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Computational Modeling of Forest Firebreak Formation by Controlled Hydrogen Explosions

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***Abstract* – The work presents the results of a numerical study of the spatiotemporal impact of a cylindrical (hose-type) hydrogen-charge blast wave on a forest area in order to assess the feasibility of forming firebreak barriers using controlled explosive loading. The study is motivated by the increasing frequency and scale of forest fires associated with climate change, which necessitate the development of new technological solutions for limiting fire spread while minimizing environmental impact. A set of several explosion power configurations (differing in hose-type charge radius) was examined for modeling the hydrogen blast near the ground surface. For each configuration, the spatial distributions of the maximum overpressure and the positive impulse of the blast wave were analyzed within the computed "air-forest cover" domain. Environmental blast impact parameter fields were generated from a hydrogen explosion model and analyzed, accounting for a given forest area height. Based on maximum overpressure thresholds, zones corresponding to different levels of forest-cover damage, including leaf stripping, twig breakage, and complete tree destruction, were identified. The extent of each zone along the ground surface was defined, enabling the quantification of the potential firebreak streak width. A comparative analysis of forest-cover damage-zone widths as a function of the charge's geometric parameter (hose-type charge radius) was performed. Additionally, the time histories of overpressure at a characteristic point near the ground surface beneath the charge were analyzed for all modeling configurations, allowing a comparison of blast-wave dynamics across different explosion powers. Grouped bar charts and trends illustrating the dependence of the damage-zone widths on the radius of the hose-type charge were constructed. The results demonstrate the fundamental feasibility of controlling the extent of forest-cover damage zones by selecting geometric parameters of hose-type hydrogen charges, thereby establishing a scientifically grounded basis for the development of environmental-safety technologies for firebreak formation.**

***Keywords* – Blast-wave overpressure history; controlled explosion impact; environmental safety; firebreak formation; forest fires; hydrogen hose-type charge; maximum overpressure; forest-cover damage zones; positive impulse.**

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Nomenclature		
R	Hose-type hydrogen charge radius	m
H	Forest stand height	m
ΔP_{max}	Blast-wave maximum overpressure (MO)	MPa
I^+	Blast-wave positive impulse (PI)	MPa·s

1. INTRODUCTION

Forest fires represent a major coupled natural–technogenic hazard, with their scale and frequency increasing significantly due to climate change, rising average air temperatures, prolonged drought periods, and the degradation of natural ecosystems [1]–[3]. Beyond their immediate environmental impacts, forest fires cause quantifiable socio-economic losses, degrade air quality and soils, and exacerbate long-term climate risks [1], [2]. In this context, the development of effective theoretical and practical approaches to localize and contain fire spread – particularly through the creation of firebreak barriers in forest areas – remains a critical scientific and engineering challenge to develop quantitatively predictive wildfire containment methods [3].

Traditional approaches to creating firebreaks include mechanical removal of vegetation (clearing, cutting), controlled burning, or the application of chemical fire retardants [4], [5]. Although these methods are relatively well studied and widely applied, they exhibit several inherent limitations, including high labour intensity, substantial time requirements, and limited effectiveness in hard-to-reach or large-scale forest areas [4], [5]. Controlled burning, in particular, is associated with the risk of losing control of the combustion process, increased emissions of combustion products, and adverse effects on ecosystems and the regional climate balance [1], [3].

An alternative research direction involves using physical methods to influence vegetation cover, particularly aerodynamic and explosive approaches [6], [7]. Explosive action as an engineering tool is widely applied in mining, construction, debris clearance, and the controlled demolition of engineering structures [6]–[9]. In the context of forest fires, explosive technologies have primarily been examined for creating gaps in combustible materials or for the rapid removal of post-fire debris (Fig. 1). However, systematic investigations into the effects of blast waves (BW) on vegetation cover to form controlled firebreaks remain limited [10].

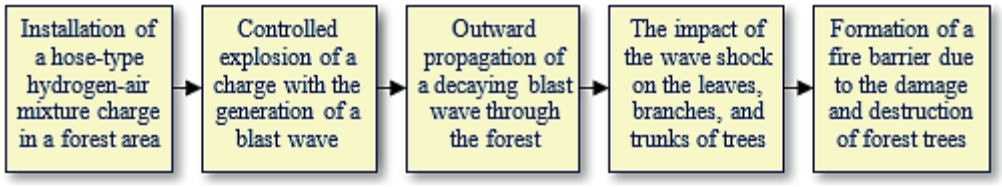


Fig. 1. Schematic diagram of the physical processes involved in the formation of a firebreak by a controlled explosion of a hydrogen hose charge as a barrier to forest fire spread.

