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STUDY OF THE EFFECTIVENESS OF EXTINGUISHING MODEL FIRES OF CONIFEROUS AND DECIDUOUS WOOD

Purpose. Establishing the feasibility of using the FDS computer model to determine the specific consumption rate of finely sprayed water for extinguishing wood as an alternative to physical modeling.

Methodology. The study utilized the functionality of the Fire Dynamics Simulator (FDS) computer model; a methodology for determining the consumption and volume of extinguishing agents for extinguishing model fires of type 1A for various wood species within a specially designed testing ground for experimental fire tests; the results of the research were processed using Microsoft Excel.

Findings. According to the results of computer modeling, it was established that for the combustion of selected wood species over a duration of 0–180 seconds, the highest temperature in the fire center occurs for fir at 173 seconds, reaching 1,180 °C. The peak temperature in the combustion environment for common pine is observed at 170 seconds, measuring 1,165 °C. The temperatures for silver birch and common oak were lower, at 1,000 °C (178 seconds) and 855 °C (173 seconds), respectively. After applying finely sprayed water to the fire center of the model fires made of pine and fir, the temperature decreased below the ignition point after 57 seconds, with a water consumption rate of 2 l/s. For the extinguishing of model fires made of oak and birch, the extinguishing effect was observed at 135 and 105 seconds, respectively. Based on the conducted research, the specific consumption rates of finely sprayed water for extinguishing common oak and common pine were determined to be 168 and 120 l/m^3, respectively.

Originality. For the first time, the Fire Dynamics Simulator (FDS) computer model was used to simulate the extinguishing process for four of the most common types of forests – common pine, Douglas fir, silver birch, and common oak. It was established that when extinguishing fires in coniferous wood species with a finely sprayed water consumption rate of 2 l/s, the extinguishing effect is achieved at 57 seconds.

Practical value. The conducted computer modeling and experimental field studies allowed for the determination of the calculated amount of finely sprayed water needed for extinguishing fires in various wood species. The specific consumption rates of extinguishing agents for fighting fires in coniferous and deciduous wood species can be used for calculating the forces and resources required for firefighting in forested areas.

Keywords: *model fire, computer modeling, field experimental studies, extinguishing wood, finely sprayed water*

Introduction. Forest fires, as fires in ecosystems, are natural emergencies that cause catastrophic consequences for the environment [1]. A range of factors – both natural and anthropogenic – contributes to the occurrence of forest fires. As a result of these fires, the overall state of the environment deteriorates, and irreversible processes can sometimes occur in ecosystems. Additionally, forest fires can have serious consequences for human health [2, 3], as they can provoke the emergence of dangerous diseases and exacerbate existing chronic conditions in people of all ages [4].

Forest fires in coniferous species, particularly pine, are especially dangerous due to the specific properties of these trees and the ecosystems in which they grow. Coniferous trees, such as pines, spruces, and firs, have a high resin content, which is highly flammable and facilitates the rapid spread of fire through the trunks and crowns of the trees [5]. At the same time, fires are also characteristic of deciduous forests, which have somewhat different biological properties [6]. Deciduous forests, especially oak and birch, do not contain resin as coniferous forests do; however, they have a higher heat release capacity, which alters the behavior of fire development in these stands compared to coniferous forests.

For both coniferous and deciduous forests, the most important task is to prevent the occurrence of fires [7]. However, equally important is the study of the extinguishing processes for such fires, taking into account the intensity of the application of extinguishing agents to burning wood depending on the types of forests – coniferous and deciduous.

Literature review. A number of works have been dedicated to the study of the processes of occurrence, spread, limitation of development, and extinguishing of fires in natural ecosystems. It is worth noting that such studies are conducted using modeling methods, including computer simulations, field tests, experimental ignitions, and comprehensive approaches. The authors of works [8, 9] conducted a comprehensive experimental study of the development and extinction processes of fire using the Wildland Fire Dynamics Simulator, which provided results close to the actual data based on experimental ignitions. In the study [10], researchers conducted an experimental investigation of the extinguishing of wooden elements used in industry and found that the results obtained were equivalent to the standards declared for such tests. In work [11], scientists investigated the extinguishing agents based on water that they proposed for extinguishing wood, including within forested areas. In their research, Shaorun Lin et al. established the effectiveness of using water as an extinguishing agent, which can be applied for extinguishing solid combustible materials of natural origin, including peat [12, 13].

