TEMPERATURE DYNAMICS IN SPRUCE WOOD UNDER FIRE

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Abstract. The potential risk of fire and burns is one of the biggest disadvantages of using wood as a building material. The cone calorimeter method was used to experimentally determine the burning process of spruce wood, which allows the reaction to the fire class according to the official EU classification system according to EN 13501-1: 2018. Using the experimental data, the dynamics of temperature change in different sample thicknesses was determined. The time required for moisture to evaporate closer to the surface of the flame is shorter than away from the surface, and the rate of temperature rise is much faster. When processing the experimental data, it was found that the influence of the sample thickness is significantly preserved up to the degree of 3, which indicates that the temperature distribution surface is inflection in relation to the thickness. The proposed mathematical model for the determination of temperature changes in wood during its combustion process shows a sufficiently good agreement with the experimental data and can be used to determine the temperature distribution in wood during the combustion process.

Keywords: spruce wood, temperature, fire, modelling.

Introduction

There are many publications on the use of wood in heating systems. Particular emphasis is placed on heating efficiency solutions as well as emissions from combustion products [1-4].

To better understand wood burning, this process is modeled. A detailed 3-D pyrolysis model using numerical solutions shows the flame shape and describes the interaction of a multiphase reactive material with several types of reactive gas mixtures [5].

Wood temperature is a key factor in wood burning, so it is important to know the dynamics of wood heating in order to predict the development of fire. Intensive wood burning process can take place only when the pyrolysis temperature is reached from 200 ºC.

Due to the widespread use of wood pellets, options are being actively sought to increase the economics of their use. Therefore, the combustion process of these pellets and also in naturally aspirated wood-burning stoves is much modeled [6-8].

An important factor in the use of wood is its use in construction, where the strength of these structures is an important condition at high temperatures, such as in the event of fire [9-11]. Various solutions are being sought to protect the wood itself. For example, using a safety net (fire-retardant material) [12], gypsum plasterboards [13], heat treatment of wood [14; 15].

In addition, it is important to understand the flow of heat inside the wood material itself at high temperatures, such as fires. This is especially important in apartments where wood is used to make doors and walls [10,13]. Wood drying, burning problems have been extensively studied, especially in terms of mathematical modeling [16-18].

This paper presents some experimental results on the burning characteristics and a mathematical model of heat transfer inside of wood samples during burning. The change of temperature during the combustion process is considered in the work. The formation of smoke, the formation of pyrolysis products, the rate of charring of wood, etc. are not considered.

Materials and methods

Spruce wood samples with dimensions 100 x 100 x 100 mm were prepared and 7 holes were made in the side face at a depth of 40 mm. The location of the holes from the plane exposed to heat radiation is 5, 15, 25, 35, 45, 55 and 65 mm. A sample holder for calcium silicate plates has been made to expose only one plane to heat radiation (Fig.1). The humidity of the samples was 10 ± 1%.

The combustion process is provided by 50 $kW \cdot m^{-2}$ heat radiation source. The study was performed in a conical calorimeter with a vertical heater position with 50 $kW \cdot m^{-2}$ heat radiation. The side faces of the sample are covered with mineral wool insulation to prevent spread and ignition of pyrolysis gases on the other side of the sample holder.

Changes in wood temperatures were recorded at 5 s intervals using data acquisition equipment and WinControl software. The tests are stopped when the sample charts more than 20 to 25 mm and begins to burn on the other side (Fig. 2).

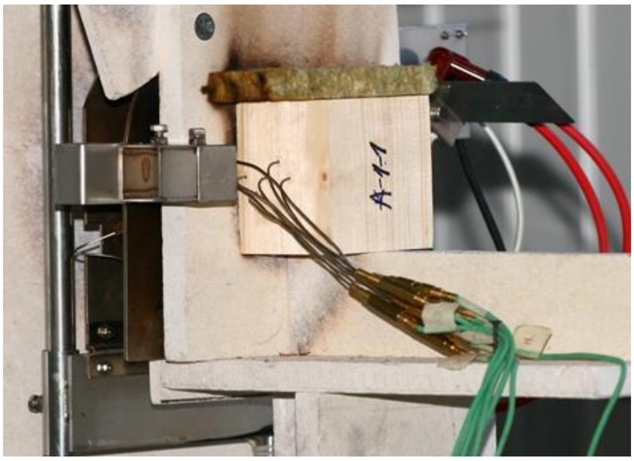

Fig. 1. **Measuring the temperature of a wood sample during combustion**

Fig. 2. **Wood sample after the experiment**

Mathematical model

The thickness of the sample is denoted by l and the heating process is solved in the interval $0 \le x \le l$, where $x = l$ is the burning surface of the sample. Burning of wood can be considered in three stages:

- I Heating to water evaporation temperature T_i
- II Water evaporation process,
- III Heating and carbon formation.

