DOI: https://doi.org/10.15276/ict.02.2025.35
UDC 534.222.2+536.464+004.942

Analysis of the explosive processes development for the creation of the explosion protection decision support systems, taking into account the possibility of secondary explosions

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ABSTRACT

This study emphasises the need to explore the possibility of secondary explosions at complex potentially explosive objects, because in some cases, secondary explosions can be much more powerful and dangerous than primary ones. Modern explosion protection decision support systems practically do not take into account the possibility of secondary explosions, so this gap must be filled. A mathematical model has been designed for the development of a primary explosion that can lead to a secondary explosion at a complex potentially explosive object. This model is based on the mathematical theory of combustion and explosion, on fuzzy logic and fuzzy set theory, and on the graph theory, including fuzzy graphs. To find directly the graph vertex corresponding to the maximum hazard of a secondary explosion, the well-known Dijkstra's algorithm for finding the shortest path in graph is used. The developed mathematical model is universal and can be applied to complex potentially explosive objects of almost any physical nature. Examples of this type of complex potentially explosive objects may include industrial enterprises, individual workshops of these enterprises, pipelines and other transport systems, various machines, aggregates and other equipment. Based on the developed mathematical model, it is possible to refine the information model of a complex potential object. The application of this mathematical model to a specific complex potentially explosive object and to specific technological process requires clarification taking into account the specifics of this object or this technological process. The mathematical basis of fuzzification must be linked to complicated problems in gas dynamics and problems of the mathematical theory of combustion and explosion. An algorithm has been developed for identifying the object that poses the greatest risk from the point of view of the possibility of secondary explosion. However, neither this algorithm nor the mathematical model as a whole takes into account the potential damage from a secondary explosion. This factor is very important for decision-making on secondary explosion prevention and should be considered in future research. The question of whether the secondary explosion is deflagration or detonation also requires separate study. This problem seems important because, as a rule, detonation explosions are more powerful and dangerous than deflagration explosions. It should be taken into account that usually the initiation of detonation is significantly more difficult compared to the initiation of a deflagration explosion.

Keywords: Explosion; secondary explosion; fire; decision support system; explosion protection; mathematical model; information model; potentially explosive object; fuzzy logic; graph; Dijkstra's algorithm

Relevance. Mathematical and information models previously developed for explosion safety decision support systems [1, 2] take into account only the possibility of an explosion occurring at one individual potentially explosive object (PEO) within a more complex system (for example, the possibility of a silo explosion at the grain elevator [3]). However, it is quite obvious that an explosion at one of the PEOs can initiate explosions of other PEOs of a complex system, of which the above-mentioned PEO is included as a component. In particular, a silo explosion at an elevator may well lead to explosions of other silos in the silo building and even, under certain conditions, to an explosion of the tower – the main working building of the elevator, where the technological equipment is concentrated. Such kinds of secondary explosions can be more dangerous and destructive than the primary explosions that initiate them.

Therefore, the creation of mathematical models (and, based on them, information models) for explosion protection decision support systems, taking into account the possibilities of secondary explosions, is really a topical task.

Literature review. From the perspective of designing explosion safety decision support systems, the problems of preventing secondary explosions have been largely ignored. This is because, in practice, chemical explosion prevention has been until recently viewed solely from the perspective of preventing ignition, meaning that the problem of ensuring explosion safety has been essentially reduced to fire safety. As a result, the problem of predicting and preventing secondary explosions following primary explosions has not been studied. A definite attempt to consider this problem was made in works [4, 5], but these works did not receive further development. In addition, works [4,5] examine only explosive objects of grain and grain processing industry enterprises, while it is desirable to formulate and solve such a problem in a general way.

The study aims to create a mathematical theory for projecting explosion protection decision support systems, which take into account the problem of predicting and preventing secondary explosions. This theory must be simple enough to avoid the use of complex numerical methods (such as the numerical solution of sets of partial differential equations), as the use of these methods requires significant computational time. In this case, the ability to control the object effectively is lost.

Methodology and solution. The methodology proposed in this study, based on the gas-dynamic theory of stability of combustion and detonation waves, fuzzy logic and graph theory, should provide a breakthrough in the field of creating decision support systems for explosion safety, taking into account the possibility of secondary explosions. Naturally, such intelligent decision-making systems must be based on a decision-making system that takes into account the possibility of only primary explosions occurring during a fire, that is, when ignition (or sometimes some sufficiently strong shock impact) has already taken place.

Let us consider complex PEO, which consists of *n* different PEOs. Such PEOs can be called elementary PEOs. It is namely elementary PEOs that are the sources of primary explosions, without which secondary explosions are naturally impossible.