Additionally, experimental studies using model fires made of various wood species were conducted in works [14, 15], where the flame spread rates across these different wood species were established. To investigate the effectiveness of extinguishing fires in pine wood using water-based extinguishing agents, the authors of study [16] employed patented stationary equipment under laboratory conditions, which allowed them to determine that at 32 minutes from the start of the fire tests, the temperature of the combustible material decreased by 1.37 times compared to the temperature at 25 minutes, which was 455 °C.

Unsolved aspects of the problem. Despite the rapid development in the field of extinguishing forest fires, the issues of standards and recommendations regarding the use of water for extinguishing coniferous and deciduous forests remain insufficiently studied. Considering that water has several advantages over other extinguishing agents and can effectively prevent the ignition and limit the spread of flames [17], it is important to have knowledge about selecting its specific consumption rate for extinguishing fires. Currently, the specific consumption rates of water are standardized only for finished products – such as round timber in stacks, sawn wood, or other wood-derived materials – without specifying their origin as either coniferous or deciduous.

Purpose and objectives of the article. As mentioned, the aim of the research is to establish the intensity of finely sprayed water application for extinguishing coniferous and deciduous wood species using computer modeling and experimental field studies, with the potential to calculate the forces and resources required for extinguishing forest fires.

To achieve the outlined goal, the following tasks were formulated:

- to conduct computer modeling of the development and extinguishing of a model fire with geometric parameters of a type 1A fire made from various wood species;
- to compare the results of computer modeling with the experimental data on the development and extinguishing of the type 1A model fire;
- to determine the specific consumption rate of the extinguishing agent for extinguishing fires made from different wood species based on the results of experimental studies.

Research methodology. The research was conducted in two stages: computer modeling and experimental field testing.

Stage I – computer modeling – was carried out using the Fire Dynamics Simulator (FDS) [18, 19] to determine the extinguishing capability of finely sprayed water when extinguishing fires made from various wood species. The fire model was created in accordance with the requirements of DSTU 3675 [20].

Under the stack, a deck with gasoline for igniting the stack was modeled, which is conditionally depicted in Fig. 1 as a square measuring 400 × 400 mm. The flammable liquid used for ignition was 95-octane gasoline. This decision is explained by the fact that 95-octane gasoline has the appropriate flash point and viscosity, making it ideal for many types of research related to fuel and its combustion behavior. Using standard fuel also allows for comparison of results from different experiments.

The volume of gasoline was 1.1 liters. The duration of fuel burning was calculated based on the specific mass burning rate, the density of the gasoline, and the surface area of the deck.

$$\tau_{burn} = \frac{\rho \cdot V}{\psi \cdot F}, \quad (1)$$

where ψ (kg/m² · s) is the specific mass burning rate; ρ (kg/m³) is the density of the material; F (kg) is the surface area of the deck.

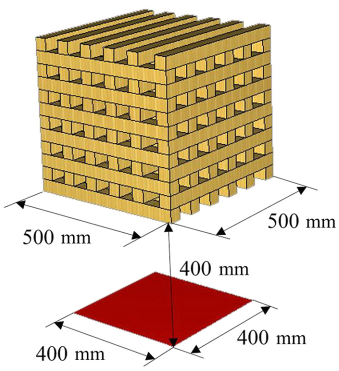


Fig. 1. The model of the simulated fire load in the form of wooden blocks

For the study, stacks made from four wood species were modeled: common oak (*Quercus robur L*), common pine (*Pinus sylvestris L*), douglas fir (*Abies alba*), and silver birch (*Betula pendula*). The thermal-physical parameters of the wood [21] are presented in Table 1.

The placement of the wooden blocks was carried out in accordance with the requirements of DSTU 3675 and is depicted in Fig. 1. The stack was formed from wooden blocks measuring 500 mm in length and with a cross-section of 40 × 40 mm.

Thus, the burning duration is 46 seconds, which is confirmed by the conducted studies [22].

To monitor the temperature of the fire center, a thermocouple was modeled and placed at the center of the stack (Fig. 2). To determine the extinguishing capability, a fire nozzle for applying finely sprayed water to extinguish the stack was modeled. The fire nozzle was positioned above the stack at a height of 1.8 m from the zero level of the surface.

To cover the entire surface of the stack with water, a spray angle of 19° was specified.

The application of finely sprayed water was carried out when 45 % of the stack's initial mass had burned. To determine the appropriate timing for applying the extinguishing agent, the specific mass burning rate of the wood, which is 0.015 kg/m² · s, was taken into account. Thus, the sprayed water was applied at the *180th* second from the moment the stack was ignited.

