Ignition of wood subjected to the decreasing radiant energy flux

V T Kuznetsov[1], A I Filkov[1,3,4], Yu N Isaev[2] and V O Guk[1]

[1] National Research Tomsk State University, 36, Lenina avenue, Tomsk, 634050, Russia
[2] National Research Tomsk Polytechnic University, 30 Lenina avenue, Tomsk, 634050, Russia

E-mail: aifilkov@gmail.com

Abstract. In this paper we analyze the ignition of wood samples subjected to the decreasing heat flow. The experimental setup was created on the base of the optical wave "Uran-1". The intensity of the heat flow was changed during the experiment by moving the test sample along the optical axis of the elliptic reflector in the setup. Pine wood was used as the test samples. We received the delay times for ignition of pine wood during heating by the decreasing heat flow. The received data were compared with the data for a static heat flow.

1. Introduction

In [1] it is reported that the ignition process is essentially dependent on the type of the heat flow, whether it is static or variable (when the ignition of fuels is initiated by the time-dependent heat flow). In recent years the dynamic regimes of ignition are mostly used in solving applied problems in the field of fire safety. In the real conditions the dynamic regimes are observed during anthropogenic and forest fires. At the same time, the ignition of fuels under variable conditions has been insufficiently studied. There are only some works [2–5], where the ignition of fuels was carried out under variable heat flux. Bilbao et al. [4] examined the ignition of wood exposed to different conditions of constant and variable heat fluxes. A time-decreasing heat flux was employed in their work, corresponding to the thermal radiation of a flame of natural gas or any other hydrocarbon produced in an accidental release of such material. However, the external heat flux always varies with the growth of a fire. Lizhong et al. [5] carried out the theoretical and experimental investigation on pyrolysis and spontaneous ignition of wood exposed to heat fluxes linearly increasing with time. Experiments were conducted for different wood species subjected to several increasing rates of heat fluxes. These results have shown that the characteristics of pyrolysis and auto-ignition of woods under variable heat flux differs from those under constant heat flux. However in examined works decreasing and increasing heat flux investigated under low heat fluxes. Taking into consideration that the variable type of the heat flow dominates in real conditions, the urgency of this problem is obvious.

2. Methods

To study the ignition of wood under variable heat flux, we created an experimental setup on the basis of the optical furnace "Uran-1" (figure 1*a, b*) with a radiation source (xenon lamp with a power of 10 kW) [6].
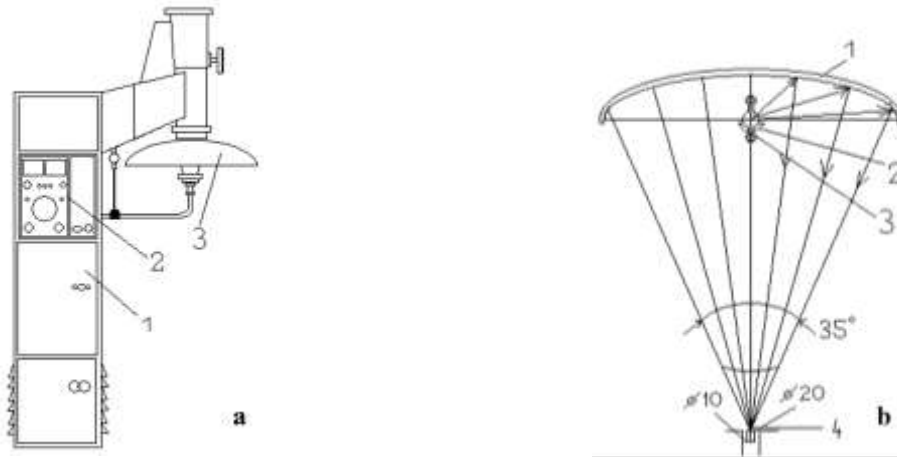

Figure 1. The scheme of experimental installation: a) optical furnace URAN-1: 1–power supply, 2–control panel, 3–radiator; b) optical radiator: 1–reflector; 2–counter reflector; 3–lamp; 4–action spot.

Optical radiation accounted for only 5.5 kW out of 10 kW generated by the xenon lamp. The radiation spectrum distribution was as follows: 0.5 kW (9%) in the ultraviolet region; 2 kW (36%) in the visible region, and 3 kW (55%) in the infrared region. The diameter of the focused flux was about $2 \cdot 10^{-2}$ m.