A key issue is establishing quantitative relationships between explosion parameters (energy release, charge geometry, detonation characteristics) and the resulting forest damage [6], [7], [11]. To analyze explosive processes, the literature employs analytical models of point and linear explosions, Hopkinson–Cranz scaling relationships [12], empirical relationships for

estimating values of MO (ΔP_{max}) and PI (I^+) of the BW defined as the time integral of overpressure over the positive phase duration, as well as numerical methods based on computational gas dynamics [13], [14]. Analytic and semi-empirical models are computationally efficient and well-suited for engineering estimates. However, they offer limited accuracy for the spatially distributed cylindrical (hose-type) hydrogen charges and complex boundary conditions [7], [12], [14]. In contrast, CFD approaches provide a detailed description of the blast-wave structure and its interaction with the surrounding environment, but require substantial computational resources and careful selection of numerical schemes [15], [16], [8]. Recent studies in Environmental and Climate Technologies demonstrate the growing application of numerical modelling approaches for solving complex environmental and engineering problems under realistic operating conditions [17].

Of particular interest in contemporary research are explosions of hydrogen–air mixtures characterized by high specific explosion energy, relatively clean combustion products (primarily water vapor), and the capability to form extended distributed gas charges [18], [19]. Such charges make it possible to employ a quasi-linear source of explosion energy, which is fundamentally important for creating firebreaks of considerable length using a single PI [20], [21]. At the same time, the influence of the geometric parameters of an elongated hydrogen-filled shell (particularly its radius) on the spatial distribution of MO and the PI in a forest environment remains insufficiently studied [22].

In this context, it is advisable to employ three-dimensional, non-stationary numerical modeling of hydrogen–air mixture explosions based on the conservation equations for mass, momentum, and energy of the gas mixture, solved using the Godunov method [15], [16]. A similar approach has been successfully used to analyze explosive loads, assess the consequences of hydrogen-related accidents, and evaluate the influence of environmental geometry on explosive blast parameters [16], [19]–[24]. This approach enables the determination of MO and PI values at each point in space, as well as a quantitative assessment of regions with varying degrees of damage [5], [6], [11] (Fig. 2).

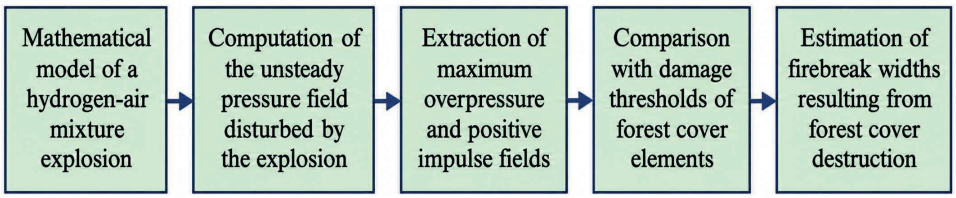


Fig. 2. Scheme for estimating firebreak width based on modeling a controlled hose charge explosion in a forest.

Thus, the relevance of this study lies in the need to develop justified research methods for the controlled formation of firebreaks in forest areas using explosion energy [1]–[3]. The advantages of the proposed approach include the ability to regulate explosion power by varying the geometric parameters of a longitudinal charge configuration, conduct spatiotemporal analysis of blast-wave effects, and establish predictive relationships between the charge parameters and the width of forest-cover damage zones [20], [21], [25]. The limitations of the study include the idealization of forest environments and the neglect of vegetation aerodynamic resistance [10]; assumptions regarding the effects of high-temperature combustion gases on heat-exchange processes in tree branches and trunks [26]; the influence of meteorological conditions on explosion impacts on vegetation [27]; the use of a purely deterministic approach to determining firebreak parameters without accounting for probabilistic indicators of forest-cover damage [28]; and the omission of such influences

as tree trunk thickness [29], strength characteristics of different plant species [30], and the amplification of PI effects due to interactions with trunks and the formation of reflected waves [31], which can improve the quality of modeling and outlines directions for further research.

The objective of the study is to simulate numerically the impact of a BW generated by a hose-type hydrogen charge of varying power on a forest area and to identify the patterns governing the formation of leaf-stripping zones, twig-breakage zones, and tree-trunk destruction zones in order to substantiate firebreak barrier parameters [6], [18], [20]. To achieve this objective, the paper consistently presents the problem formulation, the mathematical model (MM) of the explosion, the numerical implementation, the analysis of the results, and their engineering interpretation [15], [16], [19].