The temperature of the wood at time t and thickness x is $T(x, t)$, the moisture content $u(x, t)$. Thus, the temperature transfer equation is a system (1)

$$\begin{aligned} &\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\alpha(T)\frac{\partial T}{\partial x}\right) - \frac{q_0}{c^0 \cdot \rho^0}\frac{\partial u}{\partial t} - \frac{\sigma \cdot \varepsilon \cdot S}{c \cdot \rho}T^4, \\ &\frac{\partial u}{\partial t} = \alpha \frac{\partial u}{\partial x} \end{aligned} \tag{1}$$

where $\alpha(T)$ – thermal diffusion coefficients depending on T;
t – burning time;
x – thickness coordinate in $0 < x <$ l,
c – heat capacity of wood,
ρ – density of material,
c^0, ρ^0 – heat capacity and density at T = 100 ºC,
q^0 – amount of heat consumed in evaporating water,
ε – radiation ability,
$\sigma = 5.68 \cdot 10^{-8}$ – Boltzmann's constant,
S – radiation area.

The thermal conductivity coefficient:

$$\lambda = 0.026 + 1.195 \cdot \rho \cdot 10^{-3}.$$

As the density of wood depends on moisture, it is calculated:

$$\rho = \rho_0\left(1 + \frac{u}{100}\right),$$

where u – wood moisture, %.

At the initial moment the temperature of the sample is T_s, moisture u_s and the heat flow q is applied to the surface $x = l$, the other surface $x = 0$ is isolated by the initial temperature T_s. This means that equation (1) initial conditions are (2):

$$T\big|_{t=0} = T_s, u\big|_{t=0} = u_s. \tag{2}$$

And boundary conditions can be written as (3):

$$T\big|_{x=0} = T_s, \lambda \frac{\partial T}{\partial x}\bigg|_{x=l} = q, u\big|_{x=l} = 0 \tag{3}$$

The first term on the right side of equation (1) describes the change in the temperature in the sample, the second – the energy consumed by evaporating water, the third – the energy radiated by radiation. Problem (1) with initial and boundary conditions (2)-(3) is solved by the finite difference scheme.

Results and discussion

For the analysis of the research results, a specific experiment was chosen that best describes the mean values. Smoothing and averaging the data in this case compensates for the nature of the temperature change.

Looking at the dynamics of wood temperature changes at different material depths, (Fig. 3), the basic principles of the wood burning model described by Janssen [18] can be observed. Evaporation of moisture in the area of wood temperature 100 ºC and in the dynamics of wood heating it manifests itself in the fracture of temperature curves. The red curve describes the temperature change at a depth of 5 mm from the surface of the sample. In the period from the 90th to the 180th s the temperature of the wood is 100 ºC, after the wood in the area dries, the temperature of the wood begins to rise. Similar relationships can be observed at the depths of 15 and 25 mm. Due to the fact that the rate of temperature change in the deeper layers is lower, the temperature dynamics is much smoother and evaporation of water takes much longer (Fig. 3).

