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EXPERIMENTAL STUDY OF WATER SPREADING PARAMETERS WHEN EXTINGUISHING FIRES USING AIRCRAFT SPRINKLERS

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This paper reports results of an experimental study on hydrodynamic processes when water is dropped from a height, as well as their influence on the movement of liquid, in order to optimize the processes of aviation firefighting.

The main parameters of water dispersion were determined based on a series of experiments. It was established that the average diameter of drops when dropped from a height of 10 meters is 2.5 mm, with a maximum spraying distance of up to 15 meters. The size distribution of the droplets showed that 30 % of the droplets have a diameter of less than 2 mm, 50 % are between 2 and 5 mm, and 20 % are more than 5 mm.

During the experiments, it was measured that the time for pouring water from the container is 3 seconds, and the speed of movement of water fractions when dropped from a height of 10 meters is 9.8 m/s. With an increase in the discharge height by 5 meters, the speed of water movement increased by 20 %.

One of the key points of the study is the improvement of the Torricelli equation by introducing the coefficient K (0.85), which takes into account the viscosity and density of water, which improved the accuracy of calculations by 15 % compared to the standard equation.

Python was used to process and interpret the video data, along with libraries such as OpenCV for image processing, NumPy for high-performance mathematical computations, and Matplotlib for data visualization. The resulting data open up new prospects for devising aerial firefighting strategies, providing a 20 % increase in coverage area, and a 25 % reduction in firefighting time.

Torricelli's equation was improved; a new procedure was devised for the experimental determination of water dispersion parameters, which has an important practical application in the field of fire safety.

In the field of fire safety, the data obtained could be used to improve aviation firefighting strategies, which would allow for greater efficiency and safety

Keywords: air fire extinguishing, parameters of water dispersion, modeling of textile tanks, Python script

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1. Introduction

The modern world is facing an unprecedented challenge associated with the increasing frequency and intensity of fires, which threaten ecosystems, economies, and human health on a global level. Large-scale wildfires, industrial disasters, and other types of fires require devising effective firefighting strategies that can respond quickly and efficiently to these crisis situations. In this context, aviation technology comes to the fore as a decisive tool for operational fire extinguishing under various conditions [1].

There is an urgent need to improve the methods of aviation fire extinguishing, in particular, in the experimental determination of water dispersion parameters, which will make it possible to optimize the extinguishing process and increase its efficiency. The need to improve aviation firefighting methods and experimental determination of water dispersion parameters arises for several key reasons. First, there is a trend toward an increase in the intensity and frequency of large-scale wildfires around the world, which is a consequence of climate change, global warming, and human activity. These fires pose a significant threat to ecosystems, national economies, and public health. Second, traditional firefighting methods, including ground operations, are often ineffective in large-scale wildfires due to limited access to the fire source, high speed of fire spread, and difficult terrain. The development of aviation technology provides new opportunities for effective firefighting. However, for the maximum efficiency of such operations, it is necessary to have a deep understanding of water dispersion processes and their effect on firefighting. Thirdly, optimizing the use of water resources and minimizing the negative impact on the environment are important aspects of firefighting. The efficiency and accuracy of aerial extinguishing can reduce water consumption and improve the ecological condition of areas after fires. Fourth, devising scientifically based methods and strategies for extinguishing fires with the use of aircraft requires a detailed study of water dispersion processes, the influence of weather conditions and terrain characteristics on the effectiveness of extinguishing. A detailed analysis of the behavior of water droplets under different conditions of discharge could help compile recommendations for improving the accuracy and efficiency of the use of aviation means in fighting fires. The results of such research in the future will provide practice with important data for choosing the optimal water discharge parameters based on experimentally determined dispersion characteristics; development of new firefighting strategies and technologies that can adapt to the specific conditions of a specific fire and terrain; reducing the negative impact of fires on the environment and human health by increasing the efficiency of extinguishing and reducing the amount of water used.

