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# Efficiency of using a water curtain device in forest fires

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## Abstract

The article presents statistics of forest fires in Ukraine, characterizes large-scale forest fires in the world and their consequences. Presented methods of detecting and reducing the intensity of the spread of forest fires and fires in ecosystems that were under previous radioactive or chemical contamination do not always bring the desired result, so the authors suggest using their patented device to create a water curtain. The purpose of the article is to present a mathematical model of irrigation with this device. To conduct the research, a stand was used, with the help of which the results of changes in pressure, flow rate, spray radius were obtained experimentally. Empirical dependencies were established, on the basis of which a mathematical model of irrigation with a water curtain device was built. The model is necessary to determine the parameters of the device and improve the quality of calculations necessary during forest fire extinguishing.

**Key words:** cloud deposition, fire protection, irrigation intensity, liquid consumption.

## Introduction

The issue of preserving forests and protecting them from various harmful factors of both natural and anthropogenic nature is important, complex and large-scale. A prominent place in the highlighted problem is the issue of protecting forests from fires.

Large-scale studies of the long-term dynamics of forest fires have shown a constant increase in their number. In recent history, the period of rapid development of fire and rescue services in the first half of the 20th century, when the total area of fires in the world decreased, can be considered an exception. However, at the beginning of the 21st century, the number of protracted significant forest fires, which led to human casualties and material damage, continued to grow (Zibtsev et al. 2019, Lahno et al. 2022).

Scientists point to a relationship between fire and climate change that could overshadow the effects of global warming on plant distribution and migration and have significant implications for forests, forestry, human protection and the economy. Scientists call fires the main factor in the restoration of forest stands, which significantly affects the structure and functions of the forest (Flannigan et al. 2006, Neary and Leonard 2015, Sydorenko et al. 2022).

For example, in 2018, due to the long-term accumulation of a large mass of dry trees in forests and heat, large-scale forest fires occurred in the state of California, USA, as a result of which at least 86 people died, more than 500 people went missing, and more than 7200 buildings were destroyed. As a result of merciless felling, the fires of the ‘lungs of the planet‘ – the Amazonian tropical forests – are regular. In 2019, it was not possible to extinguish the fire for 10 months, 900,000 ha of forest burned. In 2019–2020, during the so-called ‘Black Summer’ in Australia, forest fires caused by seasonally high temperatures and drought – about 18 million ha were destroyed, more than 30 people died (Word and Deed 2020).

The total area of forest plots belonging to the forest fund of Ukraine is 10.4 million ha, including 9.6 million ha covered with forest vegetation. In 2022, 1009 fires on an area of 15.5 thousand ha were eliminated in the forests of this sphere. The average area of one fire was 15.4 ha, and the damage was 11 million euro. Forest fires occur mainly due to careless handling of fire by the population. In 27 % of cases, the forces and means of the State Emergency Service were involved in extinguishing them (SFRAU 2022).

Domestic scientists, observing a clear trend towards an increase in the area of large forest fires, draw attention to the high combustibility of forests in Ukraine, the key factors of which are considered to be the lack of funding of forest fire services, insufficiently effective training and interaction with operational and rescue units of their employees, as well as non-fulfillment of current legislative requirements regarding fire prevention and their imperfection (Zibtsev et al. 2019).

The negative consequences of fires in forest ecosystems arise from the great importance of forests for society and depending on the scale of their spread include in addition to economic and political losses, and aggravation of social problems – the emergence of environmental problems, namely: the release of harmful combustion products, mostly in the form of aerosols, which can be transported over considerable distances, pollution of the atmospheric air with carbon dioxide and other harmful substances, impoverishment of biological diversity, deterioration of the conditions of natural regeneration of forests, reduction of the fodder base and difficulty in the migration of species, increase in the vulnerability of forests to pests and diseases, changes in the landscape structure and soil erosion, etc.

Thus, the problem of forest fires can be safely considered global, as countries with large and small areas of forests suffer from them.

