amount of energy which matches the amount of solar radiation energy absorbed by plants in the biomass production process. The process of CO_2 assimilation involves complex biological and physical processes of energy exchange. The article presents information on how the plant uses changing thermal factors and processes in the habitat for intensifying the assimilation process. It analyses the processes of plant energy exchange stimulating the consumption of environmental carbon dioxide and at the same time the increase of biomass and the reduction of environmental air pollution. It has been found that in sunshine a thermal stomata engine (the biological prototype of heat engine) works in a plant leaf and generates mechanical energy at the expense of heat. The article presents the thermodynamic processes and cycle of the plant leaf stomata engine. Mechanical energy developed in a plant leaf is used to intensify the process of assimilation by activating leaf energy and gas exchange with the environment.

Key words: plant energy exchange, thermal processes, plant leaf temperature.

INTRODUCTION

The Sun provides energy to the Earth in the form of rays. Theoretically, the utilisation rate of the solar energy absorbed by plants for the production of organic matter could represent around 20 to 25 % (ŠLAPAKAUSKAS, 2006; IЉKYH, 1967). In practice, only around 2 % of the absorbed solar energy is used for photosynthesis. Visible light absorbed by plants accounts for 80 to 85 %, light reflected by them – 10 % and light conducted through leaves – 5 to 10 % (FITTER, HAY, 2002; ŠLAPAKAUSKAS ET AL., 2008). The share of the absorbed solar energy representing 96 to 98 % in the plant leaf is converted into energy in the form of heat. Due to a small mass and biologically limited maximum temperature (58 °C) STAŠAUSKAITĖ (1995) and LEVITT (1980) of their tissues thin plant leaves are not able to accumulate released heat. Therefore, the solar energy transformed into heat in plant leaves has to be released, in the form of heat and water vapour, to the environment as a metabolite. Heat released to the environment from energy exchange between the plant and the environment is of little value (low temperature) and non-concentrated and is, therefore, not used for further transformation in technological-energy processes. Plant energy exchange together with the process of assimilation form an important nature's generative and regenerative system by creating conditions for the existence of life on Earth (MARTIN AND HENRICHS, 2010).

In the course of its development the plant has adapted, to the maximum extent, to the natural conditions of its habitat. By their anatomic structure plant organs of different biological purpose have accommodated as far as possible to the biological and environmental physical factors inside them making it possible to use all available driving forces for the plant's vital function. The plant uses wind and gravitational forces which are created around it by temperature, humidity and gas concentration gradients. Heat conversion processes take place in plant leaf stomata transforming the thermal energy of low potential into mechanical energy. The mechanical energy generated in a plant leaf is used as a driving force to prevent friction caused by leaf gas exchange with the environment and intensify the processes of exchange, necessary for the process of assimilation in daylight (SIRVYDAS ET AL., 2011).

An analysis of thermal processes taking place in the conversion of the solar energy into mechanical one in a plant leaf at changing plant leaf temperature is presented here.

MATERIALS AND METHODS

The work employed the method of the balance of energies in a plant. The temperature of a plant growing in natural environmental conditions was measured by thermocouple temperature sensors made of Cu-

CuNi (copper-constantan) wires, 0.05 mm in diameter. To maintain the same resistance of the sensors, only wires of equal length were used. The measurements were recorded with an instrument ALMEMO 2590-9 having a microprocessor data processing and accumulation system. Temperatures were recorded by necessity taking a maximum of 100 measurements per second. This enabled us to observe short-term dynamic processes of temperature changes. Temperature sensors for all temperature measurements were used in observance of the requirements to be met by temperature measurements (in respect of the plant and its environment) (Сирвидас and Юшка, 1973; Sirvydas et al., 2006).