For the second stage – experimental studies – a methodology was proposed which involves determining the consumption and volume of extinguishing agents for extinguishing a model fire made from various wood species, as well as monitoring the temperature changes in the fire center during the development and extinguishing of the fire. The result of the research is the determination of the duration of the necessary

Table 1

Thermal-physical parameters of wood

Wood species	Quercus robur *L*	Pinus sylvestris *L*	Abies alba	Betula pendula
Thermal conductivity coefficient, W/kg. °C	0.166	0.112	0.11	0.15
Density, kg/m³	540	430	420	567
Specific heat capacity, kJ/K	2.4	2.8	2.752	1.25
Lower heating value, kJ/kg	20,200	19,200	21,000	20,000
Ignition temperature, °C	230	205	204	260

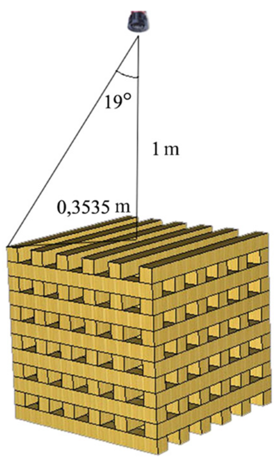


Fig. 2. Schematic representation of the nozzle placement for extinguishing the fire in the stack model

application of extinguishing agents at a constant rate for extinguishing 1 m² of fire while burning different wood species.

The testing was conducted at an experimental fire testing site in an open area. The experimental site was constructed as a platform made of reinforced concrete slabs over the entire area. The research was carried out in the absence of precipitation and with wind speeds not exceeding 5 m/s. Five minutes before the start of the tests, the initial values of temperature and humidity of the environment, as well as wind speed, were recorded. The initial temperature measured by the thermocouple was 12 °C during the first trial and 24 °C during the second trial.

For the study, the following equipment and measuring instruments were used: an eight-channel temperature measuring device PT 0102, a thermocouple (chromel-alumel) TXA, a stopwatch CASIO HS-80TW-1EF, AXIS hygrometers, laboratory scales TVE–24, equipment for photo and video recording, a 20 m pressure hose line with a diameter of 32 mm, a PROTEK 366 fire nozzle, and a fire truck APD-2(33023) "Delphin".

To create the fire load, a model fire was used, the combustion of which simulates temperature conditions similar to those of a real site. The study was conducted in two stages for extinguishing the model fire: in the first stage, the fire load was created using pine blocks; in the second stage, it was created using oak blocks. The blocks of the model fire were arranged in a grid pattern. The model fire was placed on concrete blocks at a height of 200 mm above the zero level of the experimental site. To ignite the model fire, a tray containing 1.1 liters of fuel was used. Above the center of the model fire, at a height of 10 cm, a thermocouple was placed to measure the fire temperature during free development and extinguishing (Fig. 3).

The beginning of the test was the ignition of the gasoline in the tray. Observations were made visually and through photo and video recording.

The main findings and conclusions of scientific research. The modeling process is conditionally divided into the following stages:

- ignition and combustion of gasoline in the tray under the stack;
- ignition and sustained burning of the stack;
- cessation of gasoline combustion in the tray and continued burning of the stack;
- application of sprayed water to the fire center;
- reduction in temperature in the fire center below the ignition temperature of the wood;
- cessation of burning.

Fig. 4 shows a step-by-step visualization of the modeling process for the development and extinguishing of the fire in model fire 1A made of pine blocks with a sprayed water jet, specifically at 5, 30, 90, 120, 180 and 240 seconds from the start of ignition.

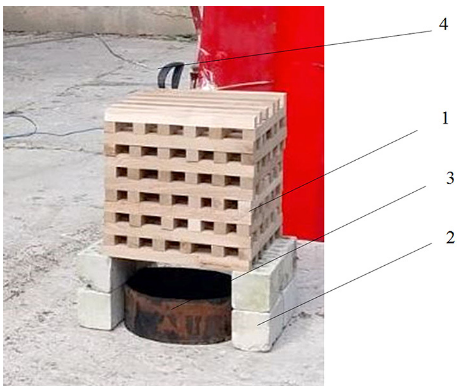


Fig. 3. View of the model fire:

1 – stack of wooden blocks; 2 – supports; 3 – tray with fuel; 4 – thermocouple

The visualization of the results was obtained using the Smokewiev application [23], which is part of the computer model's functionality. The simulation results (Fig. 5) showed that after applying sprayed water during the extinguishing of the model fire, the temperature on the surface of the material dropped sharply to 64 °C. This can be explained by sudden cooling of the combustion zone due to heat absorption, as well as the formation of water vapor. However, it was later noted that the temperature increased to 580 °C. According to the simulation results, the extinguishing lasted 57 seconds with a water flow rate of 2 l/s.

