Mathematical and Information Modeling of Grain Elevators as Potentially Explosive Objects

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Abstract

Mathematical and information models of a grain elevator as a potentially explosive control object are developed. These models create the base for software of a decision support system for explosion safety of grain elevators. Mathematical model is based on combination of the fuzzy logic and classical mathematical methods from the mathematical theory of combustions and explosions. Information model of the grain elevator as a complex potentially explosive object is also developed. Grain elevator is considered from the point of view of system analysis as the complex hierarchical system. This system is structurized, elementary potentially explosive objects are indicated. All kinds of these objects are described with their attributes and relationships, information structure diagrams are also built Appropriate software has been developed and some calculations have been done. These calculations are useful from the point of view of the grain elevator designing. It is proved that monolithic reinforced concrete silos are noticeably less explosive than prefabricated reinforced concrete silos and metal silos are much more explosive than reinforced concrete ones. It is also proved that increasing the height of the silo increases its explosion hazard. But the most interesting result is that a low degree of fire hazard does not always corresponds to a low degree of its explosiveness.

Keywords

Grain elevator, silo, decision-making, fuzzy logic, mathematical model, information model, explosion, potentially explosive object, explosion hazard

1. Introduction

There are lots of explosions at the grain processing enterprises and grain storages all over the world every year. Grain elevators are among the most explosive grain enterprises.

There were 15 grain dust explosions reported for the U.S. in 1994 [1]. This compares to 13 in 1993 and a ten-year average of 15 explosions. There was one fatality and 14 persons injured. Seven of the fifteen incidents occurred in grain elevators, three in flour mills, and one in a wet corn milling and malt plant [1]. A similar picture was observed from year to year [2], and until now.

A grain elevator is a facility for stockpiling and storing large quantities of grain and for bringing and keeping the grain in good conditions. Any grain elevator contains a tower with a bucket elevator (noria) or a pneumatic conveyor, which picks up grain from a lower level and deposits it in a silo (or, sometimes, in other storage). The construction of silo buildings, tied to the working building of the grain elevator, is widespread.

If there is a sufficient concentration of flammable flour or grain dust in the air anywhere in the elevator, an explosion may occur.

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The distribution of the dust-air mixture explosions at grain enterprises at the place of origin is such that silos and bunkers account for almost half of the total number of explosions [3] (Table 1).

Thus, the most explosive elements in the system of grain enterprises are silos and bunkers, as well as bucket elevators and conveyors.

Table 1

Distribution of explosions at grain enterprises at the place of origin

Explosion location	Number of explosions in % of the total
Silos and bunkers	47,7
Bucket elevators and conveyors	21,0
Aspiration systems, pneumatic transport	6,7
Crushers, roller mills	4,1
Grain dryers	6,1
Industrial and other premises	4
Location unknown	10

One of the reasons for the large number of explosions at grain elevators is that the automated control systems of these elevators have certain disadvantages [3, 4]. To prevent explosions, the automated elevator control system must be equipped with a decision support system (DSS) for explosion safety with appropriate mathematical support, information support and software. In turn, the creation of such mathematical support, information support and software requires correct mathematical and information modeling of the grain elevator as a potentially explosive control object.

The development of an appropriate mathematical and information models of a grain elevator as a potentially explosive object (PEO) is the aim of this research.

2. Mathematical and information models in the decision-making on hazards of grain elevator explosions

As shown earlier [5, 6] classical models for the decision-making [5, 7] on hazards of industrial explosions often are not applicable. These models naturally are not applicable for the decision-making on hazards of grain elevator explosions, because grain elevators (and other grain processing enterprises and grain storages) are very complicated systems if they are considered as PEO from the point of view of control.

Thus for the constructing of DSS for explosion safety it is preferable to use the model of decision-making under uncertainty, that is based on the fuzzy-set theory and fuzzy logic [8]. It is proved that application of such model is preferable for complicated industrial and transport systems [5, 6].

But fuzzy logic should be used in combination with the exact mathematical theory of combustions and explosions [5, 6]. This is the only effective methodology for constructing intellectual DSS for explosion safety of grain elevators, which provides an opportunity to avoid involvement of evaluators and also to avoid all problems and difficulties connected with cooperation between evaluators and decision-makers [9].