2. Problem Statement and the Calculation Domain Geometry

This study performs numerical simulations of BW propagation in an open forest area and quantifies the resulting vegetation damage zones that may be used to form firebreaks. The primary focus is on determining the spatially resolved peak overpressure and positive phase impulse distributions, and on establishing their relationships with the charge's geometric parameters.

The calculations are carried out in a right-handed Cartesian coordinate system XYZ, where the XOZ plane is parallel to the ground surface, and the OY axis is directed vertically upward (Fig. 3). The computational domain is a rectangular parallelepiped with dimensions of 38.2 m long (OZ) axis, 10.2 m width (OX), and 9.0 m high (OY). The lower domain boundary corresponds to the ground surface (y = 0 m), while the upper boundary is located at a height of 9.0 m above the ground.

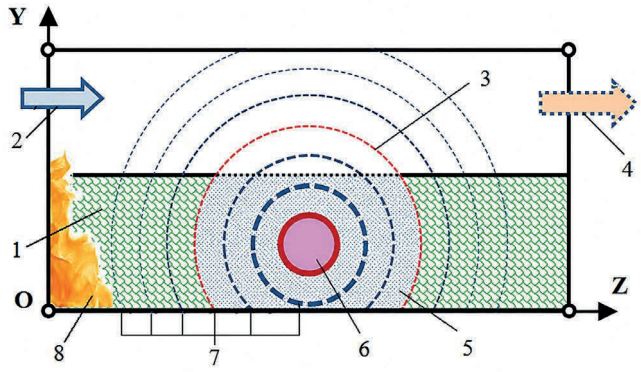


Fig. 3. Schematic diagram of safe zone formation: 1 – forest massif; 2 – fresh air; 3 – critical pressure for forest damage; 4 – gas-air mixture; 5 – fire-prevention barrier; 6 – compressed combustion products; 7 – front of the fading BW; 8 – forest fire.

For the numerical implementation, the problem domain is spatially discretized by uniformly subdividing it into cubic computational cells with dimensions of 0.2 × 0.2 × 0.2 m. As a result, a regular computational grid is formed, consisting of 191, 51, and 45 cells in the Z, X, and Y directions, respectively. This spatial discretization ensures sufficient resolution for properly capturing the blast-wave front structure and the spatial gradients of gas-dynamic parameters.

The forest is modeled as a geometrically defined region without explicit representation of aerodynamic drag or fluid–structure interaction, extending from the ground surface up to a

height of H = 3.0 m (Fig. 4). In this study, the forest cover is treated as a geometric domain in which the BW's effects are evaluated, without accounting for vegetation's aerodynamic resistance or its mechanical interaction with the gas flow. This idealization enables focusing on the analysis of blast-wave gas-dynamic parameters and their role in the formation of forest-cover damage zones.

The source of the explosion impact is a hose-type charge containing a hydrogen–air mixture, located parallel to the ground surface. The axis of the cylinder is located 1.5 m above the ground and is parallel to the XOZ plane. The charge is centered within the YOZ and XOY vertical planes of the computational domain, ensuring symmetry of blast-wave propagation in the transverse direction. The hose is 7 m long along its axis.

The study examines a series of five explosion modeling cases that differ solely in the radius R of the elongated hydrogen-filled shell cylinder, with R = 0.6, 0.7, 0.8, 0.9, and 1.0 m (Table 1). Varying the charge radius results in a corresponding increase in the hydrogen–air mixture volume and the explosion energy, thereby enabling exploration of how explosion power affects the width of the forest-cover damage zones.

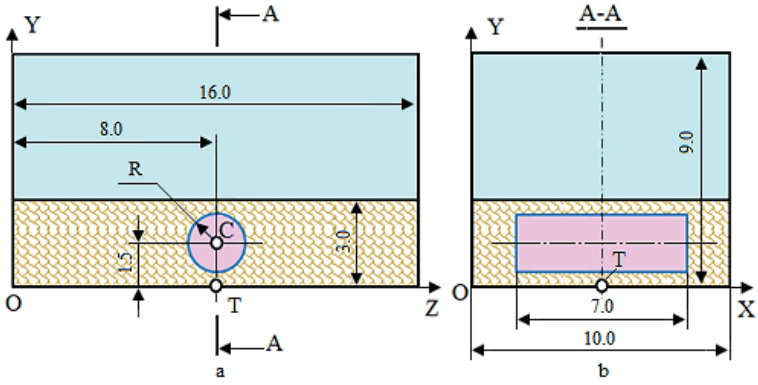


Fig. 4. Geometrical scheme of the calculation domain: a – central vertical longitudinal view YOZ; b – central vertical cross-section in XOY plane.