In order to minimize the consequences of forest fires, it is important to detect them in time, that is, before the fire becomes uncontrollable and spreads over a huge area.

The methods and means of timely detection of fires include constant surveillance, which is carried out by patrolling, inspecting forest areas from fire towers and masts using human resources or video surveillance systems, using manned and unmanned aerial vehicles, observations from space (Lahno et al. 2021).

Unfortunately, these measures do not always bring the desired result, and the forest fire develops to such a level that it is necessary to respond to it, using significant forces and means for its elimination.

Horizontal migration of radioactive

combustion products, depending on the dynamic parameters of the wind, characteristics of the soil, its protection from the wind, etc., can cause radiation pollution or an increase in its density in the surrounding areas of the forest. There is also a danger of secondary radioactive contamination of the territories, which is associated with the density of soil contamination, the effect of wind erosion and the activity of radionuclides in the ash. As a result of such fires, the concentration of radionuclides in the air compared to background values can increase almost 104 times (Sydorenko et al. 2022).

In such cases, it is necessary to remember that the only effective method that reduces the intensity of the spread of combustion products is their deposition. Deposition of combustion products, dust and other aerosols can be effectively carried out using sprayed water jets. It is necessary to carry out such works during the extinguishing of fires in the ecosystems of the exclusion zone.

According to the results of the analysis of the existing methods and devices for the deposition of radioactive aerosol (Lahno et al. 2022), dust and surface irrigation during a ground fire in the exclusion zone, it was established that all the devices and methods of their application available in the emergency and rescue units are effective only when used locally, namely under the time of the rescuer's work with fire water hose.

The problem of extinguishing forest fires is being solved by the researchers in different ways (including water curtain and water mist): they introduced the concept of a fire-extinguishing bomb of water fog, and also offered to use a combined method that combines fire lanes created by explosives, dropping water from the air and drilling wells to obtain and use underground water for extinguishing (Li et al. 2012); expanded current knowledge on the use and effectiveness of air tankers and developed recommendations for improving data collection and aviation management during wildfires in the United States (Calkin et al. 2014); offered to create a network of 30- to 70-meter-wide tunnels for forest safety, supplemented by a mobile sprinkler system to create a water curtain to moisten another tunnel 100 m away (Azari 2010); modeled the process of dropping water in the form of water mist, which it turns into when extinguishing forest fires from a great height (Satoh et al. 2004, 2005); substantiated the effectiveness of explosive water mist compared to a water curtain and dropping water from a height (Li and Wang 2011).

A significant number of works are devoted to the issues of modeling the occurrence, development, forecasting of the spread and negative impact on the environment of fires in ecosystems exposed to radioactive contamination. In particular: modeling based on a number of parameters for calculating the ecological and radiation situation under the influence of the intensity and direction of migration of radioactive combustion products using a model based on deflation parameters, as a result, graphical dependencies for the deflation coefficient under different meteorological conditions were obtained (Sydorenko et al. 2022). Determination of the scheme of forming a mathematical model for assessing the ecological impact of negative factors of a forest fire in complex radiation conditions of fire load, and construction of a corresponding block diagram (Azarov et al. 2020). Modeling and substantiation of the dependence of the scattering and deposition of radioactive materials on the ground from past meteorological data, in particular air flows, proving the significance of their influence on determining the area and scale of response in the case of nuclear accident before carrying out on-site measurements (Hernandez-Ceballos et al. 2020).

A number of studies are devoted to the study of water curtain systems as an effective method of fighting fire, in particular, it is worth mentioning the analysis of water curtains of various configurations regarding the possibilities of protection against the thermal effects of fire due to the ability of water to absorb and disperse thermal radiation (Boulet et al. 2006, Tseng and Viskanta 2007, Turco et al. 2016, Ponziani et al. 2018) and smoke, and weaken the radiation effect (Wen et al. 2008), and also substantiating the viability of Heskestad scale relations for the interaction of water curtain splashes under the condition of a high Reynolds number ($10 \leq Red \leq 500$) based on Froude simulation for large-scale simulation of localization or fire extinguishing with a water curtain (Yu 2012).