Mathematical modeling of the grain elevator as complex PEO consists of the following steps:

- Each separate object of the grain elevator (bucket elevator, silo, over-silo floor, sub-silo floor, working building, etc.) is considered as an elementary potentially explosive object (EPEO). Such EPEO is geometrically modeled as flat channel (unlocked, closed at one end or closed at both ends) or round cylindrical tube (also unlocked, closed at one end or closed at both ends).
- For each EPEO, the concentration limits of ignition and explosion are determined separately, as well as the explosion induction distance X_s [10]. These parameters are calculated by the methods of the mathematical theory of combustion and explosion (specifically, by the methods of the linear theory of stability of combustion and detonation waves), which is based on classical mathematics (specifically, on the analytical solution of linearized partial differential equations) [6, 11]. Non-linear effects are also partly taken into account.
- The estimates for the concentration limits of ignition and explosion, for explosion induction distance X_s and for the time of the fire-to-explosion transition, which are made using classical mathematical methods, form the basis of fuzzy estimates of the possibility of an explosion. The main ideas and principles

of such fuzzification are demonstrated in scientific works [5, 6].

- Conjunction of the corresponding fuzzy logical variables is, naturally, a fuzzy variable (fuzzy function), which is an estimate of the explosion hazard of EPEO [5]. Thus, certain fuzzy logical variable corresponds to each EPEO. For a given moment in time, you can find the value of each of these variables (a number between *0* and *1*; *0* corresponds to absolute safety; *1* corresponds to situation, when an explosion on ignition is inevitable). The largest of these values (i.e. the value of the disjunction of these fuzzy logical variables [8]) is an estimate of the explosiveness of the entire complex PEO as a whole, i.e. an estimate of the explosiveness of the grain elevator itself.
- The value of such a fuzzy logical function is expressed by the value of a linguistic variable that provides information for decision-makers.

Thus mathematical model for the decision-making on hazards of grain elevator explosions is constructed.

Information modeling of the grain elevator as a complex PEO is developed in accordance with the principles, which are set out in the scientific works [5, 6, 12].

Grain elevator (complex PEO) is considered from the point of view of the system analysis as the complex hierarchical system. This system is structurized, EPEO are indicated. All kinds of these objects are described with their attributes and relationships [12]. Information structure diagrams are also built.

3. Software of DSS for explosion safety of grain elevators

On the base of mathematical and information models in the decision-making on hazards of grain elevator explosions the corresponding software has been developed. The program is Russified, so all the captions in the program are made in Russian.

The following example shows how the corresponding subroutine («SilosOtdelniy») evaluates the explosion hazard of an individual silo. The silo is chosen as an example as it is the most explosive part of the elevator.

A user can choose one of the standard reinforced concrete silos or they may independently set the shape and dimensions of the silo (reinforced concrete silo or metal silo) (Figure 1).

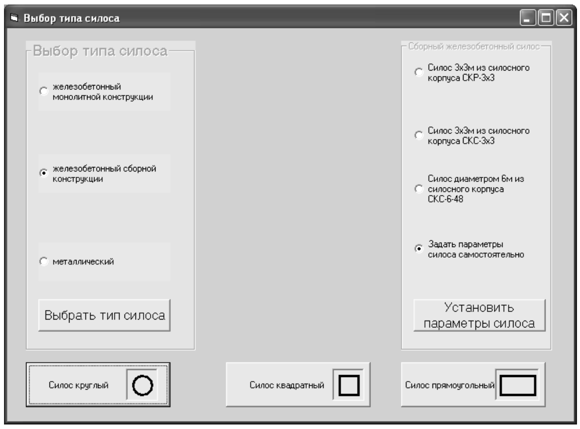

Figure 1: Form of the subroutine SilosOtdelniy for specifying the shape and dimensions of the silo. The caption on the button of the canvas on the left side of the form: "Select the type of silo". The caption on the button of the canvas on the right side of the form: " Set silo parameters". The captions on the buttons at the bottom of the form: “Round silo”, “Square silo”, “Rectangular silo”

It is assumed that each silo has a circular, square or rectangular cross-section.

More complicated cross-sectional shapes of a grain elevator silo are possible in principle, but in practice they are extremely rare. In addition, using the factor of application of fuzzy logic, the complex shape of the silo section can usually be replaced with a simpler one (one of the three above).

Further calculations require specifying the type of dust-air mixture or grain product, dust concentration, humidity, temperature and dust dispersion (i.e. average size of dust particles) (Figure 2). All these values can be measured using standard metrological devices in the operating mode of a grain elevator and the software in this case should to be a part of the software of the corresponding automated control system. In some cases, the corresponding values can be set in the program by the operator or the decision-maker.

The current values of temperature and dust concentration are compared with the ignition temperature and the lower concentration limit of ignition.

The ignition temperature and the lower concentration limit of ignition are obtained as a result of the approximation of the known empirical data [3, 4]. This makes it possible to evaluate the fire hazard in principle.