Research object – thermal-thermodynamic processes taking place in a plant leaf during the process of CO_2 assimilation. The physical processes of metabolism and energy exchange occurring in the plant are directly related with the plant's vital processes. To maintain the plant's vital processes, the physical processes responsible for the plant's energy-mass exchange must satisfy assimilation needs in daylight and bio-energy needs during hours of darkness. Processes taking place in the plant leaf ↔ environment exchange system can only be analysed after the structure of a plant leaf and the processes (physical and biological) occurring inside it have been examined. While carrying out the analysis of literature it has become observed that physical processes taking place in the plant leaf have been insufficiently examined (Šlapakauskas and Duchovskis, 2008; Nobel, 2001; New AP Biology Curriculum Units, 2013).

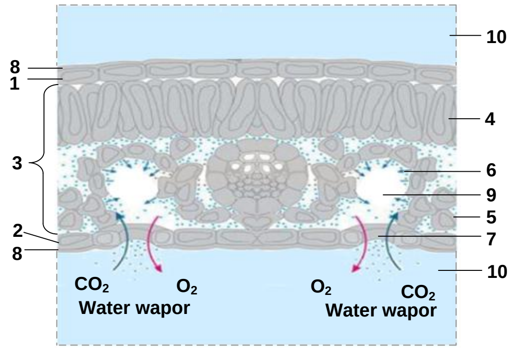

Fig. 1. – Chart of plant leaf anatomic structure and gas exchange (CO_2, O_2, H_2O vapour) with the environment. 1 – upper epidermis, 2 – lower epidermis, 3 – mesophyll, 4 – palisade tissue, 5 – spongy tissue, 6 – system of gas channels, 7 – stoma opening, 8 – cuticle 9 – gaseous environment in the spongy tissue of a leaf, 10 – ambient air surrounding the leaf

While analysing the structure of a plant leaf section we have noticed that the upper and lower surfaces are covered by upper epidermis 1 and lower 2 epidermis, respectively (Fig. 1). The thickness of leaves exposed to bright light and exposed to shadow differs (e.g. the leaves of beach (*Fagus sylvatica*) are 210–90 µm thick. The primary leaf tissue between epidermis laminae is mesophyll 3 which is responsible for the process of assimilation. The mesophyll consists of two layers – palisade tissue 4 and spongy tissue 5. The palisade tissue (palisade parenchyma) is a tissue best adapted for photosynthesis. More than 80 % of chloroplasts in a leaf (conducting the process of assimilation) occur in the palisade tissue, in the upper layer of mesophyll (Dagys et al., 1974)The thickness of this layer accounts for a mere 30 % of the leave thickness.

Large intercellular spaces form among the cells of spongy parenchyma making a gas exchange system of stomata 7 and mini-, macro- and nano-channels 6. The intercellular spaces occupy a large surface area of mesophyll cells by which they come into direct contact with air circulating in the gas exchange system. That surface is called the internal surface of a leaf. The leaf external to internal surface ratio in the plants of different ecological groups is not the same. It is known that the internal leaf surface of plants exposed to shadow (heliophobic plants) is by 6.8 – 9 times, that of mesophytes by 11.0-20.0 times, and that of leaves exposed to bright light is by 17.2 to 31.3 times larger than their external surface. Hence, having a big surface of contact with air mesophyll cells can absorb carbon dioxide from it. Since on both sides a leaf is covered by the epidermis with the cuticle which nearly does not allow water vapour and gas to pass through, air and carbon dioxide enter the leaf through stomata (Šlapakauskas and Duchovskis, 2008; Nobel, 2001; Dagys et al., 1974).