The researchers also paid attention to the modeling of extinguishing fires by deposition of a water curtain in a limited space. In particular, in rooms under different conditions (water pressure, location of combustible substance) with the proof of lower water consumption by the curtain compared to the sprinkler system (Pancawardani et al. 2017), in a small chamber using a double fluid system of the water curtain in continuous and pulsed modes (Gupta et al. 2012).

Scientists have devoted a significant amount of research to the use of water curtains to prevent and extinguish fires in tunnels: during their construction (Mehaddi et al. 2020); analysis of the use of sprinkler systems of car tunnel walls (Deng et al. 2023); evaluation of the effectiveness of the fire protection system based on a water curtain against the spread of toxic smoke and gases in railway tunnels (Terribile et al. 2017); study of the spread of heat and smoke through the tunnel – research by varying the rate of heat release of the fire source, water curtain pressure and the number of rows of the water curtain showed that these indicators affect the smoke blocking by the water curtain system (Chen et al. 2023).

Other areas of use of water curtains in fire safety are their use in fighting fires on cargo ships (Zeinali et al 2023) and passenger ferries (Hemgård 2015), as well as for protection against vapor cloud explosions in the design of technological premises (Allason et al 2019).

The subject of interest of scientists was also substantiation of the effectiveness of the water curtain in extinguishing polymethyl methacrylate fires (Yao et al. 2012) and hydrodynamic modeling to estimate the dispersion parameters of liquefied natural gas vapors (the influence of droplet sizes and temperatures and the configuration of water curtain systems was analyzed), which ascertained the effectiveness of the dispersion of LNG vapors by the water curtain system and reducing the fire hazard of gas spills (Rana and Mannan 2010, Kim et al. 2012). Also considered: the modeling of the development of smoldering fires and their elimination by a water curtain, for example, peat fires depending on the intensity of water spraying (the distance between the fire barrel and the surface of the peat), which showed the influence of particle size and permeability of peat on the spread of the smoldering front of combustion and futility of short-term extinguishing of peat fires (Ramadhan et al. 2017), as well as fires in underground coal mines for three types of coal with different ranks and sizes of coal particles, which proved that moisture content was the dominant factor in the spread of smoldering and coal oxidation temperature (Tang and Huang 2022).

Despite the considerable amount of research, the development of firefighting equipment for aerosol, dust, and surface irrigation that could be used to extinguish fires in ecosystems, especially those exposed to radioactive or chemical contamination, remains an urgent task (Lahno et al. 2020).

As one of the options for such equipment, the author's team consisting of Denys Lagno and others proposed and created a device for creating a water curtain, the intellectual property right of which is registered by Ukrainian patent No. u 2020 05865.

To extinguish forest fires, such devices can be connected in series in a dead-end or ring line built from fire hoses. This method will increase the effectiveness of extinguishing forest fires, reducing the negative consequences for forest areas. However, the operating parameters of the proposed device for creating a water curtain were not investigated.

Taking into account what has been said, the purpose of our research is defined, namely the construction of a mathematical model of irrigation with a device for creating a water curtain.

## Materials and Methods

A stand (Fig. 1) was used as a fire engine for a full-fledged study, the main element of which is a pumping unit, which includes an asynchronous three-phase electric motor with a capacity of 18 kW and a centrifugal liquid pump that can provide a flow rate of up to 48 $m^3 \cdot h^{-1}$ with a pressure of up to 1 MPa and allows conducting research with various types of hydraulic

