Theoretical Foundations of Building A Mathematical Model of Crushed Wood As An Object Of Fire Safety

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Abstract: The article considers the issues related to the possibility of using wood waste as an alternative energy source that can partially solve the problem of energy independence. However, the processing and storage of bioraw materials are associated with the risk of spontaneous inflammation of crushed wood. To prevent this, it is necessary to cope with the task of a safe method of long-term storage at processingcompanies. The paper presents the preconditions and methodology for creating a mathematical model of crushed wood during its storage in bunker bays with forced ventilation as an object of fire safety. The model takes into account the processes of heat, moisture, and gas exchange of crushed wood with the environment, along with biochemical processes, which will allow assessing the probability of spontaneous combustion of crushed wood effectively.

Keywords: Energy security, Renewable resources, Fire safety, Crushed wood, Bunker bays, Forced ventilation, Spontaneous inflammation

INTRODUCTION

The energy crisis, constant rise in oil, coal, and natural gas prices, raisethe question of their replacement by alternative energy sources (Soufer, 1985). One such source is wood waste, which has several advantages over traditional ones (Baader, 1982). These include environmental friendliness, because their burning does not disturb the thermal balance of the planet, and the carbon released into the atmosphere in the form of oxides is easily absorbed by new tree plantations; renewability, this indicator unlike traditional energy sources (oil, gas, coal) can be managed within a fairly wide range (Dubrovin, 2004). Currently, there is a clear trend aimed at expanding the use of wood biomass waste as an energy source.Per year, total global heat production from it almost equals the amount of energy generated by hydroelectric power plants.

Concurrently, there are problems associated with the uneven processing of wood waste and its use (Gomonai, 2006). To ensure regular shipment to consumers, crushed wood is stocked in the form of warehouses (Matveyko, 2002). The most common method of storage is bunker bays, which are a system of reinforced concrete bunkers of cylindrical shape. Such storage has its advantages and disadvantages. The disadvantages include large volumes of crushed wood in them, which requires special storage conditions. When storing large volumes, it is necessary to provide optimal conditions for forced ventilation of the crushed mass to prevent its spontaneous inflammation, due to the increase in temperature in the internal volumes (Skin, 2005).

The criterion for estimating the probability of spontaneous inflammation of crushed wood in bunker bays with forced ventilation is the simultaneous achievement of critical values of temperature and humidity of crushed wood on the centerline of the bunker as a body of rotation athalf of its height.

To determine the time and conditions for achieving these critical values, a mathematical model of crushed wood as an object of fire safety is needed to take into account biochemical processes with heat, moisture, and mass transfer processes.

The analysis shows (Vasiliev, 1999, 2002, 2008) that the chosen direction is relevant, practically useful, and promising from the standpoint of fire safety, as well as from an increase in the durability and safety of the crushed mass during storage.

The purpose of the article is to create a mathematical model of crushed wood to objectively assess the probability of its spontaneous inflammation during storage in bunker bays with forced ventilation.

METHODOLOGY

Shredded wood is considered as an artificial ecological system. Its structure includes wood, impurities, microflora, pests and air between wood particles. The following processes are analyzed during the storage of shredded wood: biochemical processes in wood, the vital activity of microorganisms, the vital activity of pests, heat exchange, moisture exchange and gas exchange.

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Decomposition of dry wood matter occurs as a result of its respiration and vital activity of microorganisms. We will consider both processes of respiration of wood and microflora - aerobic and anaerobic, describing each of them with the corresponding overall equation of respiration. The growth process of the population of microorganisms will be described by a differential equation. The development of microorganisms will lead to a decrease in the mass of dry wood substances, which is also described by a differential equation. On this basis, it is possible to determine the intensity of the release of heat and metabolic products - moisture, carbon dioxide and organic substances.

The specified processes will take place in conditions of exchange of heat and matter with the environment. We will consider the heat exchange process as heat transfer through the wall, and the exchange of moisture and gases as diffusion processes.

At the same time, we will take into account that the equilibrium moisture content of wood will change depending on its temperature and water vapor content.

This will make it possible to investigate the process of self-heating of chopped wood during its storage by solving a system of differential equations.

RESULTS

The model is based on the definition of crushed wood as an artificial ecological system (Vasiliev, 2008). The structure of the crushed mass includes wood, impurities, microflora, and air between wood particles. As a possible element, pests can be available in the composition of the crushed mass. The process of storing the crushed mass is associated with a decrease in mass and quality indicators, which is mainly caused by:

- biochemical processes occurring in the wood itself;

- the vital activity of microorganisms;

- the vital activity of pests.