A leaf area unit contains a large number of stomata: from 23 to 400 in 1 mm^2. They are very small. In leaves of different plants the area of stoma opening varies between 0.17 and 239 µm^2, and the total area of their openings accounts for 0.52-5.28 % of the leaf surface. Nevertheless, about 90 to 95 % of CO_2 gets into a leaf through stomata and hardly 5 to 10 % spread through the epidermis or cuticle (Šlapakauskas and Duchovskis, 2008; Nobel, 2001; Dagys et al., 1974). The literature analysing the anatomic structure of the spongy mesophyll of a plant leaf presents very different charts of water vapour movement and carbon dioxide entry into a plant leaf through stomata (Šlapakauskas and

Duchovskis, 2008; Keith, 2000; New AP Biology Curriculum Units, 2013). It is clear, however, that together with ambient air CO_2 enters the spongy tissue of a leaf through open plant leaf stomata, and plant metabolites (O_2 and water vapour) are released to the environment through them. Many charts show that each stoma is responsible for its own system of gas exchange. In our opinion, the most precise and comprehensive system of leaf gas exchange related to the anatomic structure of a leaf is presented in Fig. 2.

The anatomic structure of a plant leaf with mini-, macro- and nano-channels and physiological processes occurring therein is relevant to all fields of live nature and technological sciences (Šlapakauskas and Duchovskis, 2008; Sirvydas et al., 2011; Sajith et al., 2011). Recently, little attention has been devoted to the examination of thermal-thermodynamic processes taking place in plant leaf channels-cavities and the opportunity to transform their heat into mechanical energy (Sirvydas et al., 2011; Sirvydas et al., 2013). A CO_2 gas mass from the ambient air is moving in the direction of a plant leaf surface in the air layer surrounding the leaf. Heat, H_2O vapour and O_2 also move in the same surface air layer of a plant leaf, in the opposite direction though. Hence, two very complex flows of opposite directions simultaneously form on the plant leaf surface.

RESULTS AND DISCUSSION

Experimental investigations show that air temperature around plants in sunshine is changing (Fig. 2).We observed fluctuations in plant leaf temperature (Fig. 3)and temperature difference (Fig. 4) in natural environmental conditions in sunshine. We have found that temperature changes in a plant leaf and ambient air depend on a number of energy exchange and environmental processes which are described in publications (Sirvydas et al., 2010; Sirvydas et al., 2011).

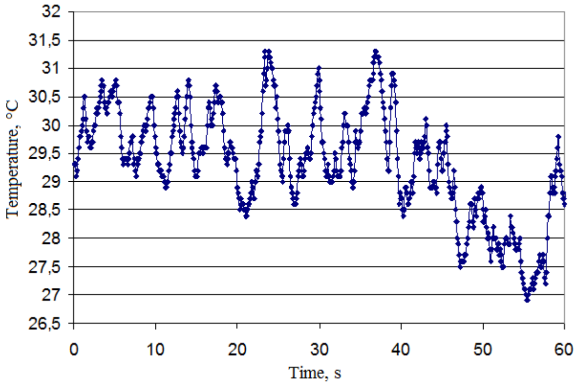

Fig. 2. – Fluctuations in air temperature around a plant in natural environmental conditions in sunshine. Wind speed v $_{vid}$ = 1.1 m/s.

Biological processes taking place inside a plant leaf depend on plant tissue temperature. As the data of investigation show, the temperature of the plant leaf and of the air around it is continually changing during the sunny period of the day. During a long period of its development the plant has accommodated as far as possible to environmental factors using them for its vital functions. It is advisable to analyse the impact of change in plant leaf and ambient temperature (as a thermal factor) on the process of assimilation which is responsible for the existence of life on Earth.

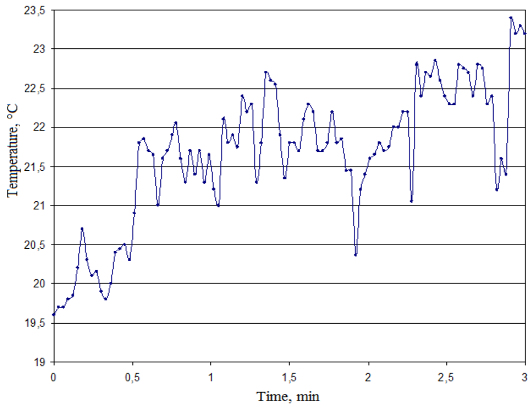

Fig. 3. – Fluctuations in air temperature around a plant in natural environmental conditions in sunshine. Wind speed $v_{vid.}$ = 5.3 m/s.