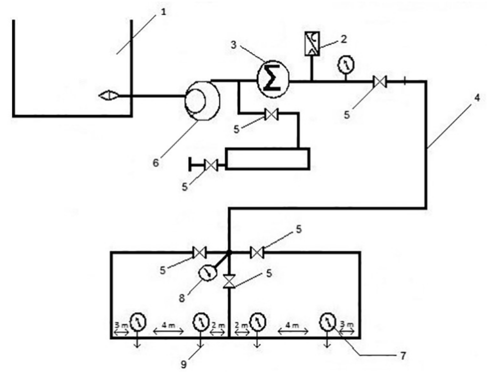


**Fig. 1. General scheme of the experimental stand.**

Note: The test stand includes: 1 – capacity 1 $m^3$; 2 – analog pressure converter; 3 – electromagnetic fluid flow converter; 4 – water hose Ø51 mm; 5 – shut-off valve; 6 – centrifugal pump.

manual fire-fighting equipment.

The pumping unit (Fig. 2) is connected to the jet forming nozzle through the hydraulic system (flow meter, pressure sensor, pressure pipelines).

The electric motor is controlled using a Danfos VLT 6000 HVAC frequency converter, which allows obtaining the required fluid pressure value.

To obtain flow data, an electromagnetic fluid flow converter SDM-1 was

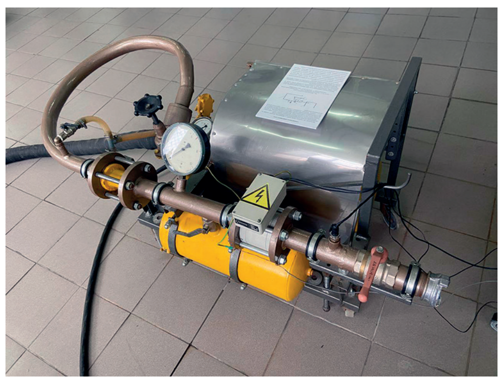

**Fig. 2. Pumping unit (photo Oleh Zemlianskyi).**

used, which is capable of working in the flow range from 0.26 to 65 $m^3 \cdot h^{-1}$ (0.07–18 $L \cdot s^{-1}$), of the second class of accuracy, the limit value of the relative error at consumption from 0.65 $m^3 \cdot h^{-1}$ (0.18 $L \cdot s^{-1}$) is 2 %.

To measure the pressure an analog pressure sensor HK1100C with a measurement limit of 1.2 MPa was used. Relative error at ambient temperature from +15 to +50 °C is 1.5 %.

Sensor signal processing is implemented using the Arduino Mega 2560 board – based on the ATmega2560 microcontroller. It has digital inputs/outputs and analog signal inputs. Information output is implemented on the LCD keypad shield 1602 display. It is also possible to output information in real time to a computer via a USB port. For this, the PLX-DAQ plugin for Microsoft Excel was used.

With the help of a pumping unit, a study of the parameters of the device for creating a water curtain was carried out. Experimental data were obtained on changes in pressure, flow rate, spray radius during water supply through the device for creating a water curtain.

Empirical dependences of water flow on pressure and spray radius on pressure were obtained by approximating experimental data in the form of polynomial equations. This, in turn, made it possible to obtain the dependence of the intensity of irrigation on pressure.

To conduct the experiment, a device for creating a water curtain (Fig. 3) is attached to the experimental stand (Fig. 1). Next, the shut-off valves were opened and water was supplied to the device for creating a water curtain.

By increasing the frequency of the current with the help of a frequency converter, an increase in the water pressure in the system was achieved. Flow and pressure data were automatically recorded every second. Starting from a pressure of 1 bar, the radius of the spray zone was measured every 0.5 bar. To obtain a reliable average result and further check with the appropriate statistical apparatus, the experiment was carried out with repetitions. In total, three repetitions of the experiment were carried out with the same starting conditions.

**Fig. 3. Spraying radius of fire extinguishing agent (photo Denys Lahno).**

## Results and Discussion

Thus, the experimental studies conducted by the authors using the developed device for creating a water curtain demonstrated the dependence of pressure on time (Fig. 4), the dependence of fluid flow on time (Fig. 5) and the irrigation area, fluid flow of the device depending on pressure (Fig. 6).

