INFLUENCE OF MOISTURE ON OSIER WILLOW CHOPS CHARACTERISTICS

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Abstract. The world energy demand and declining fossil fuel resources make renewable energy resources to receive increased attention. Lithuania is sufficiently rich in renewable natural resources, and energy can be used from various types of solid biofuels, without being tied to fossil fuels, which have to be imported from other countries. Osier willows (*Salix vinimalis*) are one of the most cultured short rotations sprouts in the energetic plantations. These sprouts are willows which grow as bushes and have almost equal diameter and height of perennial stems. Preparing osier willows for fuel, the trunks of the trees are felled every four years, usually in the cold season. Osier willows are chopped by various shredders in the process after the removal of branches and leaves. Cutting willows in other seasons leads to the high moisture content and the biological activity of carving and other significant features: density, porosity, thermal conductivity, self–heating and other properties. According to the experiments, the highest biological activity (747 ± 43.5-379 ± 34.7 $W \cdot t^{-1}$) is characterized by willow chaff from 50.4 ± 0.14 % to 30.0 ± 0.075 % humidity. When the humidity reaches 11.6 ± 0.11 %, the wood carving becomes biologically inactive. It was found that the thermal and temperature conductivity of wood carving differ based on the difference in moisture. The maximum values of the temperature field (21.56 $m^2 \cdot s^{-1}$ and 19.39 $m^2 \cdot s^{-1}$) were fixed, when the chopped osier willow moisture was 30.0 ± 0.075 % and 38.4 ± 0.088 % respectively. Moreover, it is observed that, when the osier willow dries from 50.4 ± 0.14 % to 11.6 ± 0.11 % of moisture, its true wood density decreases by 21.2 % – from 808 ± 11.25 $kg \cdot m^{-3}$ to 637 ± 63.5 $kg \cdot m^{-3}$. The density of the chopped osier willow decreased by 28.1 % – from 433 ± 5.13 $kg \cdot m^{-3}$ to 311 ± 3.05 $kg \cdot m^{-3}$.

Keywords: biological activity, density, *Salix vinimalis*, thermal conductivity, wood chips.

Introduction

Biofuel usage in various conversion technologies is still an important issue in Lithuania and in the world. Lithuania's National Energy Independence Strategy is focused on the diversification of energy sources. According to its guidelines, the share of renewables in the total final energy consumption in Lithuania will reach 35 % by the year 2030 [1]. Biomass is the main renewable resource in the Nordic countries [2]. Forests in Lithuania cover approximately 33 % territory of the country. If wood and logging residues were used rationally, that would get a large part of the required fuel from available sources [3]. It is important to find alternative sources of biofuels for the implementation of the commitments given to the European Union and not only to use natural wood for energy. Fast rotation plants, such as willows, are the most suitable for this [4].

Willows are grown as short rotation energy crops. The high calorific value of willow is about 18.7 MJ kg^{-1} [5], the ash content is up to 5 % [6]. Therefore, they can be widely used in various green technologies in the field of energy and chemistry across Europe, Northeast and Midwestern America and Canada [7]. Willow yield can range from 6.5 to 24 $t \cdot ha^{-1}$ per year, depending on the variety, agro-technics, natural conditions and other factors [7-9]. In Lithuania, declared their yield is 8.7-19.30 $t \cdot ha^{-1}$ per year [6,10]. Willow was declared as an energy crop in the statistics of agricultural land and crops in 2011. In that year, about 109 ha of willow land were declared in Lithuania. Up to now, the area of grown willows has raised by more than 35 times. According to the statistics of 2018, the area of willow land was 3853 ha in Lithuania [11].

Willow yield is usually harvested during winter, when the moisture content of the cut wood reaches 40-60 % [6,12]. Willows are harvested with special harvesters and immediately chopped [12]. Prepared raw material can be stored outdoors, but also in warehouses with or without systems of ventilation, refrigeration or drying [12].

There are several problems in storing recently removed willows in a large pile. Chopped wood material loses about 20-24 % of its mass and 15-19 % of its effective heating value after 3-6 months of storage [13]. In fresh chopped biomass stored in a pile certain processes take place, commencing with respiration of plant cells [14]. Additional problems are due to the relatively high amount of bark, which is about 16-56 % [15]. Larger amounts of bark increase the contamination by microorganisms. All of the above mentioned factors have influence on the heat and mass transfer in the pile. Their control is the most important condition for the preservation of the quality of chopped willow. It is therefore very important to know the impact of various factors on the thermo-energetic processes in the pile of willow and other energy crops.