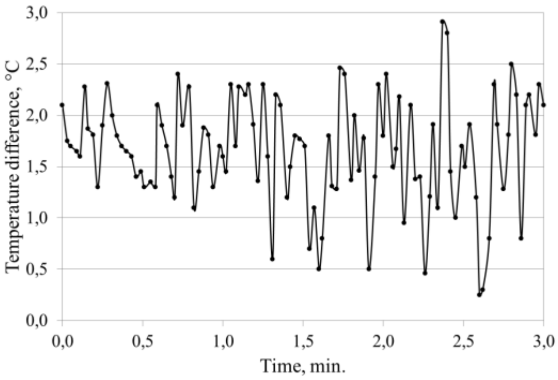

Fig. 4. – Change in the difference of temperature between a plant leaf and the environment in natural environmental conditions in sunshine

All biological and energy transformation processes occurring in a plant leaf depend on the local temperature of a plant leaf. The local temperature of a plant leaf is the result of the local balance of energies in the plant leaf. In general, during the sunny period of the day as leaf exposure with regard to the Sun changes, the plant leaf receives pulsating radiation energy flow Q_{rad} (SIRVYDAS ET AL., 2010). Due to the vertical and horizontal movement of airflows of changing temperature the plant leaf is affected by pulsating convective heat flowQ_{convec}. Pulsating heat flows Q_{rad} and Q_{convec}. will cause the pulsations of accumulated heat flow Q_{accum}. in a plant leaf. In this case of plant leaf energy exchange we can use the following equation for the balance of energies in a plant leaf:

$$\pm Q_{acum} \pm Q_{rad} \pm Q_{convec} = 0 \qquad (1)$$

The pulsating process of heat accumulation will cause temperature pulsations in plant tissues by value Δt. The pulsating temperature of plant leaf tissues in gas cavities (mini-, macro- and nano-cavities, channels) will generate respective thermodynamic processes. The thermodynamic processes in plant leaf cavities may participate in the transformation of heat into mechanical energy if the following conditions of the second law of thermodynamics are satisfied:

1. The process of heat conversion into mechanical work requires processes of periodically changing nature. This condition has been satisfied as plant leaf temperature is changing in sunshine. The temperature of the plant leaf and air around it is continually changing in sunshine (SIRVYDAS ET AL., 2011).
2. Heat sources of different temperatures have to participate in the process of heat conversion into mechanical energy. During the sunny period of the day this condition is satisfied. The solar radiation energy absorbed by plant leaves and the ambient air surrounding them are two heat sources of different temperature participating in energy exchange in plant leaves.

While analysing processes in plant leaf cavities we can see that when plant leaf temperature drops, the process of heat release to the environment takes place. During this process gas volume in leaf cavities decreases. This leads to the forced intake of ambient air into the gas cavities of a leaf. When plant leaf temperature rises, the process of heat supply to a leaf takes place. During this process temperature and pressure in the gas cavities of a plant leaf increase. The process of gas expansion takes place. Part of gas present in the cavities of a plant leaf is released to the environment through leaf stomata. As changes in plant leaf temperature repeat, processes recur and the cycle begins all over again. That means that a biological prototype of the thermal engine exists in a plant leaf which creates, for the account of heat, mechanical energy for gas movement through stomata and for the destruction of parietal layers (of heat and mass exchange) on a leaf surface. It works in sunshine. Mechanical energy developed in a plant leaf is used to intensify the process of assimilation by activating gas exchange with the environment.