During practical use, a study that showed the irrigation area, device consumption depending on the pressure was

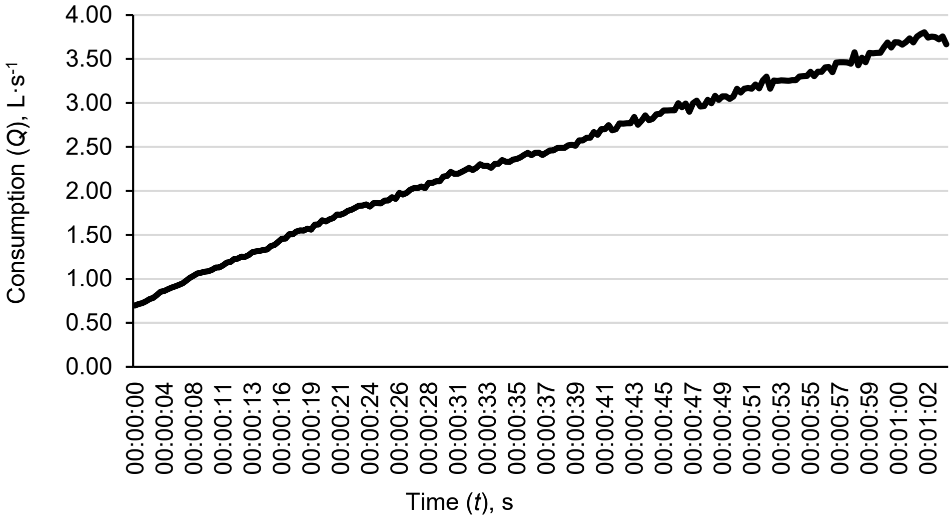


**Fig. 4. Dependence of consumption on time.**

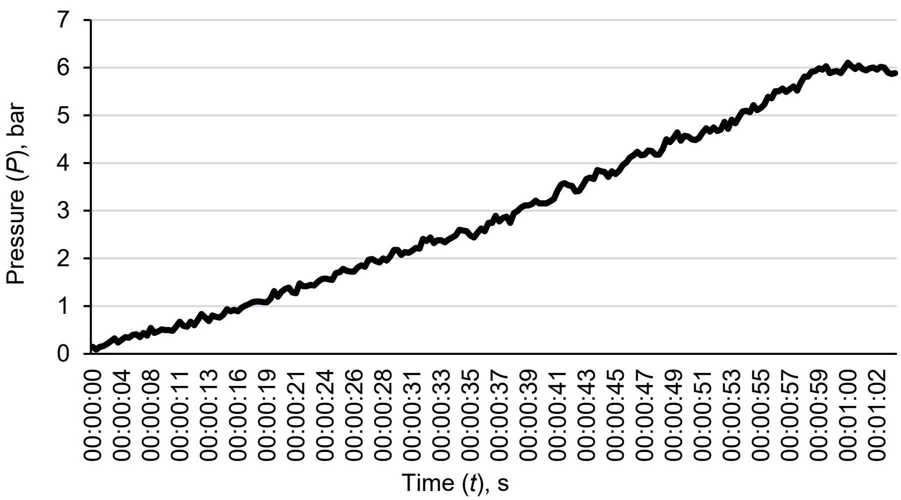


**Fig. 5. Dependence of pressure on time.**

conducted (Fig. 6).

From the graph (Fig. 6), it is clear the general dependence of the consumption on pressure, and at a maximum pressure of 6 bar, the consumption is about 3.5 L per second, which allows the device to be used both individually and in a group, using existing hydraulic fire equipment for creation of water curtains, for extinguishing and protection against excessive thermal radiation, as well as during the localisation of accidents associated with the release of toxic and radioactive substances with the purpose of deposition of toxic or radioactive clouds.