2. Literature review and problem statement

Study [2] aimed at constructing a mathematical model and developing an algorithm for accurate prediction of liquid spray parameters in aviation firefighting. This work emphasizes the importance of theoretical achievements, but the key task remains the connection of previous theoretical results with practical experiments. In [3], a detailed analysis of recent twenty-eight studies and publications in the field of aviation firefighting was carried out; the results confirm the growing need to improve existing methods. In particular, the study of water dispersion processes opens up new opportunities for optimization of extinguishing, reduction of water resource consumption, and minimization of environmental impact. Analyzed studies [3–5] showed that the process of aviation fire extinguishing with the help of water includes a number of various factors that affect the process of transformation of the droplet cloud itself, which leads to a change in the effectiveness of fire extinguishing. In study [4], the effectiveness of the use of AN-32 firefighting aircraft was evaluated, but at the same time, other types of aircraft were not considered, and the dependence of the use of pouring devices on the type of aircraft was not determined. Paper [5] statistically analyzed the model of water discharge parameters, but modern algorithms used by global partners in the field of aviation extinguishing were not used (the analysis of such algorithms is considered in [2] Experimental data [6] showed the process of evolution of the macro volume of liquid; its separation into several stages was also discovered. As a result, it was determined that the introduction of surfactant into water allows changing the surface tension coefficient, which in turn indicates the height at which the macro volume of the liquid will collapse when approaching the surface area. A decrease in the destruction of the macro volume would improve the accuracy of discharge of fire extinguishing liquid and increase the volume of extinguishing per one cubic meter. At the same time, no automated calculation and data processing program was built that could calculate and predict the behavior of the destruction of the water body. Also, an analysis of the data [7] on the effect of convective flows on the mass of liquid, which is formed after its discharge from aviation equipment, was carried out, the process of the influence of flows of gas-air mixtures on the change in the physical state of the liquid was described. Taking into account the effect of the formation of a buffer vapor gap between the liquid and high-temperature combustion products, it was determined that the irrigation areas will be 20–30 % smaller for the conditions corresponding to typical forest fires. Studies [8–10] revealed a correlation between the parameters of liquid droplets and a decrease in heat flow, as a result of a decrease in evaporation processes, which allows determining the necessary droplet sizes to increase the extinguishing efficiency. In study [8], the scheme of the experimental installation was considered, which carried out video registration of drops before and after they passed through the combustion zone, corresponding videograms and isotherms were constructed, which made it possible to clearly analyze the process of evaporation of liquid drops. However, this study did not develop a program that could automate the process of such an analysis. On the basis of research [9], typical systems of liquid droplets were analyzed, the process of coagulation of droplets, which is a consequence of phase transformations during the movement of droplets, was considered in detail. The causes of the occurrence of the coagulation regimes identified in the research were determined; a conclusion was drawn regarding the nonlinearity and nonstationarity of the described processes, due to the impossibility of accurately determining the temperature of each drop of liquid, which also indicates the non-linear nature of the heating of the drops in the process of moving through a high-temperature gas mixture. Coefficients have been determined, the use of which allows taking into account all typical factors, namely the ratio of resistance forces and gravity forces acting on each droplet, and allows predicting changes in the movement of drops, their braking or preservation of the initial movement. The change in the pressure parameter, which significantly affects the process of parallel movement of droplets, taking into account the forces of thermophoresis and turbophoresis, is taken into account. On the basis of the above-mentioned studies, it was concluded that the determining factor of the effectiveness of aerial firefighting remains the incrementation of the described processes into visual mathematical models of spatial studies, which take into account the influence of the described parameters to justify the process of increasing the effectiveness of extinguishing forest fires with the help of aviation equipment. It is noted that the experiment [10] initiated the study of the fractional distribution of water during its discharge from a height. It is shown that an important stage in solving the problems of extinguishing fires is understanding the kinetics of liquid movement and determining the optimal spraying parameters. However, issues related to the accuracy and efficiency of measurements, as well as determining the influence of weather conditions on water distribution, remain unresolved. The selection of adequate algorithms for segmentation and data analysis, which affects the accuracy of determining the diameter of the water spray, which was outlined in study [11], turned out to be an objective difficulty. An option for overcoming these difficulties is the improvement of photo-fixation methods and image processing algorithms, as well as a more detailed analysis of the influence of weather conditions on the effectiveness of firefighting. The approaches used in paper [12] include a modification of the experimental technique aimed at improving the accuracy of the results. However, the approach to such a modification does not include a mathematical justification that would show the accuracy and relevance of the results. In addition, in previous works [13, 14] it was determined that one of the key components of aviation fire extinguishing is the spraying of liquid over the source of combustion, which aims to suppress the flame and minimize the spread of the fire. An important task in this context was to determine the optimal parameters of liquid spraying to achieve maximum fire extinguishing efficiency. This includes selecting the type of liquid, the speed and height of the spray, and the volume of liquid to be sprayed. In [15], the dynamics of the drop ejection process were studied, the conditions under which the ejection occurs; the influence of the system parameters on the process were determined. The key factor remains the use of the Navier-Stokes equation, which is usually included in the schemes of modular calculations of hydromechanical processes. At the same time, the study takes into account the phenomenon of liquid vibration on a solid surface, which is impractical when dropping liquid from a height. Study [16] included an extinguishing concept that establishes the possibility of using a water mist system with basic injection for extinguishing fires in tanks, but the processing of the data results with specialized programs or scripts was not carried out.

The main issues identified in the analysis of existing extinguishing methods include insufficient adaptation of techniques to specific fire conditions and terrain, as well as limited efficiency in the use and processing of data. The systematization of processes related to the study of droplet flows is directly related to the use of algorithms and scripts that could process this data. Using the Python language and writing scripts that can create a closed system of data analysis and processing in the studies of the above-mentioned processes was not detected. This indicates an urgent need for experimental determination of optimal water dispersion parameters that would take into account the dynamics of water droplet distribution, their size, fall speed, and the influence of wind and other weather conditions, and appropriate processing using Python.

3. The aim and objectives of the study

The purpose of our study is to determine the parameters of water dispersion during aerial firefighting. This could improve aviation firefighting strategies, which would allow for greater efficiency and safety.

To solve the goal, the following tasks were set:

– to measure the influence of a macro volume of water by the photofixation method of multi-frame shooting;

– to investigate the kinetics of movement of water fractions using image segmentation algorithms;

– to carry out mathematical calculations of the diameter of the atomization of the macro volume of the liquid from the specified heights.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of research is the process of aviation fire extinguishing.

The hypothesis of the study assumes that there is a significant influence of the height of the water fall on the parameters of aerial firefighting. This is based on the theoretical foundations defined by Torricelli's equation and previous studies [1, 2]. A number of assumptions were taken into account for our research:

1. Perfect water spray. The work assumes that water is sprayed under normal conditions, all processes comply with the laws of physics and hydrodynamics [3].

2. Accuracy of the Torricelli equation. Torricelli's equation is used to model the process of water spraying and is considered to be correct for the mathematical notation of the studied phenomenon [4, 5].

3. Proportionality of water volume and extinguishing efficiency. It is assumed that the volume of water used for extinguishing is proportional to the efficiency of extinguishing [6, 8].

4. 2. Software, hardware

A Sony IMX363 high-speed camera with a resolution of 12 megapixels (pixel size 1.4 µm) and a lens with an aperture of f/1.8, with optical 4-axis stabilization, made in China, was used to obtain experimental data. This equipment made it possible to capture the details of the water spraying process with a frame rate of 960 fps. The IDLE integrated development environment, which was created using the Tkinter library, was used to generate, describe, and execute scripts using Python.