The aim is to investigate the influence of moisture on self-heating for chopped osier willow and thermal diffusion in the pile.

Materials and methods

The research of osier willows (*Salix viminalis*) was conducted at the Vytautas Magnus University Agriculture Academy, Faculty of Agricultural Engineering, Institute of Energy and Biotechnology Engineering research laboratories. It is established in the Northern part of Europe in Lithuania.

In November, after harvesting osier willows stems were loaded into a stack in the laboratory. From different willow stem locations randomly thirty 12-20 cm length logs have been cut. Samples of cutting willow logs for true density determination were prepared with 3 repetitions. The remaining willows trunks were left to dry naturally in the laboratory at temperatures of 5-15 ºC. During the studies, periodically different diameter selected willow stems were taken and chopped with the disc chipper AL–KO New Tec 2400R (2400 W/2800 min^{-1}). The samples of 12-15 litters of chopped willow were prepared for biological activity, bulk density, and thermal conductivity determination.

Research in raw material moisture. Moisture of the willow was determined according to the recommendations of the LST EN 13183-1:2003/AC:2004 standard. The small amount of willow wood samples was cut with scissors with 10 repetitions; the prepared samples were weighed before and after drying with the balance Sartorius AX 6202. The samples were dried for 24 hours at 105 ± 2 ºC in the oven Memmert Model UPF 700 until they reached the fixed weight.

True density studies. The true density of willow logs was determined using the volumetric method according to the volume of sample displaced fluid. The prepared samples were weighed on SCALTEC SPO 62. The samples were immersed in a container with water using an additional weight. The true density of willow logs was recorded periodically every 2-4 days until the moisture content of the samples decreased to 7 %. According to the obtained results, true density of the willow logs was calculated.

Determination of bulk density. The bulk density of the set of the test samples was determined using a cylinder, 191 mm in diameter and 260 mm height. The volume of the cylinder was 7450 cm^3. The cylinder is filled to the top edge with chopped willow by free falling. The filled cylinder was weighed with weighing scales Aversy Berkel FX 220 with 1 g tolerance. According to the obtained results, the bulk density of the material was calculated. All the bulk density tests on the samples of chopped willow of different moisture content were conducted in 10 repetitions. Then the porosity of the layer was calculated by the bulk and true densities of the chopped willow.

Research in biological activity. In order to determine the biological activity – amount of carbon dioxide (CO_2), which was released during breathing and heat flow, the chopped willow was placed in desiccators and weighed. In each case two samples of chopped willow of 600 and 1000 g weight were investigated. The desiccators were closed tightly and put in a climatic chamber Feutron KPK 600. Desiccators were stored at 25 ºC temperature. The concentration of carbon dioxide was measured with the gas analyser Testo 350 inside the desiccators every 3-6 hours. Measurements of the biological activity of the chopped willow of different moisture are repeated at least 4 times. The heat flow was received during breathing calculated according to the nutrient decomposition reaction [16].

Thermal conductivity studies. A special research stand has been created to determine the thermal conductivity of chopped willow. The principal scheme of the research stand is shown in Figure 1. The stand consists of polystyrene foam panels. The plastic mesh and the removable cover were mounted on the front of the stand. The thermocouples are mounted on the rear wall of the stand to measure the temperature. During the tests a heating element was installed at the stand bottom to create a heat flow and maintain 25 ºC temperature in the bottom layer of the chopped willow. During the test the research stand was stored in a climatic chamber Feutron KPK 600 at 5 ºC.

Thermocouples and sensors of temperature and humidity recorded environmental air setting in the climatic chamber and heat flow through the layer of the chopped willow; also, every 1-6 hours the test stand cover was removed, and thermal-pictures were taken with the FLUKE Tr 55 thermovisor. All the data were recorded periodically every 15 minutes in the memory of data logger ALMEMO 3290-8.

Under these conditions the heat exchange process in the chopped willow pile was observed for 24 hours.