TABLE 1. IDENTIFICATION OF NUMERICAL SIMULATION CASES

Numerical Experiment Parameters	**Simulation case identifiers**				
Simulation case identifier	R0	R1	R2	R3	R4
Hydrogen charge radius, m	0.6	0.7	0.8	0.9	1.0

For this problem, the boundary conditions of the computational domain are specified as follows: at the inlet boundaries, the air is initially stationary with an atmospheric pressure of 101 325 Pa and a temperature of 293 K, while at the outlet boundaries, the same atmospheric pressure is maintained. A no-flow condition is imposed at the ground surface. The initial conditions correspond to quiescent air throughout the domain, except within the longitudinal charge configuration domain, where the thermodynamic properties of the combustion gases are prescribed to initiate an instantaneous explosion.

This problem statement provides the basis for introducing an explosion MM, a numerical method, and the analysis of results that substantiate the feasibility of controlled formation of firebreaks in forest areas.

3. METHODS AND PROCEDURES

3.1. The Hose-Type Hydrogen Charge Explosion Mathematical Model

To explore the effects of the BW on the forest area, this study employs a model of an idealized instantaneous explosion (instantaneous energy release), using a three-dimensional, non-stationary system of conservation equations for the gas mixture's mass, impulse, and energy [20]. The model resolves gas-dynamic processes associated with the expansion of combustion products and the formation of a shock wave [6]–[8]. Recent studies on transient wave-process modelling also emphasize the importance of accurate numerical treatment of strongly nonstationary flow discontinuities in environmental CFD applications [32].

Within the computational domain, the gas environment is treated as a two-component mixture consisting of atmospheric air and combustion gases [22]. To describe the motion of this mixture, a system of conservation equations in conservative form is employed, formulated in the Cartesian coordinate system XYZ and comprising equations for conservation of mixture mass, impulse along the coordinate axes, and total energy [18].

To account for the spatial and temporal distribution of combustion products, an additional transport equation for the mass concentration of gas impurities is solved, enabling the tracking of their spatial transport via a scalar concentration field [23]. This is essential for accurately representing the thermodynamic properties of the gas mixture both within the explosion zone and in the surrounding region [21].

The system of equations is closed using the Mendeleev–Clapeyron equation for an ideal gas mixture state [7], which relates pressure to the mixture's density and temperature, determined by the mass concentrations of air and combustion products [22]. The adiabatic coefficient is treated as a variable parameter that depends on the local gas-mixture composition [18].

The initiation of the explosion is modelled by prescribing, at the initial time and within the distributed gas charge zone, a high-temperature, high-pressure state corresponding to the combustion products of a stoichiometric hydrogen–air mixture [22]. The subsequent unsteady expansion of the gases governs the subsequent evolution of the process, including the formation of the BW front and its propagation in the surrounding air [8].

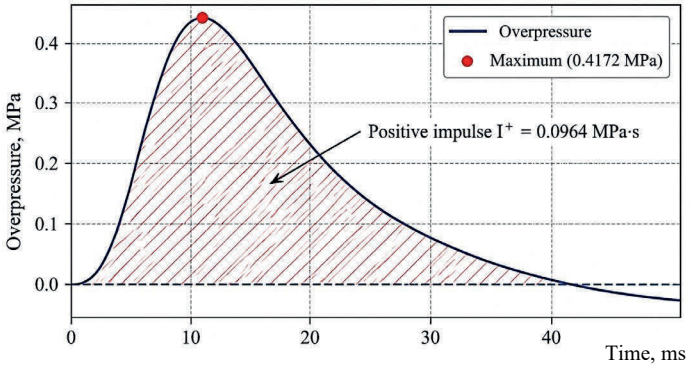


Fig. 5. Overpressure time history at one of the control points with its MO and PI values (one of the hydrogen charge options).

The model emphasizes blast-wave parameters that are critical for assessing forest-cover damage. In each computational cell, the blast-wave MO and PI values are recorded throughout

the time integration. The impulse is defined as the time integral of overpressure over the duration of the wave positive phase [33]. The typical BW history profile at control point T for one of the experiment options (R2) shows two main factors (Fig. 5). The resulting values are used as generalized criteria for evaluating the impact of explosions on forest cover [10].