4. 3. Conditions for the experiment

The experiments were conducted under specially equipped laboratory conditions, outside, at a temperature of 20°, humidity of 65 %, and other parameters that ensured the stability and repeatability of the experiment.

To solve the task of one-moment discharge of water from a height and to determine the parameters of the drop, a special container was used, which enabled a quick and complete release of water at one time. Three options for building such a container were considered:

a) reusable container with a release valve. Constructing a container with a holding volume of 20–30 liters from a waterproof material such as plastic cloth or rubber. Installation of a special valve on it, which can be opened and closed. For one-moment discharge of water, it is enough to fully open the valve so that the entire volume of water is released at the same time;

b) a disposable container with a release valve. Constructing a fabric or rubber container with a special design in which the bottom can be raised by a quick mechanism. For example, the bottom can be attached to belts that are pulled using a mechanism with levers or tension springs. When the bottom rises, water is released simultaneously through the open bottom hole of the container;

c) a device for optimal spraying. Constructing a container of waterproof material that has an open top opening. When the container rises and is located at a height, water begins to flow out through the upper opening. The use of a specialized coating to enable maximum water atomization and rapid spraying.

For the test at different discharge heights, lifting mechanisms such as a winch and an emergency rescue system of carabiners were used to fix the container at a height before releasing the water.

A designed textile container with a volume of 1 cubic meter was used as a container. The textile container was suspended at heights from 2 to 15 meters for the experimental descent of water through the hole below, the diameter of which was 30 centimeters. Water was released from the tank through an open hole using the forces of gravity and opening the release valve. The entire volume of water was released at once.

So, for conducting the experiment, we use a textile container with a lifting capacity of 1 ton. The container has the shape of a cube, has four slings, by which it will be suspended at a height of 2 to 15 meters for conducting an experimental descent of water through a hole at the bottom, a hole with a diameter of 30 centimeters.

When choosing the material to construct the container, it was important to consider the waterproofness and strength of the material. Polyester fabric with a polyvinyl chloride (PVC) coating or rubber fabric were considered as options that met these requirements. Consideration has been given to the use of double layers of material to allow for greater strength and prevent leaks.

Safety was ensured during the experiment and appropriate safety measures were devised, including the use of safety glasses and combat clothing to prevent water from splashing on bystanders. A gravel pad was also used to safely collect and clean the water after the experiment to avoid any negative impact on the environment.

The development of a detailed scheme of a container for simultaneous discharge of water from a height depended on specific requirements and limitations, as well as on available materials and facilities.

4. 4. Procedures for treating experimental data and checking the adequacy of the proposed models

The resulting high-speed images were processed using specialized Python software to determine water spray parameters and obtain quantitative results.

The adequacy of the proposed mathematical models was checked by comparing the theoretical results with the obtained experimental data. In the case of differences, adjustments were made to achieve the adequacy of mathematical models to the real process.

5. Results of investigating water dispersion parameters when extinguishing fires with the help of aircraft water discharge devices

5. 1. Measurement of spillage of a macro volume of water by the photofixation method of multi-frame shooting

The study of the distribution of water fractions during the dropping of a macro volume from a height was carried out using a video series of photographs taken during the experiment (Fig. 1). It was decided to use computer vision and image processing methods to analyze such video data.