To determine the capabilities of devic-

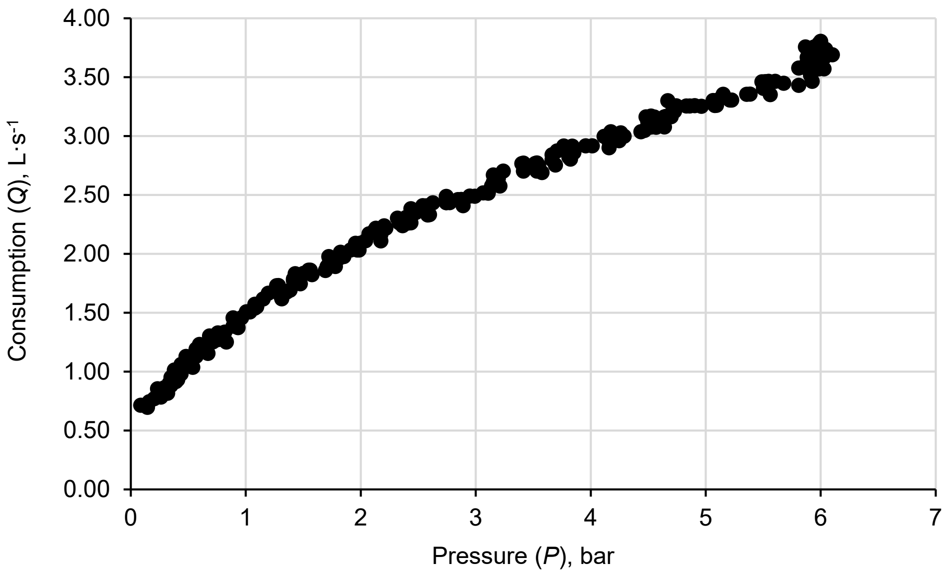


**Fig. 6. Dependence of flow rate on pressure.**

es for creating a water curtain during surface irrigation, it is necessary to calculate the surface. A irrigation intensity, for this it is necessary to identify the dependence of formula (1):

$$Q = f(Q, R), \tag{1}$$

where: $q$ is irrigation intensity, $Q$ is flow rate, $R$ is radius of the spray zone.

The dependence of the flow rate ($Q$) on the pressure ($P$) can be represented as an empirical dependence obtained by approximating the curve (Fig. 7) by formula (2):

$$Q = 0.0126P^3 - 0.1599P^2 + 1.0164P + 0.5986. \tag{2}$$

The dependence of the radius of the spray zone ($R$) is similarly obtained by approximating the curve (Fig. 6) by formula (3):

$$R = -0.0125P^3 + 0.1247P^2 + 0.2119P - 0.0433. \tag{3}$$

Taking the simplification that the irrigation intensity in meters of the irrigation zone q is uniform, we obtain the expression in formula (4):

$$q = \frac{Q}{\pi R^2}. \tag{4}$$

Taking into account dependencies (3) and (4), we get formula (5):

$$q = \frac{0.0126P^3 - 0.1599P^2 + 1.0164P + 0.5986}{\pi\left(-0.0125P^3 + 0.1247P^2 + 0.2119P - 0.0433\right)^2}. \tag{5}$$

The results of irrigation intensity calculations depending on the pressure are presented on the graph (Fig. 8).

The obtained results can be used when calculating schemes for extinguishing fires in the surface layers of peat, grass fires in forests. Based on them, it is possible to formulate a mathematical model of irrigation with a device for creating a water curtain, which consists of equations of formulas (2), (3) and (5):

$$\begin{cases} Q = 0.0126P^3 - 0.1599P^2 + 1.0164P + 0.5986 \\ R = -0.0125P^3 + 0.1247P^2 + 0.2119P - 0.0433 \\ q = \dfrac{0.0126P^3 - 0.1599P^2 + 1.0164P + 0.5986}{\pi(-0.0125P^3 + 0.1247P^2 + 0.2119P - 0.0433)^2} \end{cases}$$