The model enables parametric analysis of the elongated hydrogen-filled shell geometric parameters influence on the spatial distribution of the gas-dynamic characteristics of the BW [18]–[21]. At the same time, the model makes several simplifying assumptions, including idealizing the gas mixture and neglecting direct interactions between the flow and the forest elements [10], [14]. These assumptions outline the model's applicability limits while also providing a foundation for its further generalization and development, such as incorporating vegetation aerodynamic resistance and multiphase effects.

3.2. Numerical Method and Computational Implementation

The numerical implementation of the hydrogen–air mixture explosion MM was carried out with consideration of the non-stationarity of the process and the sharp spatial and temporal variations in gas-dynamic parameters of BW [6]. To accurately capture the explosion wave front and to prevent non-physical oscillations in pressure and velocity fields, a conservative approach to the numerical solution of the gas-dynamic equations was adopted [15].

The system of differential equations governing the conservation of mass, impulse, and energy of the gas mixture is transformed into an integral form for each computational cell [18]. This formulation enables the direct application of balance relations for mass, impulse, and energy fluxes across cell boundaries. It ensures the physical consistency of the numerical scheme, even in the presence of strong parameter gradients of the BW [14].

To approximate flows between neighbouring cells, the Godunov method was used to solve local Riemann problems at cell interfaces [16]. This method is well established for modeling explosions and blast waves, as it naturally captures discontinuities in gas-dynamic variables and does not require the introduction of artificial viscosity [13], ensuring high reliability of calculations even in the absence of direct experimental data. This feature is particularly important for accurately determining the MO value at the blast-wave front [6].

The calculations are carried out using a single minimum time step applied uniformly across all computational cells. The time step is chosen to satisfy the numerical scheme's stability requirements and is determined by the maximum local propagation speed of disturbances in the gas medium [15]. This approach treats the problem as fully non-stationary and tracks the evolution of the BW from its initiation to its attenuation within the computational domain [14].

During the time integration, time-resolved pressure data are recorded in each computational cell. Based on these data, the MO value attained during the passage of the blast-wave front is automatically determined [11]. In addition, for each cell, the PI value is calculated as the time integral of the overpressure over the interval during which the pressure exceeds the initial atmospheric level [14]. This impulse serves as an integral measure of blast loading intensity [5].

The MO and PI values obtained in each computational cell are stored for further analysis. To evaluate the impact of the explosion on the forest area, these parameters are projected onto the vertical YOZ plane, located at the center of the computational domain and perpendicular to the longitudinal charge axis [18], [20], [21]. This plane provides a representative cross-sectional distribution of blast loading along the vertical and longitudinal directions of potential firebreak formation [22].

Separately, at a ground-level control point directly beneath the charge, the complete time history of overpressure is recorded. Analysis of this time dependence allows comparison of

the explosion's impact intensity and duration across different charge-radius configurations and the identification of characteristic differences [19].

The proposed numerical implementation achieves sufficient accuracy in describing explosive processes while maintaining moderate computational costs and is well-suited for parametric studies [14]. This makes it suitable for analyzing the impact of explosion power on the formation of forest-cover damage zones and for subsequent use in environmental forecasting and fire-prevention planning [20].

3.3. Method of Deterministic Analysis and Prediction of Forest-Cover Damage Zones

To quantitatively evaluate the impact of the BW on the forest area, this study applies a deterministic threshold-based damage assessment approach by comparing evaluated gas-dynamic parameters with established threshold values for forest-cover damage [5]–[7]. This approach is widely employed in explosion engineering, industrial safety, and environmental risk assessment, as it enables a direct linkage between the physical parameters of an explosion and the expected consequences for natural objects [4], [24], [28].

Within the scope of this study, the blast-wave MO and PI are considered the primary parameters characterizing the explosion impact [14]. These quantities are standard integral blast loading metrics and are traditionally used to assess mechanical damage to a wide range of objects, including buildings, engineering structures, and biological systems [5], [9], [16]. For vegetation cover, overpressure determines the instantaneous mechanical loading on leaves, twigs, and trunks, whereas PI characterizes the overall duration and intensity of this loading [7], [10], [14].

The threshold values of overpressure and PI corresponding to different degrees of forest-cover damage are adopted based on generalized reference data derived from experimental and field studies on the effects of blast and BW on biological objects and lightweight natural structures [10]. The choice of overpressure thresholds was based on the critical values required for the mechanical clearing of the strip from leaves and small branches (the most flammable fractions), as well as the resilience limits of tree trunks. Specifically, overpressure exceeding 0.04 MPa is considered sufficient for defoliation and branch breakage, significantly reducing the fuel load within the created firebreak. Table 2 presents the threshold values of blast-wave parameters used in this study to classify the damage zones.