As regards the transformation of heat energy into mechanical energy, we usually assume that a mechanical engine of a certain structure is required for that purpose. However, there are engines which produce mechanical energy by a gas flow. The potential energy of pressure is converted into kinetic one, while the latter – into mechanical work. Technically, the transformation of potential energy to kinetic energy occurs in special tubes (de Laval nozzles). The combination of plant leaf cavities, channels and stomata is very similar to the design and operating principles of a rocket (jet) engine.

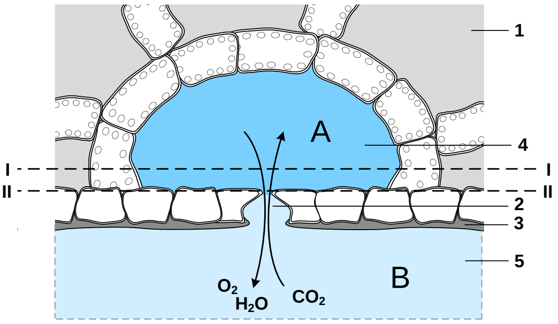

Fig. 5. – Chart showing the system of the gas cavities (mini, macro and nano), channels and stomata of a plant leaf. A – cavity in a plant leaf; B – ambient environment of a plant leaf; I–I, II–II – outside positions of alleged membrane. 1 – spongy tissue, 2 – stoma opening, 3 – cuticle 4 – gas environment in the spongy tissue of a leaf, 5 – ambient air in leaf surroundings

Energy transformations in a plant leaf are possible only during the sunny period of the day in the presence of leaf temperature pulsations. It is difficult to accurately describe the thermodynamic processes of heat transformation to mechanical energy in a plant leaf and to form a thermodynamic cycle. This is because a plant leaf is a live organism of the plant in which complex biological and physical processes are taking place simultaneously. The environment as well as biological (assimilation) processes and their intensity have an impact on the progress of physical processes in leaf cavities, channels and stomata, the biological mechanism of stomatal guard cells manifests itself. Therefore, to understand physical processes taking place in the gaseous cavities of a leaf they need to be idealised and charted as is often done in thermodynamics.

A chart of the gas cavities and channels of a plant leaf is presented in Fig. 5 for the purpose of analysing thermodynamic processes taking place in them and the operating principle of the thermal engine working in a plant leaf.

For the thermodynamic analysis of cycles the assumption is made that the same amount of air (absolutely dry in this case) in the gas cavities of a plant leaf is used in the cycle. To analyse thermodynamic processes taking place in leaf cavities an alleged membrane dividing the analysed gas cavity volume in a plant leaf into to two parts is used. In the course of thermodynamic processes in cavity A air mass remains constant. Its volume may change depending on pressure and temperature. Cavity B has contact with ambient air through a stoma channel. As volume A changes, ambient air enters cavity B through the leaf stoma or is released into the environment through it. (Fig. 1). In the case of constant energy exchange when plant leaf temperature is the highest air volume in cavity A (Fig. 1) will be maximum and in cavity B – minimum (cavity B = 0). At this moment pressure in the leaf cavity is equal to ambient air pressure and the alleged membrane will be in position II–II.

Point 1 represents the thermodynamic state of the air in cavity A in the coordinate system *pv* (pressure–volume) (Fig. 6). In point 1 the volume of cavity A is maximum and pressure *p* equals the atmospheric pressure.

As the temperature of the plant leaf drops pressure in cavity A decreases and vacuum forms. Pressure in environment B exceeds pressure in plant leaf cavity system A. Due to the formed difference in pressures ambient air enters the plant leaf cavity through the stoma moving the alleged membrane from position II–II to position I–I. When ambient air enters cavity B vacuum in cavity A does not reach the maximum value but is maintained at a certain constant level $p_2 = const$, which depends on the size of the leaf cavity and the hydraulic resistance of the leaf stoma channel. Depending on occurring biological processes the plant leaf may change the dimensions of the stoma channel (in this aspect biological channels have an advantage over static energy transformation channels used in technologies). Therefore, as temperature in cavity A drops (during the cooling process), the pressure difference between cavity A and the ambient environment remains constant ($p_1 - p_2 = const$), the volume of cavity A decreases. When the minimum temperature is reached in cavity A (point 3) the compression process in the cavity of the plant leaf continues due to higher pressure in the ambient environment. It is a polytropic compression process. It continues as long as pressure in cavity A becomes the same as pressure in the ambient environment (point 4).