The most important biochemical process that determines the decrease in the wood dry weight during storage is its respiration: aerobic and anaerobic. The influence of wood respiration on this parameter is clearly illustrated by the summary equations of respiration:

aerobic

$$C_6 H_{12} O_6 + 6 O_2 = 6 C O_2 + 6 H_2 O + Q_{аэр}, \quad (1)$$

where $Q_{аэр}$ is the amount of heat released as a result of aerobic respiration, kJ;

anaerobic

$$C_6 H_{12} O_6 = 2 C O_2 + 2 C_2 H_5 OH + Q_{анаэр}, \quad (2)$$

where $Q_{анаэр}$ is the amount of heat released as a result of anaerobic respiration, kJ.

The respiration rate, in turn, depends on the moisture content, the temperature of the wood pulp, the concentration of oxygen in the air between the particles, and the physiological characteristics of the wood.

The rate of change in the quality indicators of crushed wood under the influence of biochemical processes is determined by the same conditions as the intensity of respiration. It would be logical to assume that the intensity of the ongoing biochemical processes is determined by physiological or vital activity, which, in turn, is determined by the moisture and temperature of the wood pulp, and the concentration of oxygen in the air between the particles.

The microflora is the second in importance and degree of influence on the quality indicators of crushed wood (Vasiliev, 2008). The most important microbiological processes occurring in wood pulp are respiration and the reproduction of microorganisms. Respiration of most microorganisms occurs under the overall respiration equations (1) and (2). The change in the population size is determined by the dependence (Vasiliev, 2008):

$$\frac{dN}{dt} = \mu N \quad (3)$$

where μ is the population growth rate (depends on the parameters of the substrate), hour^{-1}; N is the population size, thousand pcs.

The nature of the effect of microflora on quality indicators is clearly illustrated by the Lotka-Volterra equation (Vasiliev, 2008), written for a flow-through chemostat. To simulate the behavior of microflora during the storage of crushed wood, it is necessary to remove the component reflecting the flow rate from the equation. Then it will be as follows:

$$\frac{dS}{dt} = -\sum_{i=1}^{n} \frac{\mu_i N_i}{Y_i} \quad (4)$$

where S is the parameter of the substrate (mass of dry substances), par. substr.; μ_i is the growth rate of the *i*-th population (depends on the parameters of the substrate), hour^{-1}; N_i is the size of the *i*-thpopulation, thous. pieces; Y_i is the coefficient of efficiency of using the substrate or the degree of influence of the *i*-th population on the parameter of the substrate, thous. pieces / par. substr.

Based on the above-mentioned, we can conclude that the degree of influence of microflora on quality indicators depends on the physiological activity of the population, which determines the rate of its growth, the potential of the population, characterized by the coefficient of the economy and population size. A similar dependence will be for the release of metabolic products by the population.

So, as a result of biochemical processes in the wood pulp, dry substances are consumed, air oxygen between wood particles, heat, moisture, carbon dioxide, and organic substances (ethanol, etc.) accumulate. The intensity of biochemical processes is determined by the physiological activity of wood pulp and microorganisms.

Along with biochemical processes, it is also necessary to take into account the processes of heat, moisture, and gas exchange of wood pulp with the environment (Ryabova, 2002). The description of heat transfer processes is usually based on the equations of heat transfer between the medium and the surface and the heat transfer through the wall. A heat-transfer equation:

$$Q_{mo} = \alpha F_{mo} \tau_{mo} \Delta\theta \quad (5)$$

where Q_{mo} is the amount of heat transferred from the wood pulp to the environment, kJ; α is the heat-transfer coefficient, kJ / (m^2 hour °C); $F_{mo}$is the heat-exchange area, m^2; $\tau_{mo}$is the heat exchange time, hour; Δθis the temperature difference °C.

The equation of heat transfer through the wall:

$$Q_{mn} = \frac{\lambda F_c \Delta\theta \tau_{mn}}{\delta_c} \quad (6)$$

where Q_{mn} is the amount of heat transmitted through the wall, kJ; λ is the heat-transfer coefficient, kJ / (m hour °C); F_c is the wall area, m^2; δ_c is the wall thickness, m; τ_{mn} is the heat-transfer time, hour; Δθ is the temperature difference, °C.

The models of moisture and gas exchange can be based on the law of diffusion (Zernov, 1992)

$$M = -D F_\partial \Delta c \tau_\partial \quad (7)$$

where M is the amount of substance, kg; D is the diffusion coefficient, kg / (m^2 % hour); F_∂ is the diffusion surface area, m^2; Δc is the concentration difference, %; τ_∂ is the transfer time, hour.