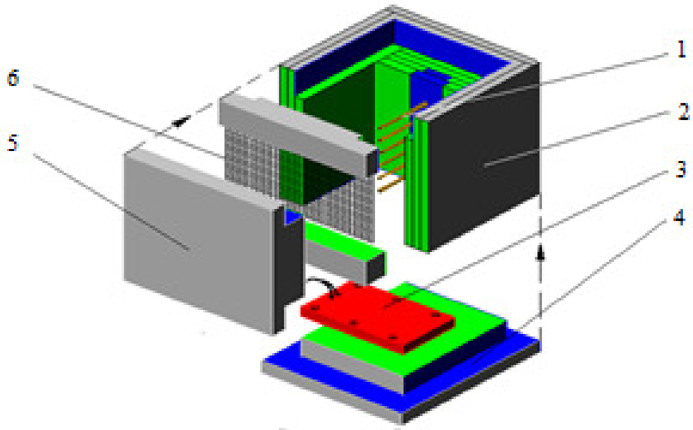

Fig. 1. **Research stand of thermal conduction for chopped willow:** 1 – NiCr thermocouples; 2 – stand walls (outer surfaces); 3 – heating element; 4 – bottom of the stand; 5 – cover of the stand; 6 – plastic mesh

According to the obtained results, the thermal and temperature conductivity of the chopped willow was calculated. All results obtained during the research were analysed using Microsoft Excel application.

Results and discussion

Stems of osier willow (*Salix viminalis*) of different moisture were used for the experimental studies. Their initial moisture was 50.4 ± 0.14 %. Researches are repeated every few days until the raw material has dried up to 7-12 % moisture.

During the research the weight of the samples of osier willow logs decreased from 0.748 ± 0.1788 kg to 0.426 ± 0.1034 kg. Slight exponential dependence on their mass was observed from moisture. The variation in the volume of the logs was most intensive, when the moisture amount of the wood changed from 50.4 ± 0.14 % to 35-38 %. The volume decreased from 9.59 ± 1.38 cm^3 to 7.34 ± 0.93 cm^3, it stabilized and changed slightly. When the logs dried up to 7.3 ± 0.012 %, the change in the volume was non-essential. On average, it decreased by 3.81 % to 7.06 ± 1.67 cm^3. As the chopped osier willow moisture was decreasing, in 7.45 cm^3 volume the capacity of mass also decreased from 3.22 ± 0.038 kg to 2.32±0.021 kg, or 28 %. According to the results of the research, the true density and the bulk density of osier willow wood dependence on moisture is shown in Fig. 2.

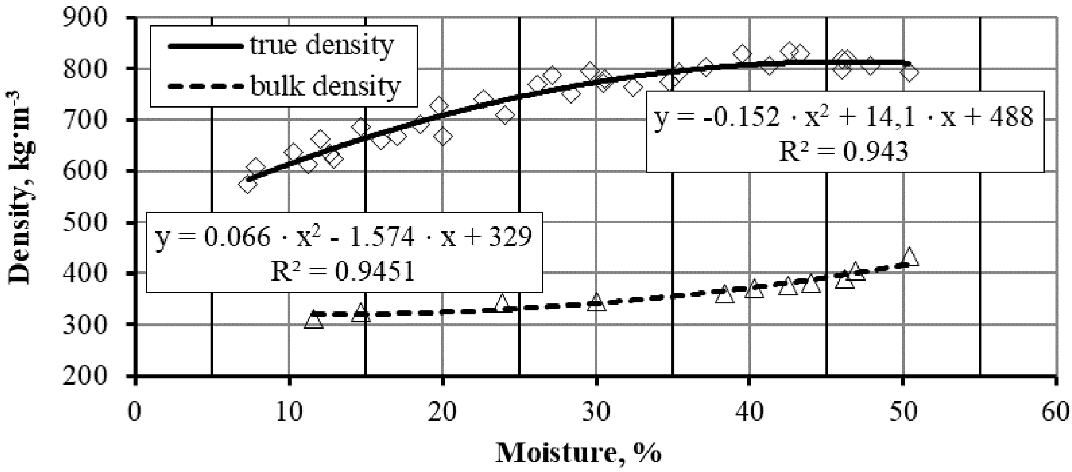

Fig. 2. **True density and bulk density of osier willow**

Decreasing the moisture of osier willow stems from 50.4 ± 0.14 % to 30-35 %, the volume and weight of wood logs are reduced proportionally, and the true density has remained at about

808 ± 11.25 kg·m^{-3}. When the wood logs are drying, the difference between their volume and mass changes is increasing. When wood logs reach 30-35 % moisture, they stop shrinking, only their mass changes. Therefore, the true density begins decreasing rapidly. The true density of osier willow logs of 7.3±0.012 % moisture content was found to be 573 kg·m^{-3}.