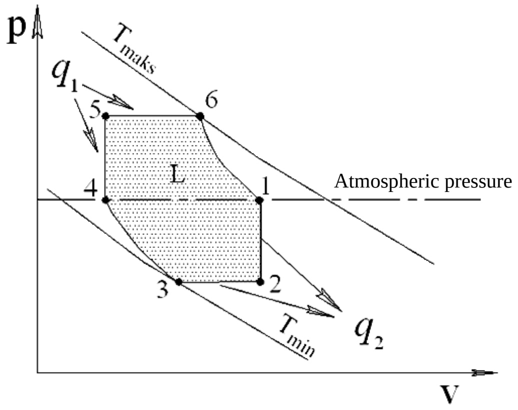

Fig. 6. - The thermodynamic cycle of the thermal engine working in the plant leaf gas system in the *pv* (pressure *p*, volume *v*) coordinate system. L – area of the cycle; 1, 2, 3, 4, 5, 6 – characteristic points of thermodynamic states describing the parameters of plant leaf cavities (explanation is in the text)

At the end of adiabatic compression (without heat exchange with the environment in process 3-4) volume in plant leaf cavity A reaches the minimum value. The alleged membrane reaches the outside position of minimum volume I–I.

As plant leaf temperature rises (solar energy is absorbed) pressure in plant leaf cavity A increases reaching the maximum value in point 5. As temperature in cavity A continues to increase, the difference in pressures in cavity A and ambient environment remains constant $p_5 - p_4 = const.$ The Volume of cavity A increases pushing the alleged membrane towards position II–II. When the maximum temperature is reached (point 6), higher pressure in plant leaf cavities A leads to the polytropic expansion process as pressure drops to continue until the pressures reach the balance in point 1. At the end of polytropic expansion (in process 6–1) leaf cavity volume reaches the maximum value in point 1. The alleged membrane reaches the outside position of maximum volume II–II.

The cycle is completed and returns to the initial position. A new wave of plant leaf temperature change will repeat the aforesaid cycle in the gas system of a plant leaf.

Processes taking place in plant leaf gas cavities are charted. That facilitates an investigation aimed at proving that the heat engine of mini-micro sizes producing mechanical energy is present in the system of plant leaf gas cavities during the sunny period of the day. Although real processes occurring during this cycle deviate from the theoretical processes discussed above, the fact that such an engine does exist in the plant leaf has been explained. Basing on the laws of thermodynamics we may state that mechanical work L performed by the processes of gas exchange in a plant leaf during the sunny period of the day is represented in the *p-v* (pressure– volume) coordinate system by cycle area 1–2–3–4–5–6–1 (Fig. 6.).

This article presents the thermodynamic analysis of the world's smallest heat engine working in a live plant leaf during the sunny period of the day. The number of engines in 1 mm^2 matches the number of stomata in the system of plant leaf gas exchange (up to 400).

CONCLUSIONS

1. In sunshine, as the temperature of plant leaf tissues changes, thermal parameters in the gas cavities of a leaf change, which leads to respective thermodynamic processes.

2. In sunshine, a thermal stomata engine (the biological prototype of a heat engine) works in a plant leaf and generates mechanical energy at the expense of heat.

3. Mechanical energy developed in the plant leaf intensifies the process of assimilation by activating leaf energy and gas exchange with the environment.

4. Plant energy exchange together with the process of assimilation form an important nature's generative and regenerative system by creating conditions for the existence of life on Earth.