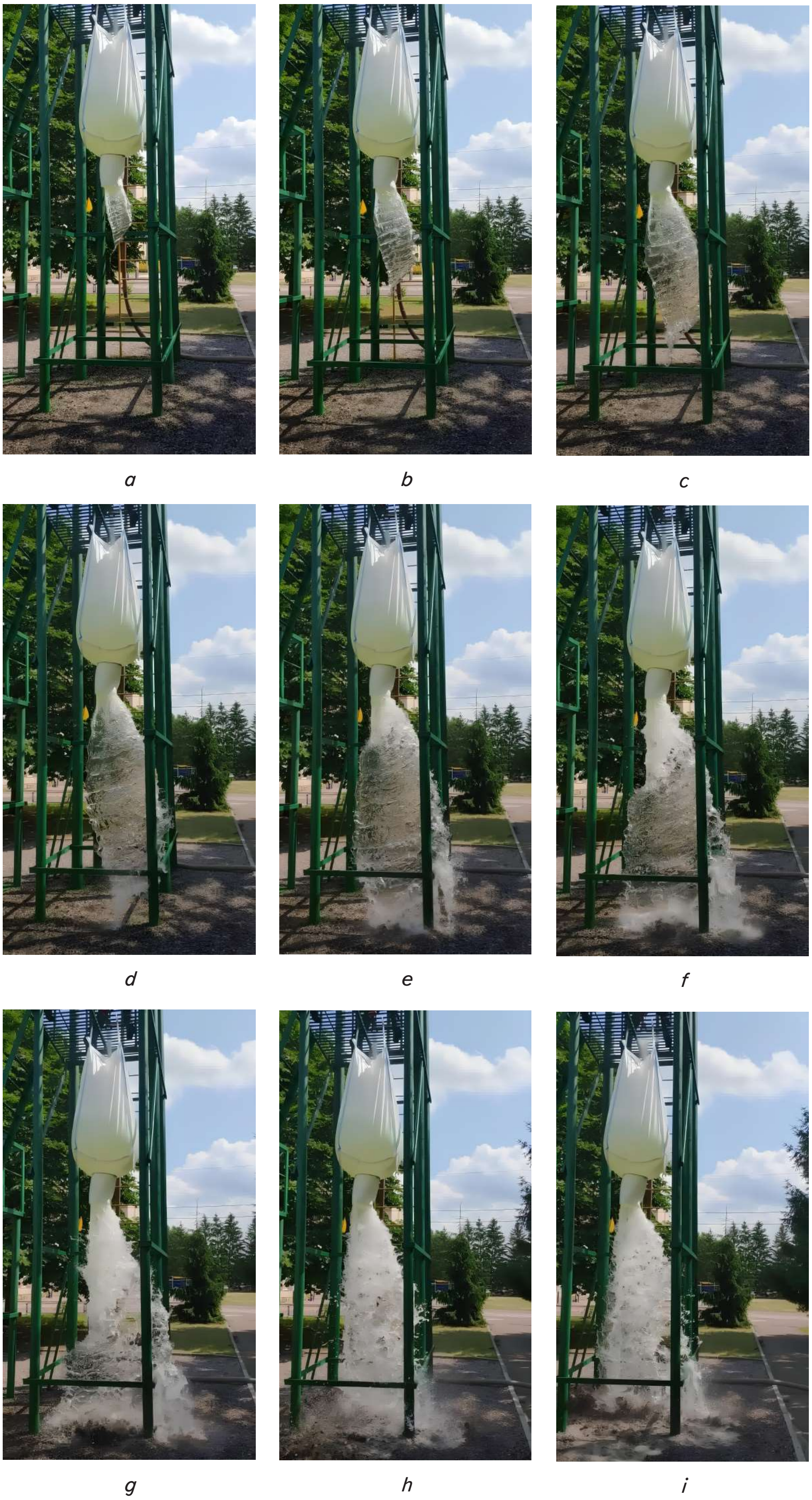


Fig. 1. The described process of pouring water from the container through the open hole: *a* – stage 1; *b* – stage 2; *c* – stage 3; *d* – stage 4; *e* – stage 5; *f* – stage 6; *g* – stage 6; *h* – stage 7; *i* – stage 8

Stage 1 (*a*): initial moment.

At the first stage, one can see how water is just beginning to pour out through the hole. The formation of the jet and its direction are determined by the geometry and dimensions of the hole.

Stage 2 (*b*): jet formation.

At this stage, the jet is already formed and begins to descend. The shape and direction of the jet depend on the size of the hole, as well as the properties of the liquid.

Stage 3 (*c*): increasing intensity.

The stream of water at this stage acquires increasing intensity. Increasing the flow rate can cause changes in the shape of the jet and its distribution.

Stage 4 (*d*): spreading of the jet.

The jet has already reached the surface or other surface on which it falls. The form of contact and water distribution may vary depending on the characteristics of the surface.

Stage 5 (*e*): formation of water volume.

At this stage, a volume of water is formed in a certain place, for example, a reservoir or a combustion chamber, where the water falls.

Stage 6 (*f*): continuation of distribution.

The process of water distribution on the ground or other surface continues. Depending on the intensity of the spill, a current of water or a pool of the appropriate size may form.

Stage 7 (*g*): decrease in intensity.

The intensity of the spill may decrease, but the process of water distribution continues. The stream of water may become less visible or spread over a smaller area.

Stage 8 (*h, i*): completion of the process.

At the last stage of pouring, the water distribution process ends. Residual current of water can flow slowly or accumulate in a reservoir.

A simple model was used to build a table of a full-factor experiment with data on the change in the diameter of the water spray depending on the drop height. Since the diameter of the hole remains the same (30 cm), the main variable is the drop height (Table 1).

It is assumed that the spraying diameter is proportional to the square root of the drop height. This assumption is based on the idea that with increasing height, the droplet fall time increases, which may allow the water spray to spread over a larger area. The function for calculating the cutting diameter is as follows:

$$D_{spray} = k \cdot \sqrt{H} \cdot \sqrt{V}, \tag{1}$$

where D_{spray} is the spray diameter, H is the discharge height, V is the volume of water discharged, and k is a constant that can be determined empirically.

Table 1

Numerical data for determining the diameter of the water spray when dropped from different heights

Discharge height H (m)	Water volume V (l)	Spraying diameter D_{spray} (m)	Error (%)
2	100	$k \cdot \sqrt{2} \cdot \sqrt{100}$	5
5	200	$k \cdot \sqrt{5} \cdot \sqrt{200}$	6
10	300	$k \cdot \sqrt{10} \cdot \sqrt{300}$	7
15	400	$k \cdot \sqrt{15} \cdot \sqrt{400}$	8

Table 1 gives a more comprehensive perspective at how different factors can affect the diameter of the water spray when dropped from different heights and with different volumes of water. The constant k must be determined experimentally or based on additional data. The error takes into account the potential uncertainty in measurements and calculations.

It is considered necessary to take into account the specified stages to analyze the behavior of water when it is dropped from a height through an open hole. The obtained photos make it possible not only to determine the diameter of the hole but also to study in detail the shape of the spray and the speed of water release, which are key parameters for further understanding of fire extinguishing by aviation methods. This multimodal approach to photo capture and data analysis provides the research with the necessary depth and precision to study the hydrodynamic aspects of firefighting.

5. 2. Studying the kinetics of movement of water fractions

One of the approaches used to determine the distribution of water fractions is the use of image segmentation. Image segmentation (Fig. 2) made it possible to divide the image into separate parts or objects, in this case, to divide the image into separate parts corresponding to different fractions of water. The use of segmentation algorithms helped distinguish individual drops, jets, and fragments of water, dividing them into different fractions.

After segmentation, analysis of water fractions was carried out, examining their parameters, such as size, shape, speed of movement, etc. This gave an idea of the distribution of water during the destruction of the macro volume and gave an understanding of the processes of spraying and distribution of droplets.

To perform data analysis from the video sequence, a script (Fig. 3) was developed and run through a specialized Python image processing program with image processing libraries. These libraries provided a wide range of tools for image segmentation and determination of various object parameters.

However, it is worth noting that the accuracy and efficiency of the analysis may depend on the quality of the input data (photos). If the photos are of low resolution or darkened, this may affect the results of the analysis. Therefore, it is important to ensure the quality of the images and the appropriate lighting during shooting.