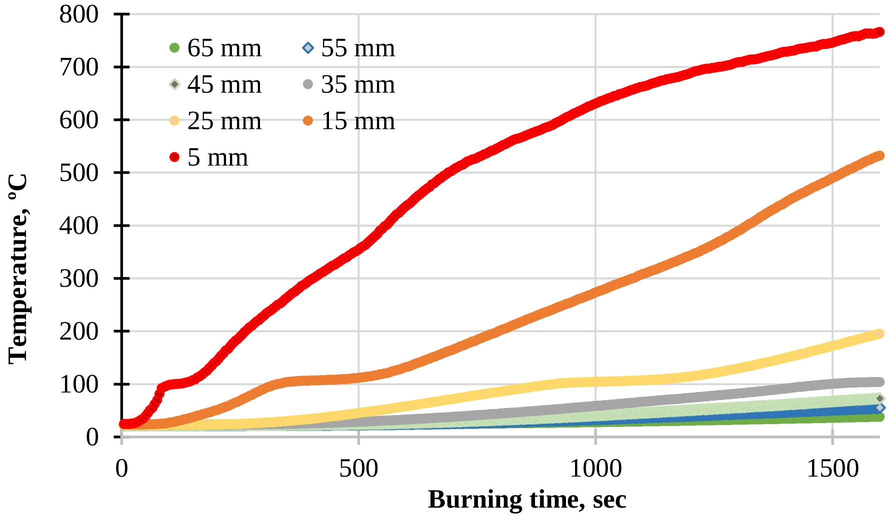

Fig. 3. **Dependence of the temperature change on the burning time in different depths of spruce wood**

Graphical interpretation of the experimental data is shown in Fig. 4.

Using the experimental data processing, a nonlinear relationship is obtained, which characterizes the temperature T(x,t) of spruce wood in the sample depending on the burning time t and the distance x to the burning surface (4):

$$T(x,t) = 668 - 61.16x + 1.49x^2 - 0.0108x^3 + 32.8t - 0.355t^2 - 0.455xt, \tag{4}$$

where t – burning time, min;
x – distance to the burning surface, mm;

all numerical coefficients are in 95% confidence bounds.

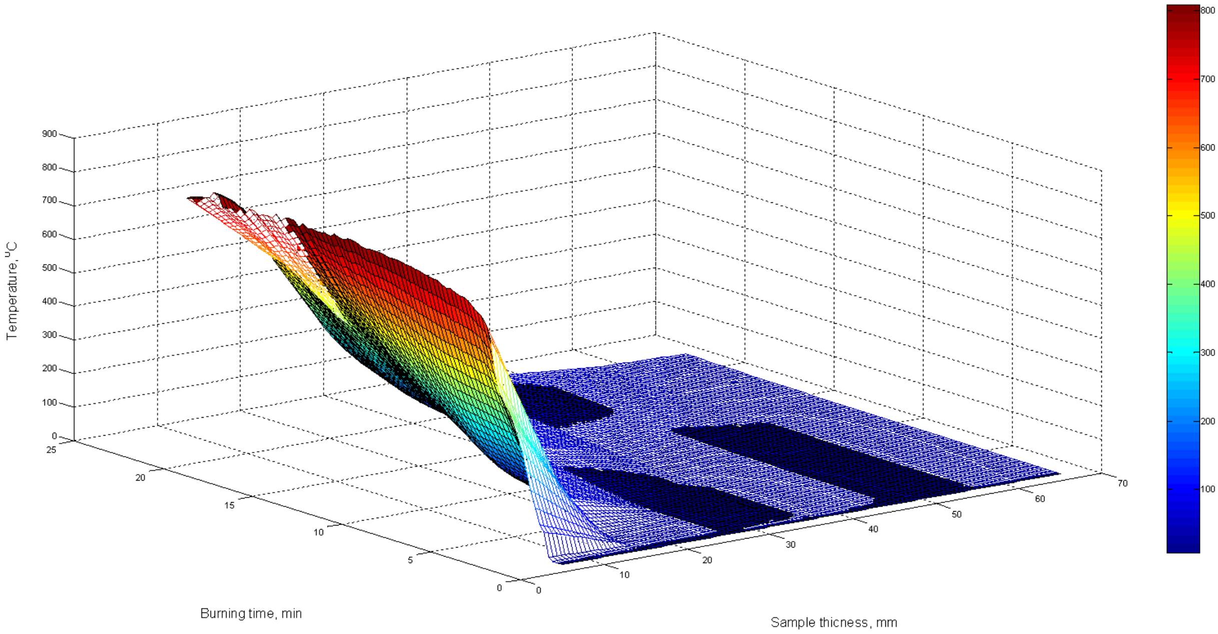

Fig. 4. **Dependence of the spruce wood temperature on the burning time and wood thickness**

The coefficient of determination η^2 = 0.933 shows a good agreement with the experimental data. Analyzing the theoretical calculation, it is shown that the thickness of wood samples takes an important role and, using cubic relation instead of quadratic for x, gives more that 6% better approximation of the coefficient of determination. This could be interpreted as a point of excess caused by water evaporation.