REFERENCES

1. Šlapakauskas, V.: Augalųekofiziologija. Lietuva, Kaunas 2006.
2. Ількун,Г.М.: Енергетичнийбалансрослин. УкраинаКиев 1967.
3. Fitter, A., Hay, R.: Environmental physiology of Plants. Academic press. 2002.
4. Šlapakauskas, V., Duchovskis, P.: Augalųproduktyvumas. Lietuva 2008.
5. Stašauskaitė, S.: Augalųvystymosifiziologija. Lietuva, Vilnius 1995.
6. Ellwagner, T., Bingham, Jr., Chapell, S.: We and Tolin SA. Cytological effects of ultra-high temperatures on Corn. Weed Sciennce, 1973: pp. 299-303.
7. Levitt, J.: Response of plants on environmental stresses. Academic Press. New York 1980.
8. Martin, J., Henrichs, T.: The European environment. *European Environment* Agency. 2010.
9. Sirvydas, A., Kerpauskas, P., Kučinskas, V.: Augalųenerginėapykaita. Lietuvos Žemės Ūkio Universitetas. Lietuva, Akademija 2011: pp. 22.
10. Сирвидас, А., Юшка, В.: Измерениетемпературырастений в микроклиматических и физиологическихисследованиях. Лит. НИИ лесногохоз-ва. Каунас, 1973: 34 с.
11. Sirvydas, A., Kerpauskas, P., Nadzeikienė, J., Stepanas, A., Tereščiuk, V. S.: Temperature measurements in research of thermal weed extermination. Proceedings of the international conference Development of agricultural technologies and technical means in ecological and energetic aspects. Lithuania. Raudondvaris. No.11, 2006: pp. 321-331.
12. Nobel, P. S.: Physiological and Environmental Plant physiology. *Academic press*. 1991: 635 p.
13. Keith, A., Mott and Thomas, N, Buckley.: Patchy stomatal conductance: emergent collective behaviour of stomata. *Trends in plant science*. 2000: pp. 258-262.
14. Gas exchange in plants: Available at: http://www.cartage.org.lb/en/themes/sciences/botanicalsciences/photosynthesis/ GasExchange/GasExchange.htm.
15. Colorado State University: CMG garden notes. Available at: http://www.ext.colostate.edu/mg/Gardennotes/144.html.
16. New AP Biology Curriculum Units: 2013. Available at: http://supercoolandawesome.blogspot.com/2013/05/gas-exchange-in-aquatic-and-terrestrial.html.
17. Dagys, J., Bluzmanas, P., Borusas, V., Šlapakauskas ,V.: Augalųfiziologija. Lietuva, Vilnius 1974.
18. Sajith, V., Haridas, D., Sobhan, C. B.: Reddy Convective heat transfer studies in macro and mini channels. International Journal of Thermal Sciences. 2011: pp 239-249.
19. Sirvydas, A., Nadzeikienė , J., Kerpauskas, P., Ūksas, T.: The principle of heat conversion into mechanical work. *Mechanika*. 2013: pp 358 – 362.
20. Sirvydas, A., Kučinskas, V., Kerpauskas, P., Nadzeikienė, J., Kusta, A.: Solar radiation energy pulsations in a plant leaf. Journal of Environmental Engineering and landscape management. 2010: pp. 188-195.
21. Sirvydas, A., Kučinskas, V., Kerpauskas, P., Nadzeikienė, J.: Theoretical modeling of temperature pulsations in plant leaf which are caused by leaf swing with respect to the sun. Journal of Environmental Engineering and landscape management. 2011: pp. 251–259.

Corresponding author:

Tomas Ūksas.Aleksandras Stulginskis University, Faculty of Agricultural Engineering, Institute of Energy and Biotechnology Engineering., Studentu 15, LT-53361 Akademija, Kaunasm phone. +37037 75 22 19, e-mail: acikuraci@gmail.com