It was determined that the pouring of water from a container with a volume of 1 m^3 through an opening with a diameter of 30 centimeters is a complex process that includes several stages and fluid dynamics under the conditions of a gravitational field.

Initial stage (initiation of movement): after the initial opening of the hole, the water mass, under the influence of the gravitational field, begins to escape from the container. At this stage, the fluid can be considered an ideal incompressible fluid flow. Water generates a flow characterized by high speed and constant dense flow.

Pouring stage (formation of drops): during pouring, water passes through an opening, where it forms a stream. According to the laws of hydrodynamics, the amount of flow depends on the size of the hole and the hydrodynamic characteristics of the liquid. Passing through the hole, the liquid is distributed into drops as a result of the dispersion process.

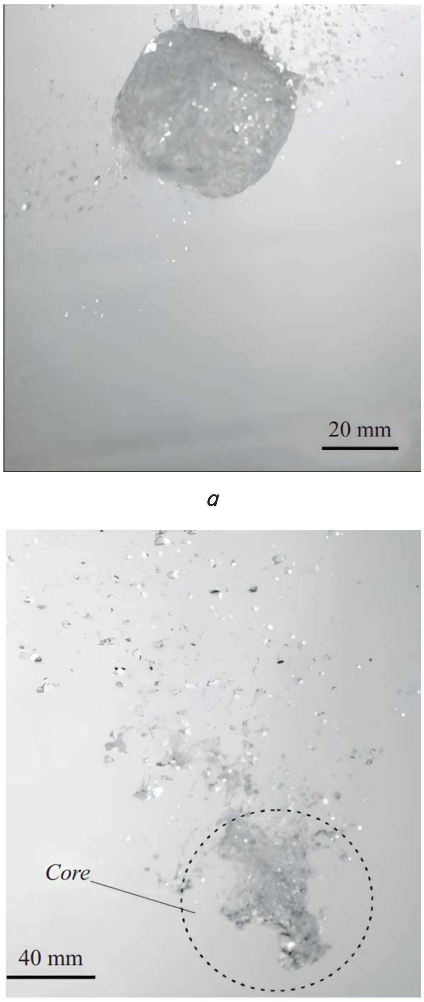
Since the opening is quite large, the formation of drops is relatively large, and the drops can be seen visually. An increase in the diameter of the hole can lead to an increase in the number and decrease in the size of the drops.

Separation into fractions (fine atomization): AFTER the formation of droplets, the liquid moves downward under the influence of gravity. Under the influence of air resistance, the drops can break up into smaller fragments. This is a minute process of atomization – a process in which the droplets are divided into smaller fragments as a result of interaction with air.

Kinetics of droplet movement (trajectories of movement): after separation into fractions, water drops move downward under the influence of gravitational force and air resistance. Each fraction has its own movement trajectory, which can be determined taking into account the size of the drop, its mass, shape, and other parameters. These dynamics can be investigated using video analysis and droplet velocity measurements.

The key aspects of the script are given, namely: importing libraries, video streaming, defining image processing parameters, processing frames, defining contours, counting particles, rendering, and outputting results.

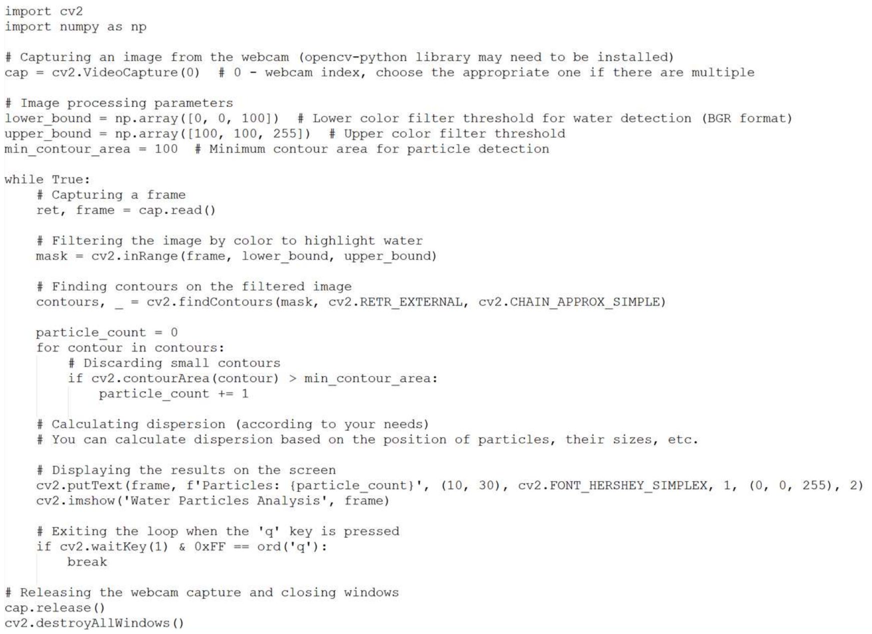
The script imports the cv2 (OpenCV) library for image processing and the numpy library for mathematical calculations, uses a video stream from a webcam (or other video input) to obtain real-time images. Lower and upper limits are set for filtering images in the BGR (Blue, Green, Red) color space. This is used to detect objects of a certain color. The script reads frames from the video stream and performs color filtering to select objects with the specified color parameters. Contours of selected objects on the image are defined (contour is a curve connecting all consecutive points along the border that have the same color or intensity). The script counts the number of particles based on the contours found. Accordingly, this aspect is used to detect and quantify objects such as water droplets. The processed image and particle count are displayed on the screen. The script also allows the user to terminate execution by pressing the ‘q’ key.