It is supposed, that fuzzy estimation $\tilde{E}_i$ $(0 \le \tilde{E}_i \le 1)$ for the explosiveness of the *i*-th object ($1 \le i \le n$) is considered to be known. Value $\tilde{E}_i$ can be estimated by the methodics, which are developed previously [1, 2].

The explosive ability $\tilde{E}_i$ of PEO is usually expressed as a conjunction of two fuzzy statements $\tilde{F}_i$ and $\tilde{L}_i$, that is

$$\tilde{E}_i = \tilde{F}_i \wedge \tilde{L}_i \;, \tag{1}$$

where $\tilde{F}_i$ expresses the fire hazard of the i-th PEO and $\tilde{L}_i$ is the ratio of the maximum linear size $L_{\max i}$ of the *i*-th object to the length X_{si} of the pre-detonation section [1,2] . It is assumed that $\tilde{L}_i = 1$ if $X_{si} \le L_{\max i}$ and so $0 \le \tilde{L}_i \le 1$.The value $\tilde{L}_i$ (that is the value X_{si}) is determined on the basis of the solution of the hydrodynamic stability problem for the flame [1,6].

It is obvious that

$$\exists m \in \{1,...,n\} \quad \tilde{E}_m = \max_i \tilde{E}_i , \tag{2}$$

where *m* is the number of the most explosive elementary PEO of the complex PEO, $\tilde{E} = \tilde{E}_m$ can be considered as the explosiveness of the complex PEO as a whole and expresses the possibility of the primary explosion.

Following the methodology [5] complex PEO can be modeled for every moment of time by graph with *n* nodes. Every node corresponds to specific elementary PEO, that is the part of the complex PEO.

This graph is an undirected graph. It can be either connected or disconnected.

If a graph is disconnected, it means that this graph consists of two or more connected subgraphs [5]. Those subgraphs correspond to such sites of the complex PEO, which are independent in terms of explosion-proof. That is the primary explosion at any object of any site can’t be a reason for the secondary explosion at any object of the other site. If the node of the graph is isolated it means that secondary explosions are not possible at the relevant elementary PEO, but only a primary explosion is possible, which does not pose any threat to other objects.

Therefore, it is necessary at first to solve the well-known problem of the graph connectivity and sometimes also to solve the graph ordering problem. Algorithms for solving both of these problems are known in graph theory. Computer implementation of these algorithms is not difficult. And then it is required to estimate separately the possibility of the secondary explosion for every site of complex PEO corresponding to a connected subgraph.

So let us consider only connected graphs.

Two nodes *i* and *j* ($1 \le i \le n$, $1 \le j \le n$) are adjacent if the possibility $\tilde{P}_{ij}$ $(0 \le \tilde{P}_{ij} \le 1)$ of the penetrating of the fire or of the weak shock wave from the PEO *i* (that is from the object, which corresponds to node *i*) into PEO *j* is more than zero; $\tilde{P}_{ij}$ is of course a fuzzy value.

The graph is weighted. The weight of the node *i* is a fuzzy estimation $\tilde{E}_i$. The weight of the edge *ij* is also a fuzzy value $\tilde{P}_{ij}$.

The value of $\tilde{P}_{ij}$ depends on the physical way (first of all of the geometrical forms and of the kind and state of the continuous medium filling these forms) of connection for objects *i* and *j*. This graph is also fuzzy graph [7], because the weights of the nodes and the weights of the edges are fuzzy logical values.

The matrix $\left\| \tilde{P}_{ij} \right\|$ is the weight matrix of the graph. In most cases, the following equality is true:

$$\tilde{P}_{ij} = \tilde{P}_{ji} . \tag{3}$$

That is the possibility of the fire penetrating or the weak shock wave propagation from the PEO *i* into the PEO *j* is equal to the possibility of the fire penetrating or the weak shock wave propagation from the PEO *j* into the PEO *i*. However, in general, equality (3) is not always satisfied, and the weight matrix is not symmetric. But this fact does not fundamentally affect the solution of the problem.

The algorithm of finding the most explosive object in a situation when object *m* explodes (that is of finding the most explosive object from the point of view of the possibility of secondary explosion) includes such a sequence of actions:

1. For every edge *ij* change the weight of the edge from $\tilde{P}_{ij}$ to $N\tilde{P}_{ij}$, where

$$N\tilde{P}_{ij} = \neg\tilde{P}_{ij} = 1 - \tilde{P}_{ij} \quad . \tag{4}$$

Value $N\tilde{P}_{ij}$ is fuzzy estimation for inability of penetrating of explosion from PEO *i* to PEO *j*.