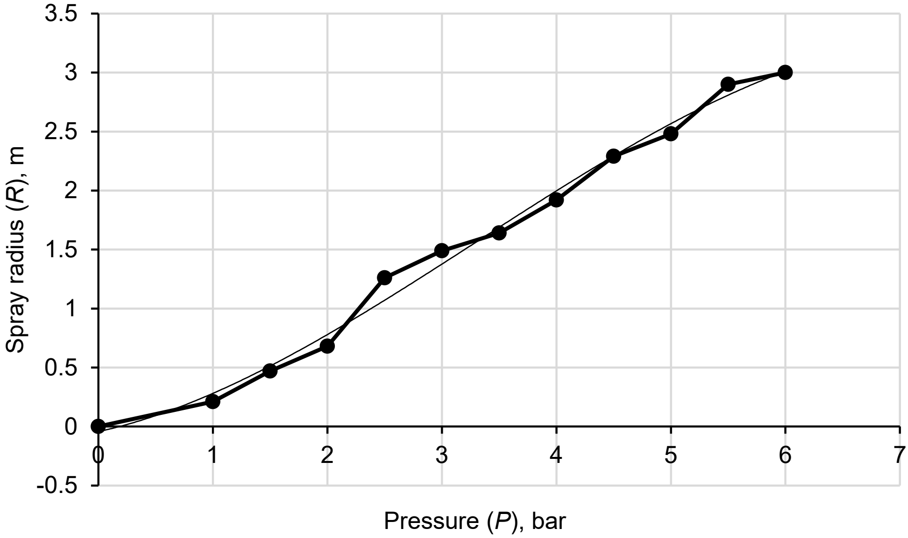


**Fig. 7. Dependence of spray radius on pressure.**

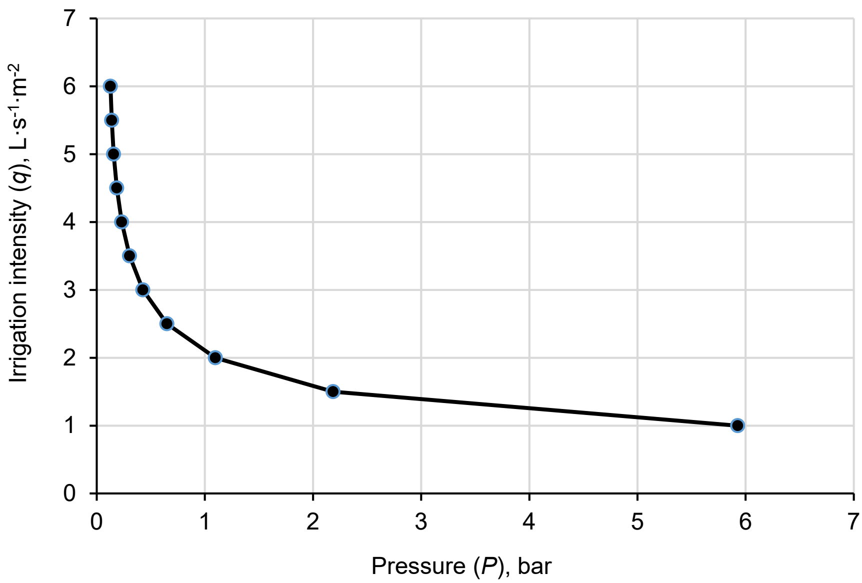


**Fig. 8. Irrigation intensity depending on pressure.**

Analysing the reproducibility of experiments requires quantitative measures of test adequacy. The adequacy check was performed on the basis of experimental information obtained during the experiment and its repetitions.

In order to find out the adequacy of the results of the experimental data during the tests, a number of criteria were selected, which are described below.

Fisher's F-test is used for sequential comparison of variances of indicators. Its application enables the verification of the hypothesis about the equality of general variances, the distribution of parameter values at each minute of the tests. We calculate the criterion according to the formula (6):

$$F = \frac{S_{ad}^2}{S_y^2}, \quad (6)$$

where: $S_{ad}^2$ – adequacy variance, $S_y^2$ – reproducibility variance.