The graphical contour plot of (4) is shown in Fig. 5.

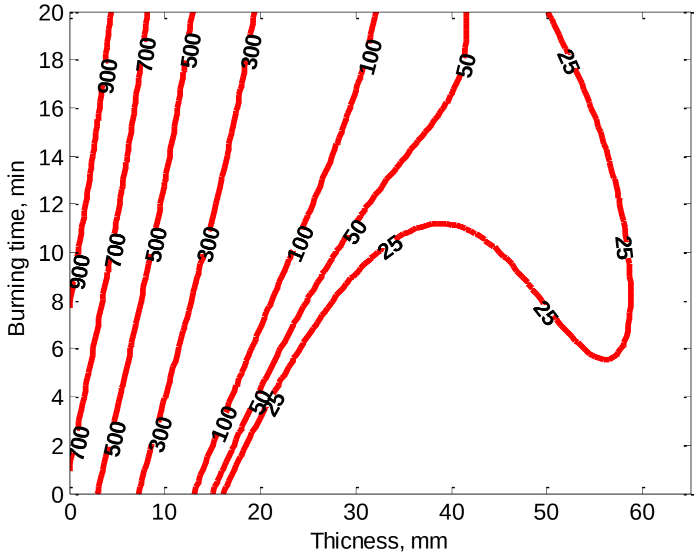

Fig. 5. **Contour plot of temperature distribution in the spruce sample**

Differentiating the temperature change over time gives the rate of temperature change shown at the depths 5mm, 15 mm and 25 mm (Fig. 6 and Fig. 7). The fastest rate of temperature increase is in the top layers of wood, it reaches a rate more than 2 $^{\circ}C\cdot s^{-1}$. The rate of change of the wood temperature clearly indicates the period of time when the wood temperature is 100 °C. Graphically this is expressed as a drop in the velocity to almost 0 $^{\circ}C\cdot s^{-1}$, at a depth of 5, 15 and 25 mm from the surface of burning. In the deeper layers, the temperature of the wood did not reach 100 ° C during the experiment.

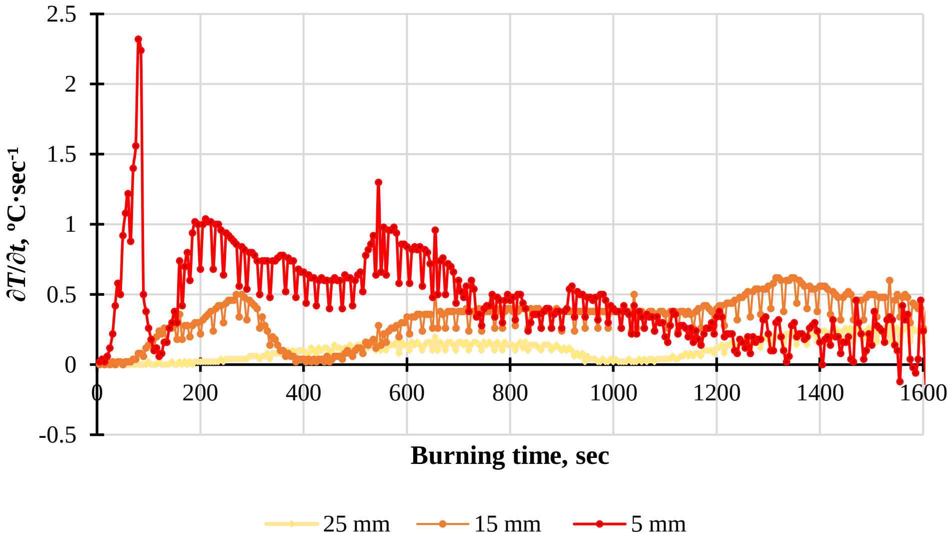

Fig. 6. **Velocity of temperature change in spruce wood at depths of 5, 15 and 25 mm from the burning surface**

Even over a long period of time, there is a significant difference between the temperature inside the burning wood and on the top layers. The temperature of wood in the upper layers increases at a rate of about 0.5 °C·s^{-1} in the case of stable wood combustion, while in the deeper layers (40 mm and more of the burning surface) the rate of increase of the wood temperature is less than 0.05 °C·s^{-1}.