2. In this modified graph with new weights find for every node *i* (except node *m*) the shortest path from node *m* to node *i*. Problem of finding of the shortest path in the graph is solved by Dijkstra’s algorithm [8].

3. Every node *i* (except node *m*) gets a value $\tilde{P}_i^m$, where $\tilde{P}_i^m$ is the length of the shortest path in this (modified) graph from node *m* to node *i*. The value $\tilde{P}_i^m$ expresses the inability of the elementary PEO*i* to explode in the case of the primary explosion at the elementary PEO *m*.

4. It is obvious that

$$\exists u \in \{1,...,n\}\, u \ne m \qquad \tilde{P}_u^m = \min_i \tilde{P}_i^m \ . \tag{5}$$

Elementary PEO *u* is the PEO with the minimal inability for secondary explosion, that is elementary PEO *u* is the most explosive elementary PEO in the presence of the primary explosion at the elementary PEO *m*.

Thus, an algorithm was created to search for the most explosive elementary PEO from the point of view of the possibility of a secondary explosion among all the objects that make up the complex PEO.

The elementary PEO of the primary explosion (elementary PEO *m*) should be the elementary PEO that is most explosive according to formula (2). If control is operative and takes place in real-time mode, then the elementary PEO of the primary explosion is the elementary PEO, where the explosion occurred or the fire is present.

When designing a complex PEO or predicting its behaviour in various emergency situations, by varying the value of *m* from 1 to *n*, one can obtain a map of all possible secondary explosion scenarios.

The constructed mathematical model of the possible occurrence of a secondary explosion is quite universal and allows for the refinement of the corresponding information model of the complex PEO [2].However, the use of these models (mathematical model and information model) in the explosion safety decision support systems faces a number of challenges.

The main problem is calculating of the weight matrix $\left\| \tilde{P}_{ij} \right\|$, that is assessing the possibility of propagation of combustion waves or weak shock waves initiating an explosion from one elementary PEO to another.

Obviously, this type of assessment requires solving rather complex gas-dynamic problems. That's understandable that it's significantly easier to calculate the explosion hazard of a single elementary PEO than the possibility of a fire or explosion spreading from one PEO to another. For example, it is much easier to assess the explosion hazard of a single silo [3] than the possibility of an explosion spreading from that silo to the elevator tower. A solution to such a problem as assessing the possibility of propagation of combustion waves or weak shock waves from one elementary PEO to another cannot be universal. Such a solution can only be found for a specific type of complex PEO.

Finding matrix elements $\tilde{P}_{ij}$ requires solving problems regarding the propagation of flame, shock, and detonation waves through various channels, pipes, passages, corridors, etc. The obtained results must be converted to fuzzy variables $\tilde{P}_{ij}$. A methodology for such fuzzification has already been developed and is used to determine values $\tilde{E}_i$ (in this case, the mathematical basis for determining fuzzy variables is solving the problem of the hydrodynamic stability of combustion waves, developed deflagration, and detonation).

An enterprise where explosions are possible in principle can be considered as a complex PEO. The technological process at the enterprise can always be modeled as a definite sequence of steps. Those steps are connected with the most important technological operations and/or organizational events. Every step in sequence of technological processes corresponds to the graph described above. Every transition from one step to another changes weights of nodes and weights of edges. That means that explosiveness of different PEO of the enterprise changes and ability for penetration of explosion from one PEO to another change also.

Transition from one step of technological process to another sometimes leads to changing of the structure of corresponding graph. New edges can be added to graph; some edges can be deleted. Removal of a node means vanishing of PEO (corresponding to this node). At the enterprise, such appearances and disappearances are possible only as a result of the reconstruction or rebuilding of the whole enterprise. So nodes of the graph are invariable, but their weights are changeable.

Explosion protection decision support systems, taking into account the possibilities of secondary explosions, has to suggest the system of control actions, which aims to decrease or to liquidate fully explosiveness of the PEO. The decision maker determines, which control actions to apply in a given situation, but in some cases such a choice is or can be made automatically.

Explosion protection decision support systems, taking into account the possibilities of secondary explosions, has to suggest the system of control actions, which aim to decrease or to liquidate fully explosiveness of the PEO. The decision maker determines which control actions to apply in a given situation, but in some cases such a choice is or can be made automatically. The latter option is important when the time for decision-making is very limited or clearly insufficient.

Control actions can be technical, technological or organizational.