Similar studies were conducted for the model fire made from blocks of oak, fir, and birch.

During the computer modeling using Smokeview, changes in temperature distributions in the combustion environment were obtained. Additionally, an increase in the heat flux in the combustion environment of the pine blocks was observed, specifically at 30 seconds after ignition.

As shown in Fig. 5, the combustion of fir and pine occurs more intensively. One of the factors influencing this difference is the significant disparity in material density. After spraying water into the fire center of the model fires made from pine and fir, a decrease in temperature below the ignition point is observed after 57 seconds, with a fire extinguishing agent flow rate of 2 l/s. In contrast, when the same amount of spray water is applied to extinguish the model fires made from oak and birch, the fire extinguishing effect is observed later – at 135 and 105 seconds, respectively.

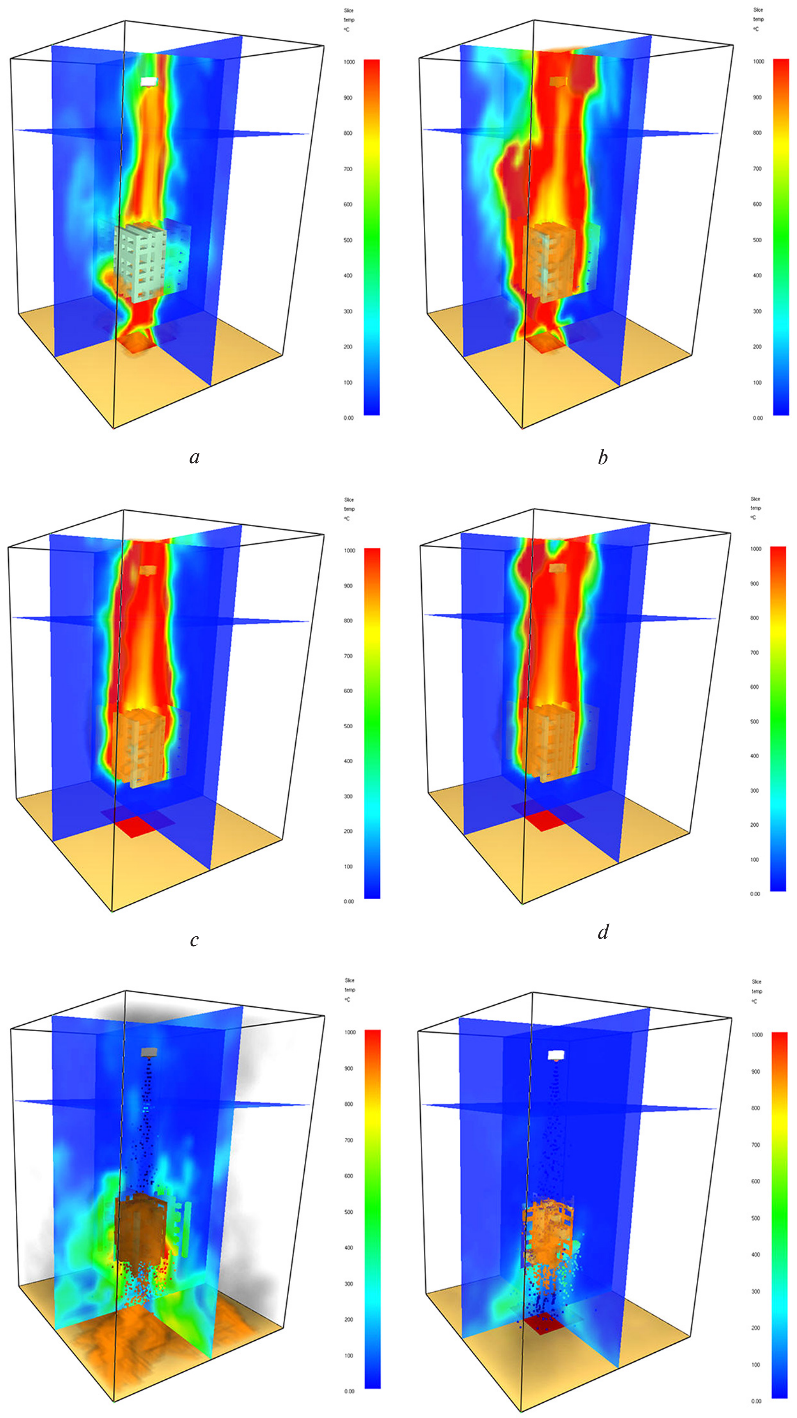
During the experimental studies, the free burning of the model fire lasted for 5 minutes, after which the extinguishing process began. The tests were concluded once the combustion stopped, and no re-ignition of the wood occurred after the experiments were finished.