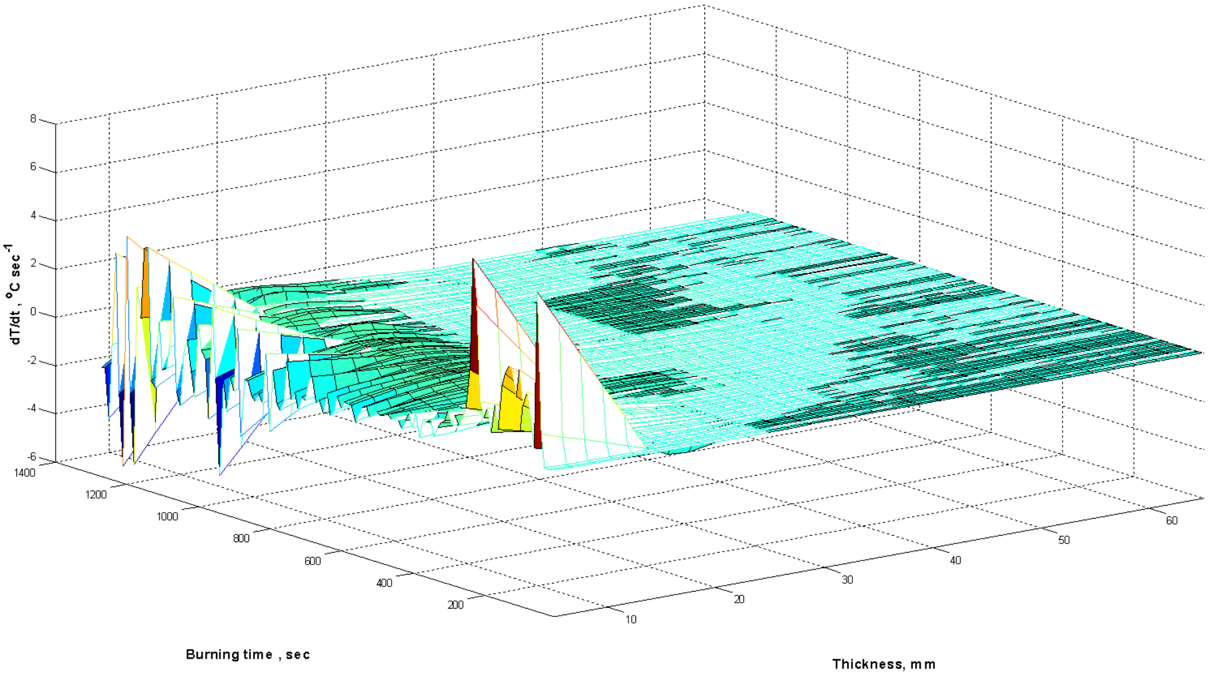

Fig. 7. **Velocity of temperature change in spruce wood depending on the burning time and depths of the material**

To numerically solve equation (1) with initial and boundary conditions (2)-(3), the area of the burning time and sample thickness are discretized.

The heat transfer is considered in 1-D space domain. Following discretization is used: $x_j = jh$, $j = 0, N_x, N_x \cdot h = l$, $t_n = n\tau$, $n = 0, N_t, N_t\tau = t_f, N_t = 1200, N_x = 50$.

The following values are taken for modelling: S = 100 cm^2, ε = 0.95, q = 50 W·(cm·°C)$^{-1}$, T_s = 20 °C, u_s = 10%, $\alpha(T)$ = 0.04 – 7.5·10$^{-6}T_s$, c = 2.3·103 kJ·(kg·°C)$^{-1}$, q_0 = 2256 kJ·kg^{-1}, ρ = 460 kg·m^{-3}, ρ_0 = 480 kg·m^{-3}.

The modelling results comparison with the experimental results is given in Fig. 8.