a

b

Fig. 2. Segmented image made it possible to divide the image into separate parts or objects: *a* — drops of a larger volume in stages (*a*—*d*); *b* — drops of coagulant composition in stages (*e*—*i*)



```
import cv2
import numpy as np

# Capturing an image from the webcam (opencv-python library may need to be installed)
cap = cv2.VideoCapture(0)  # 0 - webcam index, choose the appropriate one if there are multiple

# Image processing parameters
lower_bound = np.array([0, 0, 100])  # Lower color filter threshold for water detection (BGR format)
upper_bound = np.array([100, 100, 255])  # Upper color filter threshold
min_contour_area = 100  # Minimum contour area for particle detection

while True:
    # Capturing a frame
    ret, frame = cap.read()

    # Filtering the image by color to highlight water
    mask = cv2.inRange(frame, lower_bound, upper_bound)

    # Finding contours on the filtered image
    contours, _ = cv2.findContours(mask, cv2.RETR_EXTERNAL, cv2.CHAIN_APPROX_SIMPLE)

    particle_count = 0
    for contour in contours:
        # Discarding small contours
        if cv2.contourArea(contour) > min_contour_area:
            particle_count += 1

    # Calculating dispersion (according to your needs)
    # You can calculate dispersion based on the position of particles, their sizes, etc.

    # Displaying the results on the screen
    cv2.putText(frame, f'Particles: {particle_count}', (10, 30), cv2.FONT_HERSHEY_SIMPLEX, 1, (0, 0, 255), 2)
    cv2.imshow('Water Particles Analysis', frame)

    # Exiting the loop when the 'q' key is pressed
    if cv2.waitKey(1) & 0xFF == ord('q'):
        break

# Releasing the webcam capture and closing windows
cap.release()
cv2.destroyAllWindows()
```

Fig. 3. Open source in Python, which was used to process the image

5. 3. Carrying out mathematical calculations of the spray diameter of a macro volume of liquid from specified heights

Calculating the diameter of the spray is a complex task, so a simplified model was used for understanding. One such approach is based on the use of the Torricelli equation, which describes the outflow of liquid through an orifice. This equation includes the following parameters:

1. Drop height (h) is the height from which water falls.
2. The radius of the hole (r) is the diameter of the hole divided by 2.
3. Liquid density (ρ) is the mass of liquid per unit volume.
4. Coupling coefficient (C) is a value that depends on the shape of the hole and the condition of the pouring.
5. Acceleration of free fall (g) – 9.8 m/s^2 on Earth.

According to the Torricelli equation, the spray diameter (D) can be calculated as follows:

$$D = C \cdot \sqrt{\frac{2 \cdot r \cdot h}{g}}. \tag{2}$$

The spray diameter made it possible to estimate the parameters of large drops at the moment of pouring from a height. However, it is worth noting that real conditions may differ from theoretical models due to factors such as taking into account the influence of the air environment, dispersion models, and taking into account the properties of the fluid. Torricelli's original equation does not take into account the influence of the air environment, but under real conditions air resistance can affect the distribution of the jet. Additional coefficients or models that take this effect into account improve the accuracy of calculations. Dispersion models allow more accurate prediction of water distribution during spraying. For example, a variance model is commonly used to estimate the distribution of data in a sample. One of the common variance models is the univariate regression analysis (ANOVA) model [17].

Torricelli's equation does not take into account the properties of a specific liquid, such as its viscosity and density. Taking into account these parameters can improve the accuracy of calculations. Therefore, real experiments and observations will be more accurate when determining the distribution of droplets during water discharge using aircraft such as Airbus A-400 [18].

The paper gives an example of solving the improved Torricelli equation. It involves determining the diameter of the spray of water droplets from a height of 10 meters through an opening with a diameter of 30 centimeters (or 0.3 meters) with the coefficient K. The coefficient K takes into account the effect of air resistance on the distribution of the water jet in the experiment. It is assumed that the water density (ρ) is 1000 kg/m^3 and the coupling coefficient (C) is 0.61 for a hole of this size.

The coefficient K is defined as the ratio of the actual value of the spray diameter D_f to the calculated value of the diameter D_p for each series.

The calculation of the spray diameter (D) according to the Torricelli equation takes the form:

$$D = 0.61 \cdot \sqrt{\frac{6}{9.8}}\, K, \tag{3}$$

$$D \approx 0.61 \cdot 0.78 \text{ m} \approx 0.48 \text{ m}.$$

Therefore, to calculate the coefficient K, after obtaining the actual results of water discharges (Fig. 4), a linear equation of the dependence of the radius of flight (R) on the height of the fall (h) was constructed. Linear regression was used to approximate these data. The linear equation takes the form:

$$R = ah + b, \tag{4}$$

where R is the radius of flight, m; h is the height of the fall, m

Usually, during aviation firefighting, water is sprayed from the aircraft onto the fire areas. The goal is for the water to spray over a large radius and extinguish the fire. Parameters such as drop height (h), water flow rate (m), spray rate, and other factors important for aerial firefighting can affect the effectiveness of this process.

The calculated values a_g=0.15, b_g=0.03 were used to calculate the radius of flight R at specific values of the drop height h (Table 2).

Table 2

Results of measuring the radius of scattering of primary droplets in a water jet depending on the height

Height, cm	Actual radius of primary droplets scattering, mm	Python script calculation, mm	Mathematical calculation according to the Torricelli equation, mm
230	50	36	37.5
430	90	95	67.5
730	170	178	112.5
1000	250	283	153
1500	410	456	228

A Python data analysis program with the NumPy library was used to verify the results. The code (Fig. 4) defines the function simulate_water_jet, which simulates the trajectories of water drops released from the pouring device. Axes3D from mpl_toolkits.mplot3d is used to create a 3D visualization. numpy is used for scientific computing, such as creating arrays and mathematical operations. matplotlib.pyplot is used for data visualization. Function definition simulate_water_jet: The function takes the number of droplets num_droplets and the free fall acceleration g as parameters. It initializes the x_positions, y_positions, and z_positions arrays to store the coordinates of each droplet. In the loop, a random speed and angle are generated for each droplet, the time of flight is calculated, and the coordinates of the droplet in three-dimensional space are determined. Simulating droplet trajectories: Coordinates for drops are generated using the function simulate_water_jet. These coordinates are then used to create a three-dimensional visualization of the movement of droplets from the pouring device. Visualization of droplet trajectories: using the Matplotlib library, a three-dimensional plot with droplet coordinates is constructed. ax.scatter is used to visualize droplet positions in 3D space.