In the chopped osier willow bulk density, different from the true density, the most significant variation is observed in the range of 50.4 ± 0.14 % to 30-35 % moisture. Moisture of chopped willow had a direct effect on its flowability and better filling up capacity. The bulk density decreased by 21 % from 433 ± 5.13 kg·m^{-3} to 342 ± 1.85 kg·m^{-3}. However, a further reduction in chopped willow moisture of up to 11.6 ± 0.11 % had less impact on the bulk density. When the moisture content of the osier willow decreased from 30.0 ± 0.075 % to 11.6 ± 0.11 %, its density changed only by 9.1 %, from 342 ± 1.85 kg·m^{-3} to 311 ± 3.05 kg·m^{-3}.

The moisture content of the raw material also had influence on the porosity of the chopped osier willow. The maximum porosity of the chopped osier willow was established to be 0.55, when the moisture was 30-38 %, Fig. 3.

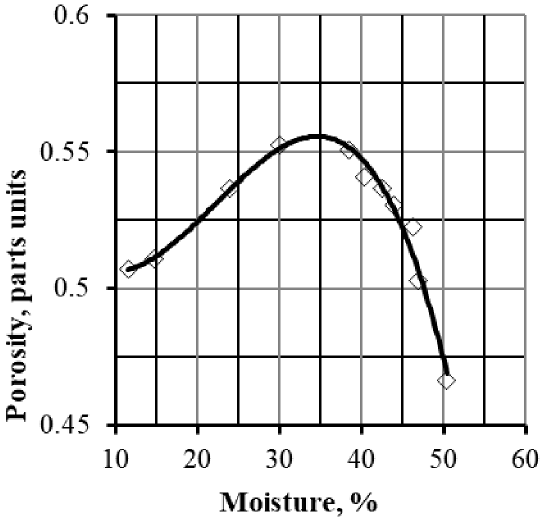

Fig. 3. **Porosity of chopped osier willow**

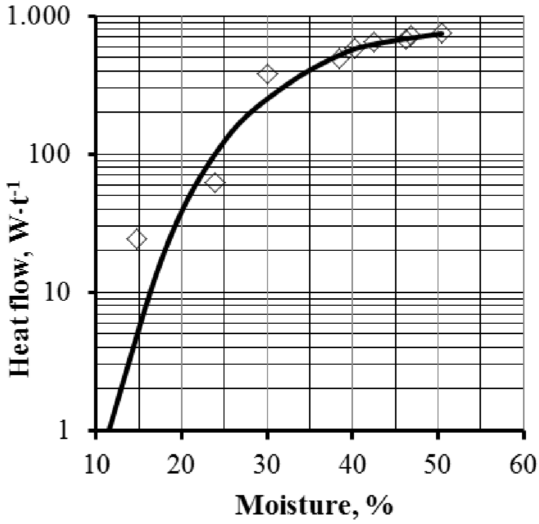

Fig. 4. **Biological activity of chopped wood**

As the moisture decreased or increased, the porosity of the chopped osier willow decreased. The highest change was observed, when the moisture increased: from 38.4 ± 0.088 % to 50.4 ± 0.14 %, the porosity decreased by 14.5 %. Though, that decisive influence on the process has been the higher chopped willow mass. It has created the conditions for more compression and forms denser bulk. When the chopped osier willow dries, the chopped particles are less compressed, but they are more easily flowing and filling up capacity. As a result, the moisture of the osier willow was reduced to 11.6 ± 0.11 % and the porosity of the pile also decreased, but only by 7.3 % to 0.51.

Biological activity was determined by ten different moistures of the chopped osier willow: 50.4 ± 0.14 %, 46.9 ± 0.068 %, 46.2 ± 0.049 %, 42.5 ± 0.065 %, 40.3 ± 0.093 %, 38.4 ± 0.088 %, 30.0 ± 0.075 %, 23.9 ± 0.096 %, 14.7 ± 0.092 % and 11.6 ± 0.11 % moisture. The results are presented in Figure 4.

The maximum heat flow of 747 ± 43.5 W·t^{-1} was received from 50.4 ± 0.14 % moisture chopped willow. Many biological wood wreckers settle on the surface of the wood, so this heat radiation is associated with the breathing of wood, the activity of fungi and bacteria. They disassemble wood, reduce the volume and density by emitting metabolic products into the environment [17]. However, the decrease in the moisture of the chopped osier willow to 30.0 ± 0.075 % resulted in a decrease in the heat flow to 379 ± 34.7 W·t^{-1}, which is 1.97 times less. When the chopped osier willow dries up to 11.6 ± 0.11 %, it became biologically inactive. So, moisture is one of the main factors determining the efficiency of chopped wood processes. It directly determines the biological activity of the chopped wood and the activity of the microorganisms [17].