TABLE 2. THRESHOLDS OF BLAST WAVE PARAMETERS FOR ASSESSING FOREST-COVER DAMAGE

Forest-cover damage degree	**Maximum overpressure, MPa**	**Positive impulse, MPa·s**
Leaf stripping	≥ 0.02	≥ 0.01
Twig breakage	≥ 0.04	≥ 0.10
Complete tree destruction	≥ 0.10	≥ 0.30

These threshold values represent average limits for the onset of the corresponding mechanical damage and may vary with tree species, age, planting density, and moisture conditions [10]. At the same time, they are sufficiently representative for preliminary engineering and environmental assessments, as well as for forecasting blast-wave damage zones [4], [24], [28]. The application of such thresholds enables conversion of continuous fields into discrete damage classification zones [6], [11].

The methodology for determining the damage zones involves a spatial comparison of the calculated MO and PI values with the corresponding threshold values within the region corresponding to the forest area height [18], [20], [21] (Table 2). For each degree of damage,

a binary mask of the zone is formed to indicate the presence or absence of the corresponding impact at a certain spatial point [20], [23]. Subsequent projection of these zones onto the horizontal direction along the axis OZ makes it possible to determine the extent of the damage zones and to interpret them as the width of a potential firebreak [20], [25].

The PI's contribution to the formation of damage zones is analyzed separately. A comparison of the calculated impulse values with reference threshold values indicates that, for the explosion configurations considered, the computed values are significantly lower than the critical levels required to cause substantial forest-cover damage [7], [10], [14]. This observation supports the conclusion that MO plays a dominant role in defining the boundaries of the damage zones under the explosion conditions examined [6].

The proposed deterministic approach to forest-cover damage-zone analysis offers several advantages, including transparency in result interpretation, the direct use of reference data, and suitability for predicting explosion parameters required to achieve a specified firebreak width [4], [20], [28]. At the same time, it should be noted that this approach does not account for probabilistic aspects of forest-cover damage or the local heterogeneity of the forest area, which may be addressed in future studies through the application of stochastic or combined analysis methods [24].

4. Results and Discussion

The simulation results provide a quantitative assessment of blast-wave effects generated by a hose-type hydrogen charge in a forest area and an assessment of the feasibility of forming firebreaks of a specified width [20]. The analysis was conducted for a series of five explosion scenarios differing in the charge radius R (Table 1), which directly determines the explosion impact power [6].

At the first stage, the spatial distribution of the impulse during the blast-wave positive phase was analyzed in the vertical YOZ plane, aligned with the computational domain center and perpendicular to the charge axis [19] (Fig. 6).

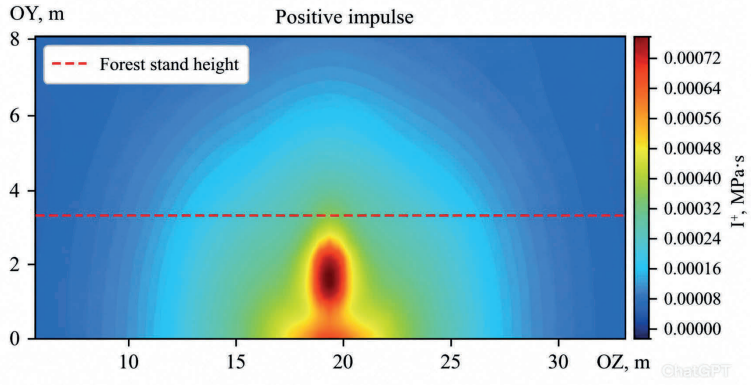


Fig. 6. PI distribution generated by the controlled hydrogen charge explosion (option R2).

These results show that, for all considered distributed gas charge radius configurations, the impulse values remain significantly below the threshold levels associated with forest-cover damage [10]. This implies that the cumulative effect of the BW during the positive phase is insufficient to cause substantial mechanical destruction of forest cover components [14].

Therefore, under the conditions examined, the PI may be seen as an auxiliary parameter that does not play a decisive role in the formation of forest-cover damage zones [6], [11].

In contrast, the distribution of MO reveals clearly delineated regions where threshold values are exceeded, corresponding to different degrees of the forest-cover damage [6]. The resulting overpressure maps clearly identify areas within the forest cover up to $H = 3.0$ m in height where leaf and twig breakage, and complete tree destruction are expected [10] (Fig. 7).