The recording unit of the experimental setup provided the measurements of the radiant flux density, exposure time, initiation of flame and controlled experimental conditions. It included a radiant flux density sensor, photodiodes, time relays and an N-117 light-beam oscillograph.

The density of a radiant energy flux in a focal spot was controlled by using radiation attenuators and changing electric power applied to the xenon lamp. The attenuators of the radiant energy flux were a metal grid that was placed perpendicularly to the optical axis at a distance of 0.3-0.4 m from the focal plane. The system of gates protects the test sample against early heating by the radiant flux and dosed supply of energy radiation.

The variable flow was modeled by the movement of the sample along the optical axis. For the movement of the sample it was used the following installation (by the example of the decreasing radiant energy flux, figure 2).
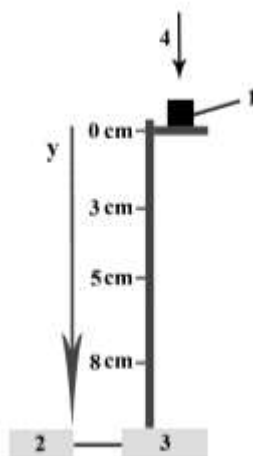

Figure 2. Installation for the movement of the sample: 1 – sample, 2 – control panel for motion of the site with a sample; 3 – mechanism that moves the sample; y = 0 cm is the focal plane; 4 – radiant heat flux; 3, 5, 8 cm are the distance from the focal plane.

Simultaneously with the opening of the gate, the transporter was turn on and the sample started moving with a constant speed of 0.117 m/s. The opening (closing) time of the gate was $4 \cdot 10^{-2}$ sec.

The test procedure was as follows. The intensity of the radiant flux was measured by a calorimeter fixed to the holder at the upper and lower points of the optical axis. Then the test sample was located on the place of the calorimeter and tested. The registration unit recorded the opening time of the gate and the initiation of flame. Ignition of the condensed substance was determined by the initiation of flame on the sample surface.

The calorimeter was a copper disk $1 \cdot 10^{-2}$ m in diameter and $3 \cdot 10^{-3}$ m in thickness with a thermocouple calked in the center of the disk to a depth of $1.7 \cdot 10^{-3}$ m. The measurement error of the radiation intensity did not exceed 10%. To determine the density of the radiant flux, we experimentally measured the heating rate of the copper disc subjected to radiation supplied to a blackened surface. The heat flux density was measured in the range $q = 20–110$ W/m^2.

The delay time of ignition was determined by a photoelectric method. The ignition time was considered to be a time interval from the exposure to the radiant energy flux up to the initiation of flame above the surface of the sample. Radiation of flame was registered using photodiodes. The H-117/1 oscilloscope was used for recording electrical signals. The measurement error for the ignition time is not more than 4% and is determined mainly by the physicochemical properties of the material studied.

Pine wood was used as the test samples. The samples were cylinders $1.9 \cdot 10^{-2}$ m in diameter and $1.5 \cdot 10^{-2}$ m in height. The surface of the samples, absorbing radiation, was covered by lampblack. The light radiation reached the sample perpendicularly to the wood fibers. The initial temperature of the samples corresponded to room temperature (297 K). The moisture content of the samples was 1.8 % and determined by using an A&D MX-50 moisture content analyzer with an accuracy of 0.01%. Unchangeable moisture content of the samples was provided by a desiccator filled with silica gel.

In this paper we analyze the ignition of wood samples subjected to the decreasing heat flow. To compare the delay time of ignition under static and variable conditions, the heat flux was averaged under variable conditions. For this purpose, the following method was used. The intensity of the radiant energy flux was measured with a microcalorimeter at fixed distances from the focal plane of the reflector.

Knowing the speed of the sample along the optical axis of the elliptical reflector, we can turn from fixed values of the distance to the time. In this case, the dependence of the heat flow on time is well enough (correlation $R^2 = 0.997$) approximated by the function (figure 3):

$$q = a\,\mathrm{e}^{-0.7t} - 2 \qquad\qquad (1)$$

where q is the heat flow, W/m^2; t is the time, s; a is the nondimensional coefficient.
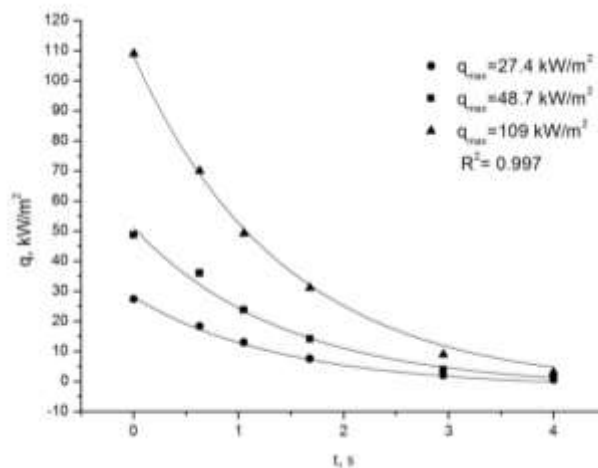

Figure 3. Heat flow versus time when the sample is moved from the focal plane.