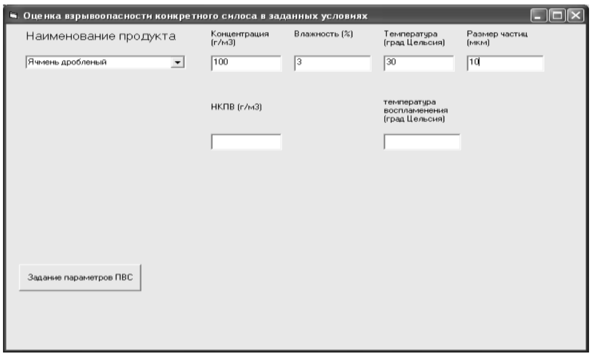

Figure 2: Form of the subroutine SilosOtdelniy for setting parameters of the dust-air mixture. The caption on the button at the bottom of the form: "Setting the parameters of the dust-air mixture"

The result of evaluation of the possibility of ignition and fire occurrence is depicted on the monitor screen as shown in Figure 3.

As it can be seen from Figure 3, the decision-maker is not dealing with the numerical values of fuzzy logical variables, but with linguistic variables.

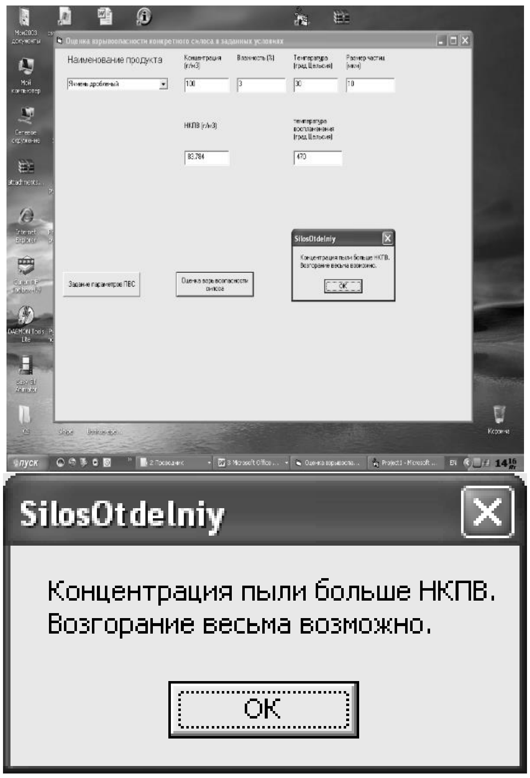

Figure 3: A message about the degree of fire hazard of the silo on the monitor screen. This message means: “The dust concentration is greater than the lower ignition concentration limit. Combustion is highly possible”

Evaluations for the possibility of a fire-to-explosion transition, the explosion induction distance and the time of the fire-to-explosion transition are carried out according to [6, 11] using an estimate of the width of the flame zone for dust-air mixtures.

For a monolithic reinforced concrete silo [3, 4], the calculated explosion induction distance is reduced by 2 times in the program, both in order to increase the reliability of the explosion hazard evaluation, and due to the possibility of the presence of separate roughness on the walls of the silo.

For a prefabricated reinforced concrete silo [3, 4], the calculated explosion induction distance is reduced in the program by a factor of 20, since the walls of such silo are assembled from ribbed or even smooth volumetric elements [3, 4], or from strained curved-linear elements with a ring cut by 3 or 4 parts [3] (if the silo have a circular cross-section, i.e. if the silo is round), so the silo has periodic or quasiperiodic roughness on the walls.

For a metal silo made by rolling or winding, the explosion induction distance is reduced in the program by 50 times, since the inner wall surface of such silo resemble the Shchelkin spiral.

All the above estimates of the explosion induction distance are approximate (especially for prefabricated reinforced concrete and metal silos), therefore, the estimates of the explosiveness of the silo given below are “fuzzy”. Therefore, the corresponding fuzzy variables are introduced into consideration, over which logical operations are performed according to the laws of fuzzy logic.

The computer program (subroutine «SilosOtdelniy») displays various kinds of messages on the monitor screen as a result of the calculations.

Messages about the explosion induction distance and the time of the possible fire-to-explosion transition (Figure 4) represent the necessary information for decision-making on ensuring explosion safety and/or explosion protection.

It is obvious that if the time of the possible transition of combustion into an explosion is long enough, then it is possible to make a wide variety of decisions (organizational, technical, technological).

If this time, on the contrary, is short, then the only possible solution is to stop immediately the technological process with the simultaneous evacuation of personnel.

In the latter case, it is possible to replace the automated control with an automatic one.

Calculations show that the time of the possible fire-to-explosion transition in organic dust-air mixtures is hundreds and thousands of times longer than the development time of an explosion in combustible gas mixtures.