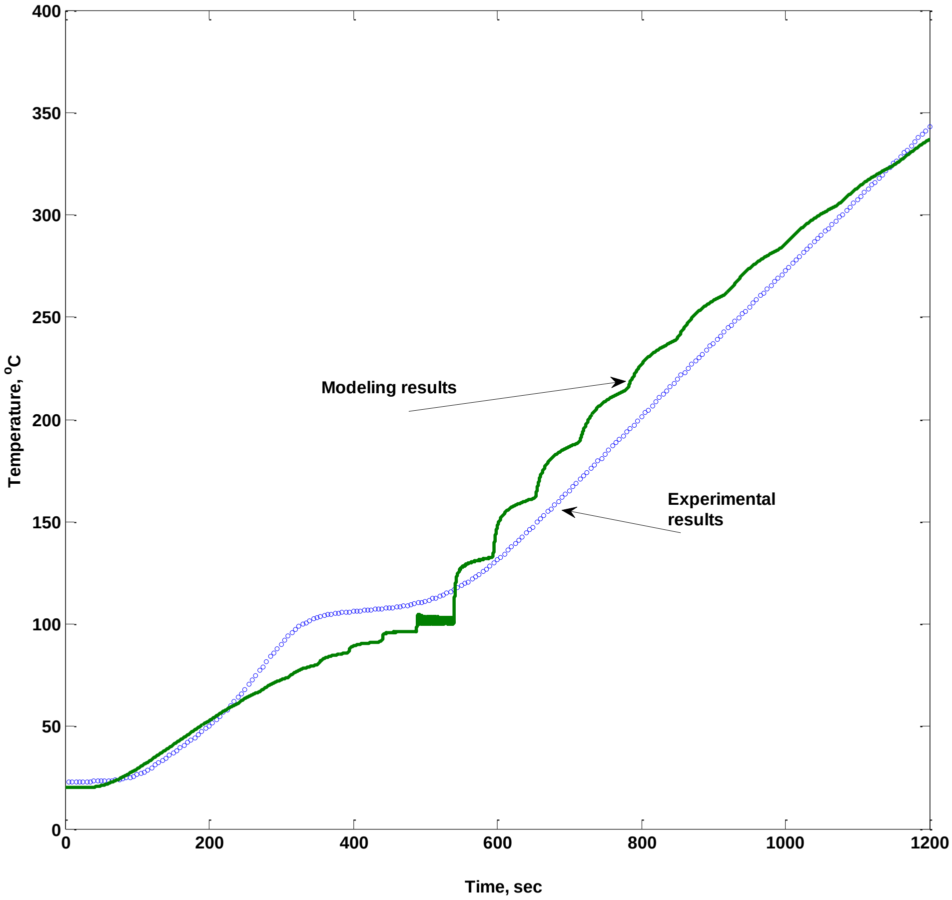

Fig. 8. **Temperature change in a spruce wood sample 5 mm from the burning surface**

It can be seen that the nature of both curves is the same. The experimental results show the evaporation time of water at 100 degrees Celsius. This time is less as a result of modeling, which could be explained by the difference in the moisture content (in the experimental and theoretical case), as well as the accuracy of the calculation results, the inhomogeneity of the experimental sample, etc. Most important in this case is the nature of both results, which shows that the given nonlinear Cauchy problem can be used to model the temperature of wood during the combustion process.

Note. Cone calorimeter method (standard EN ISO 5660-1:2015) is not included in the official EU classification system according to EN 13501-1:2018. There is no direct relationship between the obtained results of the cone calorimeter and reaction to fire classes. However, the results of the cone calorimeter could be used to predict results obtained in SBI test (standard EN 13823) [19].

Conclusions

1. The temperature of wood in the upper layers increases at a rate of about 0.5 $^{\circ}C \cdot s^{-1}$ in the case of stable wood combustion, while in the deeper layers (40 mm and more of the burning surface) the rate of increase of the wood temperature is less than 0.05 $^{\circ}C \cdot s^{-1}$.
2. The temperature dependence on the burning time and the thickness of the material obtained shows a good agreement with the experimental data. Analyzing the theoretical calculation it shows that the thickness of wood samples takes an important role and, using cubic relation instead of quadratic for x, gives more that 6% better approximation of the coefficient of determination. This could be interpreted as a point of excess caused by water evaporation.
3. The proposed mathematical model (1)-(3) of wood burning shows a good agreement with the experimental data and can be used to determine the temperature distribution in wood during the burning process.

Acknowledgements

The author thanks Dr.sc.ing. Edgars Buksans for the proposed experimental data.

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