The extinguishing of the model fire is carried out by spraying finely atomized water using the PROTEK 366 fire nozzle, supplied from the APD-2(33023) "Delphin" fire truck through a 32 mm diameter fire hose (Fig. 6).

To determine the flow rate of the fire nozzle, after extinguishing was completed, a cylindrical container was filled with water without changing the position of the nozzle lever or the RPM of the internal combustion engine driving the fire pump. The time taken to fill the container and the volume of water were measured using a stopwatch. The results of the temperature measurements in the fire area during the experiments are presented in Fig. 7.

In Fig. 7, we see that the combustion temperature of the model fire made of pine logs increases after 100 seconds from the start of ignition compared to that of oak, and its decrease is observed after 300 seconds of the fire. The rise in temperature in the combustion zone of the model fires during the physical experiments occurs more slowly than in computer simulations. This can be attributed to changes in the specific mass burning rate under physical modeling conditions. During the experimental studies, after the application of fine mist water at a rate of 0.4 l/s to the combustion zone of the model fires made of pine and oak, the extinguishing took 30 and 42 seconds, respectively, until the flame ceased, which coincided with the temperature dropping below the self-ignition point. However, this duration is significantly shorter than that observed in the computer simulations. After the extinguishing of the fire with fine mist water, no re-ignition of the wood was observed. Additionally, the readings from the thermocouple continued to decrease after the cessation of fine mist water application. Comparing the results of computer simulations and experimental studies, we find that the results show acceptable divergence.

The results of the conducted research provided the basis for determining the calculated amount of water spray needed for extinguishing fires in different types of wood. The volumetric actual specific consumption of extinguishing agent, l/m³, for fire suppression was determined using the following relationship



a, *b*, *c*, *d*, *e*, *f*

Fig. 4. Modeling of the combustion and extinguishing processes of the model stack made of pine blocks:
a – at 5 s; b – at 30 s; c – at 90 s; d – at 120 s; e – at 180 s; f – at 240 s

$$Q_{swe} = \frac{Q_f \cdot \tau_{ext}}{V_b}, \qquad (2)$$

where Q_f is the actual consumption of the extinguishing agent for fire suppression, l/s; V_b – volume of the model fire, m³.

Thus, after performing the calculations, we obtain the values of the specific consumption of extinguishing agents for extinguishing fires from different types of wood, as shown in Table 2.

The obtained results will allow for the calculation of the forces and means that will be used to extinguish fires in forested areas, particularly regarding logging residues, taking into account the types of forests.

Conclusions and prospects for further development in this area. Alongside the issue of fire prevention in forests, extinguishing them remains an essential task. One aspect of this is determining the consumption of extinguishing agents, as the diversity of forest areas generates scientific interest in researching the necessary intensities of water application for effective firefighting.

In this study, using the Fire Dynamics Simulator (FDS) computer model, the intensities of finely atomized water application for extinguishing fires in four types of wood were investigated: common oak (*Quercus robur L*), Scots pine (*Pinus sylvestris L*), European silver fir (*Abies alba*), and silver birch (*Betula pendula*).

Through experimental research, after applying atomized water at a rate of 0.4 l/s to the fire centers of model fires made from pine and oak, the extinguishing process until the flame's

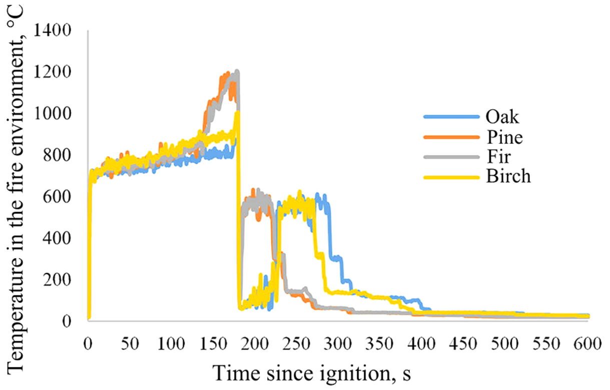


Fig. 5. Temperature of the focal point of the model fire, constructed from various wood species, considering the extinguishing of the fire with a spray of water