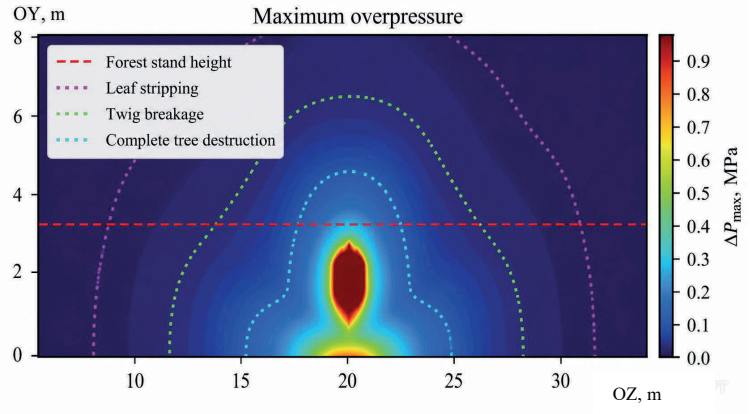


Fig. 7. Forest cover damage zones generated by the controlled hose-type hydrogen charge explosion (option R2).

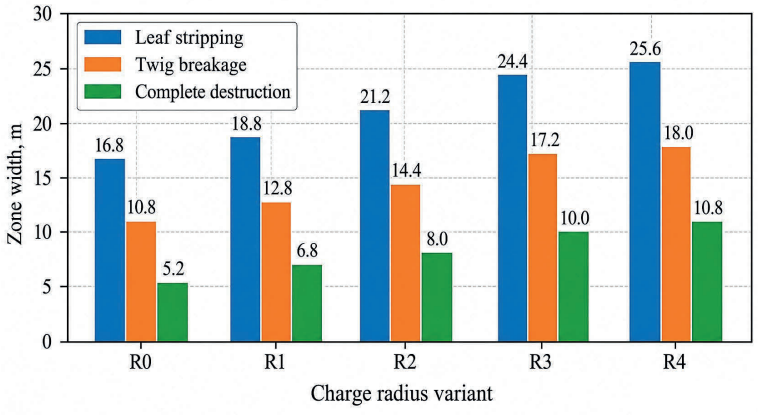


Fig. 8. Comparison of affected zone widths for different charge radius (options R0–R4)

As the radius of the elongated hydrogen-filled shell increases, a systematic expansion of these zones along the direction of blast-wave propagation is observed, indicating enhanced effectiveness in forming a firebreak.

The projection of the damage zones onto the horizontal direction along the OZ axis made it possible to determine the widths of the leaf-stripping, twig-breakage zones, and complete tree-destruction zones for each explosion scenario [18], [20] (Fig. 8). The resulting values are clearly presented in a grouped bar chart, enabling a comparative analysis of the impact of the longitudinal charge configuration radius [25].

The findings indicate that even a relatively small increase in the charge radius results in a substantial expansion of the damage-zone widths, particularly in the case of complete tree

destruction [22]. This confirms the high sensitivity of the explosion-impact spatial scale to the charge's geometric parameters [14].

In addition, the dependence of the damage-zone width on the charge radius is shown in scatter plots with corresponding linear trend lines [20] (Fig. 9). The resulting trend dependencies can be used to predict the required charge parameters to form a firebreak of a specified width [28]. This approach is particularly valuable in real-world applications, as it facilitates the transition from numerical modeling to practical recommendations [25].

The time histories of overpressure at the ground surface control point T directly beneath the distributed gas charge show an increase in peak pressure amplitude with increasing charge radius, while preserving the overall shape of the blast-wave profile [19] (Fig. 10). This observation confirms the validity of our comparative analysis of different explosion scenarios and is consistent with the physical principles governing the expansion of combustion products [13], [14].

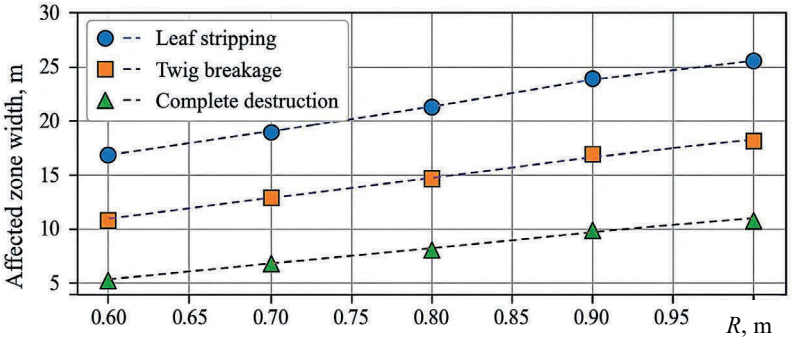


Fig. 9. Dependence of affected zone width on charge radius: markers – calculation data; lines – trends.