The range of possible control actions for preventing and suppressing explosions for a particular enterprise is always limited by the financial, technical, and technological capabilities of that enterprise. In general, the formation of a set of control actions for preventing explosions (primary and secondary) for each specific complex PEO while minimizing costs should be singled out as a separate engineering and economic task.

For a grain elevator, the example of technical control action is phlegmatization or inhibition (chemical actions); the example of technological control action is technological operation, such as silo filling; the examples of organizational control action are cleanup and wet cleaning [5]. A universal example of organizational control is the immediate evacuation (managerial action)of enterprise workers in the event of a high level of explosion hazard or in the event of a primary explosion.

Research results. A mathematical model has been designed for the development of a primary explosion that can lead to a secondary explosion at a complex, potentially explosive object. This mathematical model serves as the basis for creating a corresponding information model of the object. The information model of an object, combined with its mathematical model, is in turn the basis for developing software for the explosion protection decision support system.

The developed mathematical model is universal, but its application to a specific potentially explosive object requires refinement based on the specifics of that object. The model is also rather simple mathematically. This makes it possible to perform the necessary calculations without extremely high costs of computer time, as well as without exclusive requirements for speed and other computer resources. This is one of the main advantages of this mathematical model.

This mathematical model does not take into account the potential damage from a secondary explosion. However, this factor is highly significant for decision-making on preventing secondary explosions and should be considered in future research. The question of whether the secondary explosion is deflagration or detonation also requires separate study, since this significantly affects the destructive power of the explosion.

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DOI: https://doi.org/10.15276/ict.02.2025.35
УДК: 534.222.2+536.464+004.942

Аналіз розвитку вибухових процесів для створення систем підтримки прийняття рішень з противибухового захисту з урахуванням можливості вторинних вибухів

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АНОТАЦІЯ

Дане дослідження підкреслює необхідність вивчення можливості вторинних вибухів на складних потенційно вибухонебезпечних об'єктах, оскільки в деяких випадках вторинні вибухи можуть бути значно потужнішими та небезпечнішими за первинні. Сучасні системи підтримки прийняття рішень з противибухового захисту та вибухобезпеки практично не враховують можливість вторинних вибухів, тому цю прогалину в дослідженнях необхідно усунути. Розроблено математичну модель розвитку первинного вибуху, що може призвести до вторинного вибуху на складному потенційно вибухонебезпечному об'єкті. Ця модель базується на математичній теорії горіння та вибуху, на нечіткій логіці та теорії нечітких множин, а також на теорії графів, включаючи нечіткі графи. Для безпосереднього знаходження вершини графа, що відповідає максимальній небезпеці з точки зору можливості виникнення вторинного вибуху, використовується відомий алгоритм Дейкстри для знаходження найкоротшого шляху в графі. Розроблена математична модель є універсальною і може застосовуватись до складних потенційно вибухонебезпечних об'єктів практично будь-якої фізичної природи. Прикладами таких складних потенційно вибухонебезпечних об'єктів можуть бути промислові підприємства, окремі цехи цих підприємств, трубопроводи та інші транспортні системи, різні машини, агрегати та інше обладнання. На основі розробленої математичної моделі можливо уточнити інформаційну модель складного потенційного об'єкта. Застосування цієї математичної моделі до конкретного складного потенційно вибухонебезпечного об'єкта та до конкретного технологічного процесу потребує уточнення з урахуванням специфіки цього об'єкта або цього технологічного процесу. Математичні основи фазифікації повинні бути пов'язані зі складними проблемами газодинаміки та проблемами математичної теорії горіння та вибуху. Розроблено алгоритм ідентифікації об'єкта, який становить найбільший ризик з точки зору можливості вторинного вибуху. Однак ні цей алгоритм, ні математична модель в цілому не враховують обсяг потенційної шкоди від вторинного вибуху. Цей фактор є дуже важливим для прийняття рішень щодо запобігання вторинним вибухам і повинен розглядатись у майбутніх дослідженнях. Питання про те, чи є вторинний вибух дефлаграційним або детонаційним, також потребує окремого вивчення. Ця проблема видається досить важливою, оскільки детонаційні вибухи, як правило, потужніші і небезпечніші, ніж дефлаграційні. При цьому слід враховувати, що зазвичай ініціювання детонації значно утруднене порівняно з ініціюванням дефлаграційного вибуху.

Ключові слова: вибух; вторинний вибух; пожежа; система підтримки прийняття рішень; противибуховий захист; математична модель; інформаційна модель; потенційно вибухонебезпечний об'єкт; нечітка логіка; граф; алгоритм Дейкстри