a *b*

Fig. 6. The procedure for conducting the tests (model fire with pine beams) includes the following stages:

a – free development of the fire; b – the process of extinguishing the fire

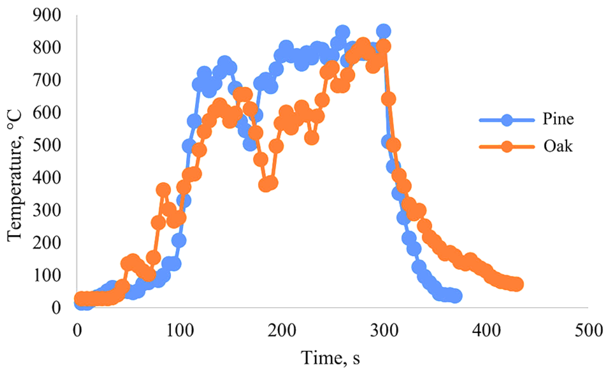


Fig. 7. Values of thermocouple readings during experiments

Table 2

Specific consumption of extinguishing agents for extinguishing fires

Wood species	Oak	Pine
Specific consumption of finely dispersed water, l/m³	168	120

being completely out occurred within 30 and 42 seconds, respectively, which coincides with the observed decrease in temperature below the self-ignition point.

According to the calculated specific water consumption for extinguishing fires in model fires, it was established that the specific consumption of atomized water for extinguishing common oak is 168 l/m³, which is 1.4 times higher than the value for common pine.

The results obtained in this study can be used for calculating the resources and means for extinguishing fires in coniferous and deciduous forests, as well as for planning firefighting measures for different types of forests.

Prospects for further development may include research based on computer modeling and field experiments aimed at determining the extinguishing agent requirements for fire suppression in grassland ecosystems.

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Дослідження ефективності гасіння макетних вогнищ деревини хвойних і листяних порід

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Мета. Встановлення можливості використання комп'ютерної моделі FDS для визначення величини питомої витрати тонкорозпиленої води на гасіння деревини як альтернативи фізичному моделюванню.

Методика. У роботі використано функціонал комп'ютерної моделі Fire Dynamics Simulator (FDS); методику визначення витрат та об'єму вогнегасних засобів для гасіння модельного вогнища типу 1А для різних порід деревини в межах спеціально розробленого полігону для експериментальних вогневих випробувань; оброблення результатів досліджень виконано в середовищі Microsoft Excel.

Результати. За результатами комп'ютерного моделювання встановлено, що для горіння обраних порід деревини тривалістю 0–180 сек. температура осередку пожежі є найвищою для ялиці на 173-ій сек. та становить 1180 °С. Найвище значення температури в середовищі горіння для сосни звичайної спостерігається на 170-ій сек. і становить 1165 °С. Температури для берези повислої та дуба звичайного були нижчими та становили 1000 °С (178 сек.) та дуба 855 °С (173 сек.) відповідно. За результатами подавання розпиленої води до осередку пожежі макетних вогнищ із сосни та ялиці зниження температури нижче температури самозаймання відбувалось через 57 сек. за витрати тонко розпиленої води 2 л/с. При витраті води на гасіння макетних вогнищ дуба й берези ефект від гасіння наступив на 135-ій і 105-ій сек. відповідно. На підставі проведених досліджень отримані значення питомих витрат тонко розпиленої води для гасіння дуба звичайного – 168 л/м^3 та сосни звичайної – 120 л/м^3.

Наукова новизна. Уперше з використанням комп'ютерної моделі Fire Dynamics Simulator (FDS) проведене моделювання процесу пожежогасіння 4-ох найпоширеніших типів лісу – сосни звичайної, ялиці гребінчастої, берези повислої й дуба звичайного. Встановлено, що при гасінні пожежі хвойних порід деревини з витратою тонко розпиленої води величиною 2 л/с вогнегасний ефект досягається на 57-ій сек.

Практична значимість. Проведене комп'ютерне моделювання та експериментальні полігонні дослідження дали змогу встановити розрахункову кількість подавання тонко розпиленої води при гасінні вогнищ із різних порід деревини. Величини питомої витрати вогнегасної речовини на гасіння пожежі хвойних і листяних порід деревини можуть використовуватись для розрахунку сил і засобів для гасіння пожеж у лісових масивах.

Ключові слова: *модельне вогнище, комп'ютерне моделювання, полігонні дослідження, гасіння деревини, тонко розпилена вода*

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