The dispersion of flow adequacy is calculated as the deviation between the flow rates at the same pressure value and is presented in the formula (7):

$$S_{ad}^2 = \frac{\sum_{i=1}^{n}\left(Qs_i - Q_i\right)}{n}, \quad (7)$$

where: $n$ – number of flow measurements, $Qs_i$ – the average value of the flow at the same significant pressure, $Q_i$ – data during the test.

The dispersion of reproducibility is calculated as the deviation of the flow and the average value of the flow at different pressure values (taking into account the error of the flow meter). This indicator is calculated according to the formula (8):

$$S_y^2 = \frac{\sum_{i=1}^{n}\left[Q_i - (1+\delta)\overline{Q}\right]^2}{n}, \quad (8)$$

where: $n$ – number of measurements; $(1+\delta)\overline{Q}$ – average flow rates, taking into account the relative error $\delta$; $Q_i$ – flow rates at a given pressure.

Next, the adequacy variance was compared with the reproducibility variance and Fisher's test was calculated (F) (tables 1 and 2).

**Table 1. Dispersion parameters of the results of determining the flow rate based on the results of three experiments.**

| Maximum deviation, $L \cdot s^{-1}$ | Average deviation, $L \cdot s^{-1}$ | Relative deviation, % | F-criterion | Critical value of F-criterion |
|---|---|---|---|---|
| 0.093 | 0.018 | 0.91 | 1.35 | 7.26 |

**Table 2. Dispersion parameters of the results of determining the radius of the spray zone based on the results of three experiments.**

| Maximum deviation, $L \cdot s^{-1}$ | Average deviation, $L \cdot s^{-1}$ | Relative deviation, % | F-criterion | Critical value of F-criterion |
|---|---|---|---|---|
| 0.19 | 0.067 | 15.5 | 2.15 | 2.36 |

Similarly, the determination of the dispersion of adequacy compared to the dispersion of reproducibility was carried out and the Fisher criterion (F) was calculated during the determination of the spraying zone.

According to tables 1 and 2, the calculated adequacy criteria do not exceed critical values.

Therefore, a mathematical model of irrigation with a water curtain device has been developed and published for first time, which can be used to calculate the irrigation zones of each individual sprinkler in a system with a series connection for extinguishing forest fires. The model will allow, after the hydraulic calculation of the pump-hose system using serially connected nozzles, to determine the parameters of such a system, in particular, the input pressure in the system and the distance between the nozzles.

Prospects for further research include the determination of the effective intensity of irrigation and the determination of possible options and maps for the placement of sprinklers to ensure the necessary efficiency of the deposition of harmful substances in the air, provided that the effective intensity of irrigation is ensured in horizontal and vertical projections.

## Conclusions

The obtained results can be used during modeling of areas of spraying of fire-extinguishing liquids by devices for creating a water curtain for extinguishing forest fires or deposition of clouds with radioactive and poisonous substances. However, in order to qualitatively solve the problem of precipitation of clouds with radioactive and poisonous substances, it is necessary to conduct experimental studies on the formation of the vertical projection of the spray zone by the proposed device.

Similarly, studies can be conducted with different types of sprayers and water curtain devices to obtain empirical relationships similar to (2) and (3). Thus, the approach considered in this work can be used to obtain mathematical models of irrigation with other types of sprinklers, similar to the represented model.

The mathematical model obtained as a result of the research is an important aspect of the forest fire extinguishing methodology, as it allows you to calculate the operating parameters of the device for creating a water curtain. The model and similar models are necessary for the hydraulic calculation of the pump-hose system when extinguishing forest fires with the use of serially connected sprinklers.

The use of research results will improve the quality of calculations required during forest fire suppression and the deposition of clouds of radioactive and poisonous substances. This, in turn, will make it possible to use available forces and means more efficiently and, as a result, reduce the negative effects of fires on forest plantations.

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