The intensity of the temperature heating rose not only from the heat flow of the chopped osier willow. It also depends on the dispersal potential of the released heat, which is directly affected by the thermal conductivity of the chopped willow. A special stand was developed for thermal conductivity and temperature sensors and thermovisual analysis were used for the process monitoring, Figure 5.

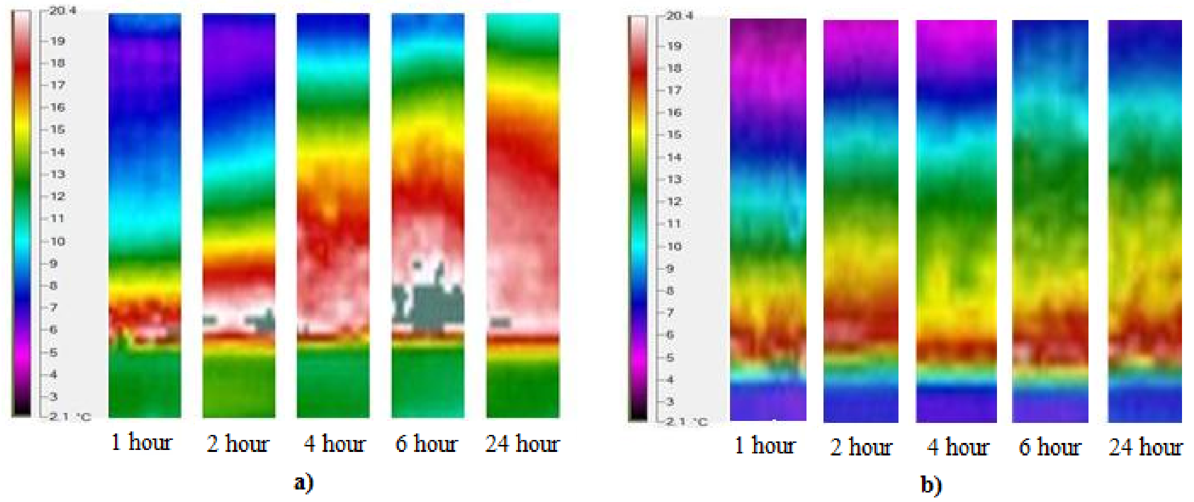

Fig. 5. **Heat diffusion on chopped wood surface, moisture 46.2 ± 0.049 % (a) and 23.9 ± 0.096 % (b)**

The thermal images show how the 46.2 ± 0.049 % and 23.9 ± 0.096 % moisture chopped wood layer distributed in the different temperature zones after 1, 2, 3, 4, 5, 6 and 24 hours. The higher moisture chopped wood pile captured a bigger zone of higher temperature (higher than 17 ºC). Within 24 hours of the bottom of the pile temperature had risen 6.3 times above than 23.9 ± 0.096 % moisture of chopped wood in the layer. Wetter material layer heat rose slower. Even after 6 hours the process was not steady. At that time, 23.9 ± 0.096 % moisture pile thermal images after 5, 6 and 24 hours were basically unchanged. In the drier chopped willow, balance of the thermal processes was reached faster. In this case, at the 35 % moisture of chopped willow also the heat diffusion process speed changes were observed. The 50.4 ± 0.14 % moisture chopped wood pile of 130 mm high overheated over 19.75 hours. This lasted 2.32 times longer than for the 14.7 ± 0.092 % moisture pile. At that time, the temperature field displacement speed of the chopped osier willow decreased by 57.1 %, from 2.12 to 0.91 ºC·h^{-1}, then the moisture increased from 14.7 ± 0.092 % to 50.4 ± 0.14 %.

Rising up the chopped wood layer, the temperature recorded by the thermocouples gradually increased. The intensity of the temperature field dissipation depends on the material's temperature conductivity. The maximum values of the temperature field (21.56 m^2·s^{-1} and 19.39 m^2·s^{-1}) were fixed, when the chopped osier willow moisture was 30.0 ± 0.075 % and 38.4 ± 0.088 % respectively, Fig. 7. As the chopped wood moisture decreases and increases, the thermal conductivity decreases, too.