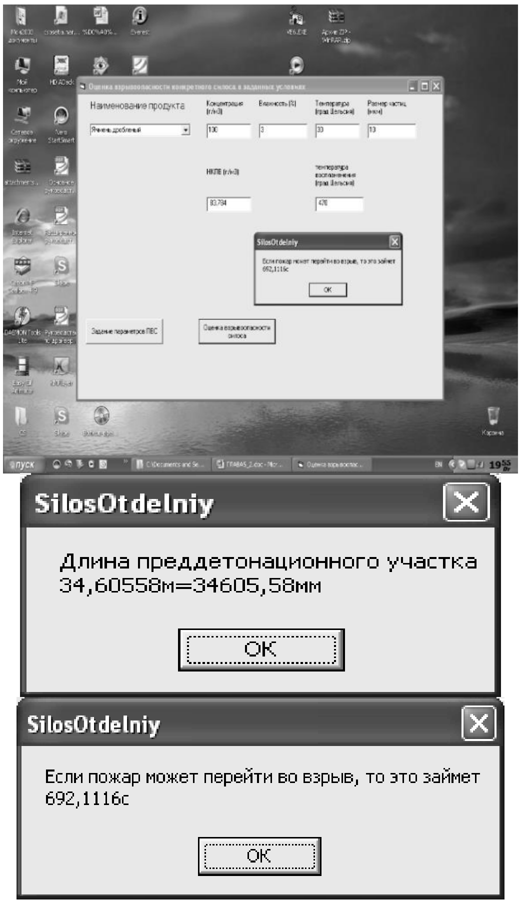

Figure 4: Messages about the explosion induction distance and the time of the possible fire-to-explosion transition. The first message means: "The detonation induction distance is 34,60558 m = 34605,58 mm". The second message means: "If a fire can develop into an explosion, it will take 692,1116 seconds"

The type of message with a fuzzy evaluation of the explosiveness is shown in Figure 5.

An important point is that all the above estimates are made without the participation of experts (evaluators).

The complications of experts' interaction with each other are well known [13, 14]. Even greater difficulties arise when evaluators interact with decision-makers [13, 15, 16].

Therefore, it is advisable to avoid the participation of experts in solving such decision-making tasks [12, 13, 16, 17].

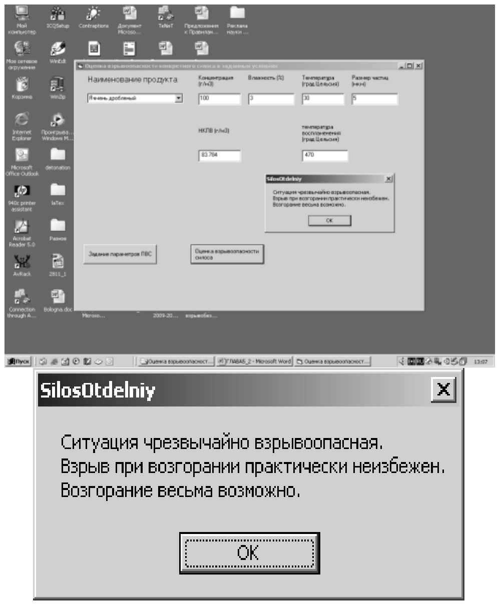

Figure 5: A message about the degree of the explosion hazard. This message means: "The situation is extremely explosive. An explosion is almost inevitable. Combustion is highly possible"

4. Conclusions

Mathematical and information models of a grain elevator as a potentially explosive object are developed. These models create the base for software of DSS for explosion safety of grain elevators.

Appropriate software has been developed and some calculations have been performed.

These calculations are useful not only from the point of view of testing the proposed method of mathematical modeling of a grain elevator as a potentially explosive object or testing the software itself, but also from the point of view of the grain elevator designing (i.e. appropriate decisions on the explosion safety and explosion protection can be made already at the stage of the elevator design).

The results of the calculations are summarized in the following conclusions (some of which are quite obvious in themselves):

- If the humidity rises, then both the explosion hazard and the fire hazard of the grain elevator decrease.
- Temperature fluctuations within a few tens of degrees have little effect on the fire

hazard and explosion hazard of the grain elevator.

- A decrease in the average size of dust particles in the dust-air mixture leads to the increase of the explosion hazard of this mixture. Fine dust is much more explosive than coarse dust (this conclusion is theoretically quite obvious).
- Monolithic reinforced concrete silos are noticeably less explosive than prefabricated reinforced concrete silos.
- Metal silos are much more explosive than reinforced concrete ones.
- Increasing of the height of the silo increases its explosion hazard.
- A low degree of fire hazard does not always corresponds to a low degree of its explosiveness (in this case, the explosiveness is understood as the possibility of an explosion in case of ignition).

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