Thus, depending on the value of heat flow in the focal plane (t=0) we can determine a coefficient *a* and changes of the heat flow at the surface of the moving sample by using the formula (1). The delay time of ignition was measured using a photodiode determining the initiation of flame. Knowing the ignition delay time of the sample we can find a heat flow in the ignition point using a distribution curve q(t). Since the sample of pine ignites within one second in the tested range of the heat flow, then from figure 3 it can be seen that the curve is quasilinear in this range. In this connection, the average heat flow was determined as the arithmetic mean value for variable conditions.

3. Results and discussion

Figure 4 shows the ignition delay times of the pine samples for variable (q=f(t)) and static (q=const) [6] heat supply.
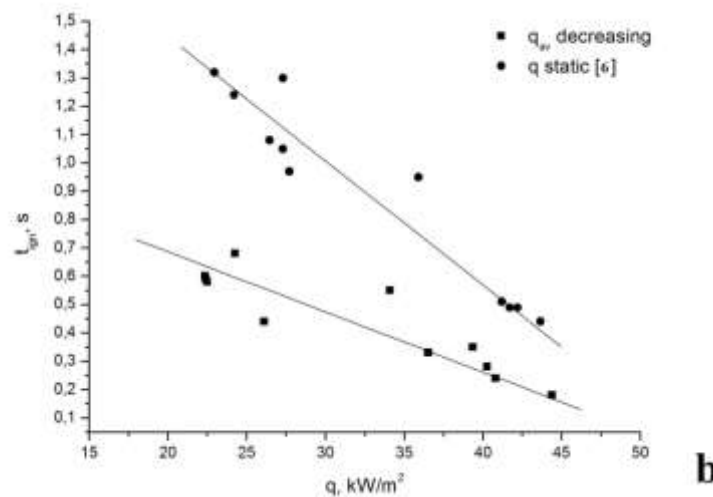

Figure 4. Ignition delay times of the pine samples versus heat flow for variable and static conditions [6].

When the radiation flux decreases, the delay time for ignition of the pine samples is 2-2.5 times less than that for the constant radiation flux. At the same time, figure 4 shows that the decrease in value of heat flux leads to the fact that the delay time of ignition increases faster under static conditions than under variable ones. It should be noted the fact that when we compared the time of ignition for the variable and static heat flow in this work, the variable mode was determined by the average heat flow during the experiment.

The physical considerations imply the following facts. If the ignition time is substantially less than the thermal relaxation time for the material under study in the experiment, the variable supply of radiant energy results in the formation of the heated layer on the sample surface. Heating of this layer requires less energy for ignition of wood.

Estimation of the thermal relaxation time of pine wood gives the following values

$$t_r \approx \frac{a}{u^2} = 1.84 \cdot 10^3 \ s \tag{2}$$

where a is the thermal conductivity of pine wood, $1.84 \cdot 10^{-7}$ m^2/s [7]; u is the normal combustion rate, 10^{-5} m/s [8]. It is seen that the relaxation processes of heat distribution in wood is much slower than the ignition process for the considered heat flows. At the same time, the temperature gradient on the sample surface is generally higher in a variable mode than that in the static mode, i.e. the surface temperature reaches a critical value faster than in the static mode. Therefore, for the same heat flow,

the ignition time in the variable mode should be smaller than in the static mode. The increase in flow of radiant energy leads to the fact that the difference in the ignition delay decreases for variable and static conditions (figure 4), which confirms this assumption.

These results do not contradict the paper [9], where the mathematical modeling shows that in the case when the heat flow decreases, the delay time for ignition of wood is less than that for the constant heat flow.

The next step of this work is to study the properties of ignition for the increasing heat flow and the data analysis. The received results can be used to improve the prediction of dangerous zones for ignition of wood during wildland and anthropogenic fires.

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