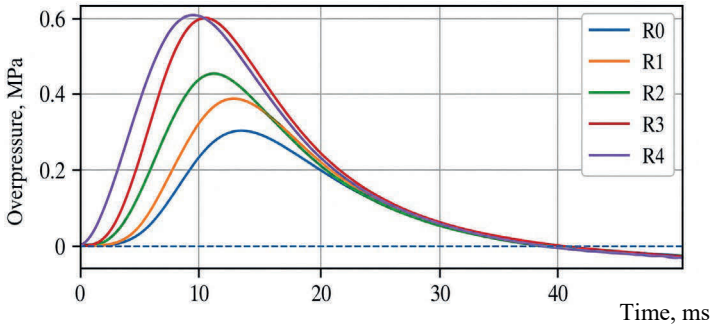


Fig. 10. Overpressure time histories in control point T (comparison of charge radius variants R0–R4).

The verification and validation of the mathematical and numerical model employed require specific attention. The importance of numerical model validation and sensitivity analysis for environmental simulation problems has also been highlighted in recent computational studies [34]. Within the scope of this study, no dedicated analyses were performed to assess the stability of the numerical solution with respect to spatial grid resolution, nor was the influence of time-step selection on solution accuracy examined in the present study. The sensitivity of the results to the proximity of the actual blast-wave impact zone to the inlet and outlet boundaries of the computational domain was likewise not explored [8]. Conducting

such analyses would require substantial additional computational resources [16]. Under these conditions, comprehensive verification of grid and time-step variations becomes considerably more challenging.

It should be noted that a single simulation run using the specified spatial grid and a physical process duration of 80 ms from the moment of explosion initiation required approximately 20 minutes of computational time on an Intel® Core™ i7-3630QM CPU @ 2.40 GHz operating under a 64-bit Windows 10 Pro system with 16.0 GB of RAM, which is typical for three-dimensional unsteady CFD simulations of explosive processes [13], [15].

At the same time, the MM of the hydrogen–air mixture explosion and the numerical solution method have been previously verified and validated in the works of other authors [6], [7], [14], as well as in the author's earlier studies [18]–[22], where numerical results were compared with experimental data and established analytical and semi-empirical models of explosive processes. The corresponding references are provided in the bibliography. This enables considering the presented results to be physically sound and suitable for preliminary environmental and engineering assessments, and taking into account the model's stated limitations.

The obtained results, while building upon established numerical frameworks, provide a critical refinement of hose-charge blast parameters, representing a necessary advancement in the precise design of fire protection systems under realistic industrial threat scenarios.

5. Conclusion

This study presents a three-dimensional CFD analysis of blast-wave interaction with forest vegetation to assess the feasibility of forming controlled-width firebreaks. The modeling is conducted in a three-dimensional framework utilizing the conservation equations of mass, impulse, and energy for a gas mixture, solved by the Godunov method, enabling the non-stationary propagation of the BW to be traced within a bounded computational domain.

The obtained spatial distributions of the MO and PI values in the vertical plane passing through the center of the elongated hydrogen-filled shell demonstrated a monotonic increase of blast intensity with increasing charge radius. It was established that increasing the charge radius from 0.6 to 1.0 m results in a systematic increase in explosion power and the expansion of forest-cover damage zones. Analysis of the wave propagation time intervals (up to 0.08 s) demonstrates that the primary energetic impact on the environment is formed within the first tens of milliseconds, which allows for a rapid assessment of the fire localization zone.

It has been demonstrated that, for the configuration considered, the PI of the BW is insufficient to serve as a determining criterion for forest-cover damage assessment. In contrast, the MO is the primary factor governing the formation of leaf-stripping, twig-damage, and complete tree-destruction zones. Based on a deterministic analysis using overpressure threshold values, the widths of the corresponding damage zones have been quantitatively determined for each explosion power scenario.

The developed grouped diagrams and trend relationships describing the dependence of the damage-zone widths on the longitudinal charge configuration radius enable the results to be applied for predicting the explosion power required to form firebreaks of a specified width. Accordingly, the proposed approach provides a basis for selecting charge parameters required to achieve a target firebreak width, while accounting for environmental constraints and the controllability of the impact.

While this study is limited to a parametric CFD analysis, the results establish a necessary theoretical foundation for future experimental validation and the optimization of hose-charge parameters in field conditions.

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