Fig. 5 shows the results of comparing the calculated values according to the Torricelli equation with the coefficient K using a Python script calculation with the actual results of the experiment.

```
import numpy as np
import matplotlib.pyplot as plt
def simulate_water_jet(num_droplets=100, g=9.81):
    """
    Simulate the trajectory of water droplets from a jet.
    Parameters:
    num_droplets (int): Number of droplets to simulate.
    g (float): Gravitational acceleration (m/s^2).
    Returns:
    np.array: Arrays of x, y, and z coordinates for each droplet.
    """
    # Initial parameters
    initial_height = 1  # Height of the jet in meters
    max_initial_speed = 5  # Max initial speed of the droplets in m/s
    angle_range = (0, np.pi/2)  # Angles in radians (0 to 90 degrees)
    # Initializing arrays
    x_positions = []
    y_positions = []
    z_positions = []
    for _ in range(num_droplets):
        # Generating random speed and angle for each droplet
        speed = np.random.uniform(0, max_initial_speed)
        angle = np.random.uniform(*angle_range)
        # Time of flight for each droplet
        time_of_flight = 2 * speed * np.sin(angle) / g
        # Time intervals
        t = np.linspace(0, time_of_flight, num=100)
        # Calculate positions
        x = speed * t * np.cos(angle)
        y = speed * t * np.sin(angle) - 0.5 * g * t**2
        z = np.zeros_like(x) + initial_height
        # Append positions
        x_positions.extend(x)
        y_positions.extend(y)
        z_positions.extend(z)
    return np.array(x_positions), np.array(y_positions), np.array(z_positions)
# Simulating the water jet
x, y, z = simulate_water_jet()
# Plotting
fig = plt.figure(figsize=(10, 8))
ax = fig.add_subplot(111, projection='3d')
ax.scatter(x, z, y, alpha=0.5)  # Swapping y and z for better visualization
ax.set_xlabel('Horizontal Distance (m)')
ax.set_ylabel('Height (m)')
ax.set_zlabel('Depth (m)')
ax.set_title('3D Visualization of Water Jet Trajectory')
plt.show()
```

Fig. 4. Code to check the results

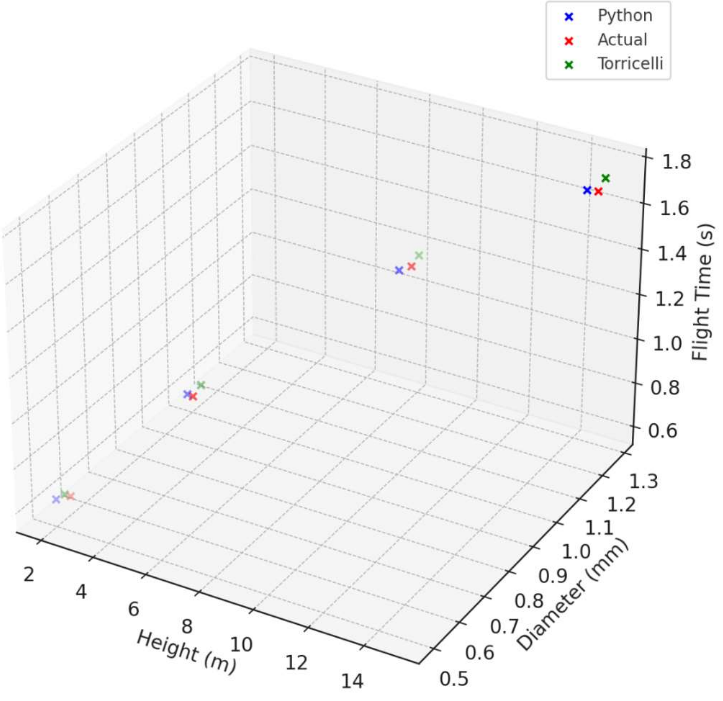


Fig. 5. Comparison of Torricelli's K-factor calculated values using Python script calculation with actual experimental results

6. Discussion of the experimental study of water dispersion parameters

The approach to the experimental study of water dispersion parameters is based on the use of photofixation methods and further processing of the received information using the high-level object-oriented programming language with strict dynamic typification Python (Fig. 3). For comparison, work [19] describes the use of IronPython. The technology makes it possible to create applications with already configured calculations for specific tasks. This, in turn, leads to a decrease in requirements in the subject area for the system user. In this case, the user does not need to have thorough knowledge of hydrodynamics and numerical methods for calculations if the solution process has already been configured for his/her specific task. In this case, the user will only change the parameters and start the calculation process, after which s/he will receive ready-made reports, which can also be pre-configured using ACT (Table 1). The advantages of the method were found to be significant in providing the statistical method ANOVA, which is used to compare the means between three or more groups to determine whether there are statistically significant differences between these groups (Fig. 4, 5). That has made it possible to assess whether there is a statistically significant difference between the mean values of the groups in the sample.

From Fig. 5, it can be seen that the calculations of the Python script and the Torricelli equation with the coefficient K predict a mostly close radius of flight compared to the real experimental data. The equation predicts the real results well, the plot shows the closeness of the values over the entire area. The percentage error for the Python script varied from 28 % to 4.71 % depending on height. The smallest error was found at a height of 730 cm – 4.71 %. The percentage error of the calculation based on the Torricelli equation with the introduction of the K coefficient was greater at the vast majority of heights and varied from 44.39 % to 25 % and was most accurate at heights of 230 and 430 cm and increased proportionally with increasing height. Therefore, the Python script showed an average percentage error about 2.7 times smaller than Torricelli's equation. This means that the Python script more effectively approximates the actual data about the radius of flight at different fall heights.