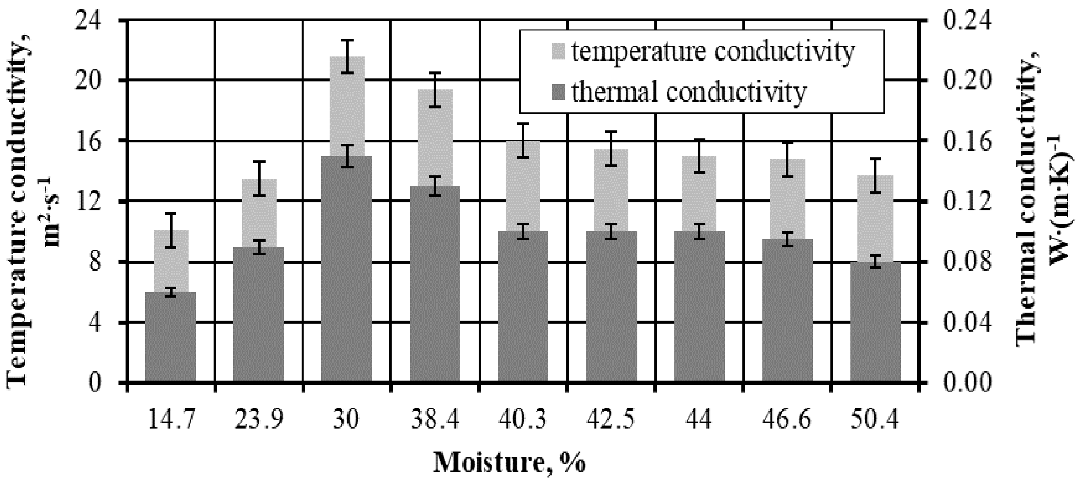

Fig. 7. **Temperature and thermal conductivity of chopped wood**

Analogously, but slower the chopped osier willow pile thermal conductivity changed. The maximum value of the thermal conductivity (0.15 to 0.13 W·(m·K)$^{-1}$) is typical for 30-38 % moisture of chopped willow. When the moisture decreased to 14.7 ± 0.092 %, the thermal conductivity also decreased to 0.06 W·(m·K)$^{-1}$, when the moisture increased to 50.4 ± 0.14 %, the thermal conductivity decreased to 0.08 W·(m·K)$^{-1}$. Therefore, the moisture of 30-38 % marks the beginning of the dominance of the moisture effect on the thermal properties of chopped wood. The higher the moisture content of osier willow, the bigger the influence on its thermal properties the moisture evaporation process has. During the evaporation process a large amount of heat is consumed, which is taken from the chopped wood or fluid flowing through it. As a result, the intensity of the chopped wood temperature rising slows down and also the heat flow, which passes through the pile.

Conclusions

1. The highest biological activity 747 ± 43.5-379 ± 34.7 W·t^{-1} was determined in chopped willow biomass with a moisture content of 50.4 ± 0.14 to 30.0 ± 0.075 % at a storage temperature of 25 ºC. In drying the released heat flow decreases intensively and after dried to 23.9 ± 0.096 % moisture, it reaches only 62.8 ± 8.23 W·t^{-1}. The chopped osier willow becomes completely biologically inactive, when the moisture decreases to 11.6 ± 0.11 %.
2. When the osier willow dries from 50.4 ± 0.14 % to 11.6 ± 0.11 % of moisture, its true wood density decreases by 21.2 % – from 808 ± 11.25 kg·m^{-3} to 637 ± 63.5 kg·m^{-3}. The density of the chopped osier willow decreased by 28.1 % – from 433 ± 5.13 kg·m^{-3} to 311 ± 3.05 kg·m^{-3}.
3. The studies and calculations have shown that the highest porosity (0.55), thermal conductivity (0.15 W·(m·K)$^{-1}$) and temperature conductivity (21.56 m^2·s^{-1}) are characterized by 30-38 % moisture of chopped willows. It is determined that higher or lower chopped wood moisture reduces porosity, thermal conductivity and temperature conductivity. When the osier willow moisture was 50.4 ± 0.14 % and 14.7 ± 0.092 %, the porosity, thermal conductivity and temperature conductivity decreased to 0.47, 0.08 W·(m·K)$^{-1}$, 13.69 m^2·s^{-1} and 0.52, 0.06 W·(m·K)$^{-1}$, 10.1 m^2·s^{-1}, respectively.

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