Moisture exchange of wood with air between particles is carried out based on the equation of equilibrium moisture content of wood:

$$W_p = a_1 - a_2 \theta_\partial + (a_4 - a_5 \theta_\partial) \lg \sqrt{\frac{1}{1-\varphi_{oc}}} \quad (8)$$

where a_1, a_2, a_3, and $a_4$are coefficients that depend on the type of crushed wood and the current value of the relative humidity of the air; θ_∂ is the wood temperature, °C; φ_{oc} is the relative humidity of atmospheric air, %.

For crushed wood, expression (8) is as follows:

$$W_p = 4{,}0 - 0{,}035\theta_\partial + (19{,}7 - 0{,}075\theta_\partial) \lg \sqrt{\frac{1}{1-\varphi_{oc}}} \quad (9)$$

where θ_∂ is the wood temperature, °C; φ_{oc} is the relative humidity of atmospheric air in fractions of a unit, %.

The equation is valid in ranges: $0{,}1 < \varphi_{oc} < 0{,}75$; $0°C < \theta_\partial < 80°C$.

Consider a classic example of the development of a spontaneous heating center (Vasiliev, 2008).

According to this example, for 6 days of development of the spontaneous heating center, the temperature of the crushed wood increased from 21.7 °C to 41.7 °C, while the oxygen content changed from 20 to 14%, and the humidity increased from 21.65 to 21.95 %.

To do this, we fixT_2 = 1 h, T_3 = 1 h, and T_4 = 1 h. $K_{жа1}$ will change in the dependencies. We need to calculate the coefficients K_{10} and K_{12}. To normalize dependence (9), the assumption was taken as a basis. According to it, as a result of aerobic and anaerobic respiration of the same intensity, the same decrease in dry matter mass occurs. Then the ratio of the amount of heat resulting from these two types of respiration will be 25:1. This means that $K_7 = 25\ K_8$. Were obtained the optimal values of the coefficients $K_7 = 1600$; $K_8 = 64$; $K_{10} = 25$ and $K_{12} = 502$.

So, having regard to the above said, in the working model, the main dependencies will be as follows. Dependencies (5), (7), and (8) will be written as follows:

$$T_1 \frac{d\,M_{CB}}{d\,t} = -K_1 K_{жа1} - K_2 K_{жа2} \quad (10)$$

$$T_2 \frac{d\,\theta_\partial}{d\,t} = K_7 K_{жа1} + K_8 K_{жа2} \quad (11)$$

$$T_3 \frac{d\,W_\partial}{d\,t} = K_{10} K_{жа1} \quad (12)$$

$$T_4 \frac{d\,c_K}{d\,t} = -K_{12} K_{жа1} \quad (13)$$

The dependence of the vital activity coefficient of wood on the oxygen concentration in the air between the particles of crushed wood duringaerobic respiration is normalized taking into account that the maximum intensity of aerobic respiration will be at an oxygen concentration equal to the average statistical value of this parameter for the Earth's atmosphere, i.e. for 21%. It is logical to assume that theoretically the minimum intensity of aerobic respiration will be observed when the oxygen concentration is close to 0%. The value of the vital activity coefficient on the oxygen concentration during aerobic respiration in the working concentration range (from 0 to 21%) is determined by the relationship:

$$K_{жа1}(c_k) = e\frac{(c_k - 21)^2}{98} \quad (14)$$

The normalization of the working model should be made according to the data obtained by L.A. Trisvyatsky, Sholts, B.C. Sergunov et. al., which are published in the fundamental literature on the storage of bulk stock (Drysdale, 1990).

We will make the standardization for crushed wood stored in the outer bunker bay in its middle zone with a diameter of 6 m and a height of 20 m.

CONCLUSIONS

The obtained mathematical model of self-heating of chopped wood as a result of its respiration and vital activity of microorganisms (formulas (3) - (13)) makes it possible to predict the process of increasing the temperature of wood. At the same time, both possible processes of respiration of wood and microorganisms (aerobic and anaerobic) are taken into account, and no restrictions are imposed on their ratio. This provides the possibility of applying the model to the storage of chopped wood of various species and a wide class of microorganisms.

Since the many factors that influence this process are random, the process of self-heating of chopped wood is also a random process. Thus, the occurrence of a fire during the storage of chopped wood is a random event.

The assessment of the probability of spontaneous inflammation of crushed wood pulp stored in a bunker bay with forced ventilation should be made according to the values of the mathematical expectation $D(t)$, the variance $\sigma(t)$, and the probability density $f(t)$ in conditions of the Weibull distribution law, using formulas (3) - (13).

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