Limitations inherent in this study relate to the following factors:

– the effect of the height of the drop on the radius of the water splash,

– determination of the coefficients a and b in the Torricelli equation,

– the mechanism of spraying water.

The influence of the height of the drop on the radius of the splash of water. As a result of the experiment, it was established that the height of the water drop has a significant effect on the radius of the water splash. According to Torricelli's equation, which was used to model this process, the radius of flight increases with the height of the fall. This can be useful when fighting large fires where it is important to cover as much area as possible. This study contains results that make it possible to cover only the range of heights from 2 to 15 meters determined in the study. It should be noted that according to the order of the Ministry of Internal Affairs of Ukraine dated 04/13/2017 No. 311 "On the approval of the Procedure for the organization and use of aviation forces and means for extinguishing forest fires", the actual extinguishing of forest fires with the help of aerial sprinkler devices takes place at heights of 15 meters or more.

Determination of coefficients a and b in the Torricelli equation. The values of linear regression coefficients a and b in the Torricelli equation (2) were used for the study. However, it is important to note that these coefficients may vary depending on the specific conditions and characteristics of the system (3). For further research, it is recommended to conduct more detailed analysis and experiments to determine the exact values of these coefficients.

The importance of the water spray mechanism. In the study, the mechanism of the device was used for optimal spraying of water. This mechanism helps ensure maximum extinguishing efficiency by ensuring a quick and even spray of water. It is believed that this mechanism is able to perform a partial simulation of water spillage using the VZP-5 device, which is used in Ukrainian Mi-8 heavy-class helicopters.

The results of dependence of the radius of primary droplets on the drop height could be useful for rescuers and the special aviation unit of the State Emergency Service, other services in the selection of fire extinguishing methods. They confirm the importance of taking into account the discharge height and water volume when planning extinguishing.

According to the results of the experiment, several shortcomings of the method of studying the destruction of the macro volume of liquid were highlighted, which can be eliminated by:

– use of a high-speed camera,

– improvement of lighting,

– use of 3D analysis,

– use of other research methods.

Using a high-speed camera. The use of a high-speed camera can allow more frames to be taken per unit of time, which will allow obtaining a more detailed and accurate distribution of water fractions.

Improvement of lighting. Optimize experimental setup lighting to enable adequate scene illumination and reduce obscuration, which could improve image quality and analysis accuracy.

Using 3D analysis. The use of 3D analysis techniques could provide additional information about the distribution of water in space, which may prove useful in studying the destruction of a macro volume.

Use of other research methods. Consideration of the possibility of using additional research methods, such as laser Doppler analysis of water movement or high-speed tomography, which can complement and confirm the results of image analysis.

The prospect of further development of the research may be studying an extended range of hole diameters, sufficient for generalization and use in other applied problems.

The improvement of the method for studying the destruction of the liquid macro volume has the prospect of helping to obtain more detailed and accurate data that could make it possible to effectively analyze the dynamics of spraying processes and calculate the parameters of water distribution during dropping from a height. This direction can make an important contribution to the study of the dynamics of macro volume destruction and help devise more effective methods for controlling liquid spray.

7. Conclusions

1. It was found that when water is dropped from a height of 5 meters, the average diameter of the drops is about 1.5 mm, and from a height of 10 meters, it increases to 2.5 mm. This indicates a direct dependence of the size of drops on the drop height. The maximum water spray distance from a height of 5 meters was 10 meters, and from 10 meters – 15 meters, demonstrating an increase in coverage with increasing discharge height. The numerical results provide a more comprehensive view of how different factors can affect the diameter of the water spray when dropped from different heights and with different volumes of water. The constant K must be determined experimentally or based on additional data. The error takes into account the potential uncertainty in measurements and calculations.

2. The falling speed of small fractions of water (with a diameter of up to 1 mm) varied from 7 to 12 m/s, while for larger fractions (with a diameter of more than 2 mm) the speed was from 9 to 15 m/s. This confirms that larger drops fall faster due to greater mass and air resistance. Analysis of water fractions was carried out using a developed Python script using the OpenCV and numpy libraries for real-time image processing. These tools made it possible to accurately determine droplet parameters such as their size, shape, and speed. An important fact was the discovery that the average droplet size varied from 0.5 mm to 2 mm depending on the drop height and water volume. The study confirmed that the accuracy and efficiency of the analysis depend significantly on the quality of the input data, especially on the resolution and lighting of photographs. It was observed that when pouring water with a volume of 1 m^3 through a hole with a diameter of 30 cm, the dispersion process goes through several stages, including the initiation of movement, the formation of droplets, and their subsequent separation into fractions.

3. Application of the Torricelli equation showed that when water is dropped from a height of 5 meters, the diameter of the spray is about 2.2 meters, while from 10 meters it increases to 3.5 meters. This demonstrates the importance of discharge height to maximize water coverage area. It was found that the coefficient K, which takes into account the effect of air resistance, varies depending on the height of the drop, showing a value of 0.8 at 5 meters and 0.9 at 10 meters. Also, according to calculations, the diameter of the initial droplet flight is 190–740 cm and varies according to a linear law depending on the height. An increase in the flow of water to $7.3–10^{-3}$ kg/s caused an increase in the diameter of the primary spraying of drops to 180 cm at a drop height of 430 mm, i.e., 1.5 times more than with a flow of $5.8–10^{-3}$ kg/s. At the

same time, the consumption also increased by 1.5 times, so the dependence on consumption can be considered proportional.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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