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Mathematical and information models of decision support systems for explosion protection

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ABSTRACT

This paper is dedicated to the issue of mathematical and information modeling of the combustion-to-explosion transition that makes it possible to create an adequate mathematical and information support for decision support systems (DSS) for automated control of explosive objects. A simple mathematical model for the transition of combustion to explosion is constructed. This model is based on solving mathematical problems of the hydrodynamic stability of flames and detonation waves. These problems are reduced to solving eigenvalue problems for linearized differential equations of gas dynamics. Mathematical model is universal enough. It provides opportunities for making simple analytical estimates for the explosive induction distance and the time of the shock wave formation. The possibilities of the transition of slow combustion to both a deflagration explosion and a detonation wave are considered. Theoretical estimates of the explosive induction distance and the time of the combustion-to-explosion transition are obtained. These estimates are expressed by algebraic a formula, the use of which save computer resources and does not require significant computer time. The application of fuzzy logic makes it possible to use the proposed mathematical model of the combustion-to-explosion transition for real potentially explosive objects in industry and transport. Mathematical models of potentially explosive objects are based on combination of the fuzzy logic and classical mathematical methods. These models give possibilities for creating corresponding information models. Thus mathematical and information support of DSS for automated control systems of explosive objects is developed. The main advantage of these DSS is that it makes it possible for decision makers to do without experts. In particular, developed mathematical and information models create the base for software of DSS for explosion safety of grain elevators. Appropriate software is developed and some calculations are 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.

Keywords: Explosion; deflagration; detonation; fire; flame; decision support system; explosion protection; mathematical model; information model; potentially explosive object

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INTRODUCTION

Rapid progress in computing machinery and telecommunication equipment enlarged greatly the human potentialities in sphere of the decision making for solving different problems. One of such problems is prevention and mitigation of accidental explosions. The explosion prevention is one of the most topical and difficult problems of the present-day industry, up-to-date transport systems and everyday life.

Despite the significant costs for the appropriate technical equipment and theoretical studies the prevention of accidental explosions is still an urgent problem. One of the reasons for this situation (along with the complication of technological processes, the emergence of new combustible materials and explosives, etc.) is the inadequate efficiency of automatic and automated systems for preventing and suppressing explosions.

The main idea of the modern organization of explosion protection is to prevent the occurrence of accidental fires [1, 2], [3]. So automated control systems for explosive objects are aimed mainly to prevent or to suppress timely accidental ignitions and spontaneous combustions.

Indeed, if a fire does not occur, then an explosion is impossible. Therefore, the solution of the fire safety problem simultaneously solves the problem of explosion safety. Thus, the problem of explosion safety is not solved as a separate problem, but only within the fire safety problem. This idea is sound and generally true, but there are some weaknesses in it.

First, it should be taken into account that the possibility of an explosion in the event of a fire may be great [1, 4], [5] in spite of the relatively low probability of ignition. This is especially true for coal mines [6, 7], [8] and for those enterprises, where explosive dust-air mixtures are formed during the technological process [4, 9]. These cases need to be specifically diagnosed, because the damage and loss of life from explosions is much greater than from fires.

Secondly, in many cases it is not possible to detect and suppress a fire on time [3, 9], [10]. For lots of enterprises and for many kinds of equipment the fire safety problem cannot be properly solved, i.e. it is impossible to guarantee complete (or almost complete) absence of fires. This is critical if there is a danger of explosion.

And, finally and thirdly, some enterprises (primarily those associated with the production of various explosives) allow such stages in the technological chain, when an explosion can occur instantly, without a preliminary fire. In all these cases it is necessary to have additional safety "mechanism" to prevent explosions. This mechanism must be implemented using an automatic or automated control system. The main part of such control system should be decision support system (DSS) for the decision making on the explosion safety problems. And this system requires, in turn, appropriate mathematical and information models.

LITERATURE REVIEW

An attempt to project DSS for the decision making on the explosion safety problems was done in 2008 [11]. It was shown that the main theoretical problems for decision making on explosions are problems of the flame stability [12, 13], [14], the detonation stability [14, 15], the definition of the explosion induction distance and the time of such induction [14, 15].

There are two different kinds of explosions: deflagration explosion (sometimes called simply "explosion") and detonation [10, 16], [17]. Detonations are more devastating and less studied than deflagration explosions [10]. The necessity of preventing detonations by special program-technical systems is obvious.

The DSS on the explosion safety must help a decision maker:

1) to research principal possibility of the transition of combustion to explosion in the presence a fire (as a result of accidental ignition or spontaneous combustion);

2) to define the type of explosion (deflagration explosion or detonation);

3) to quantify the time for transition of combustion to explosion if such transition is possible;

4) to prompt measures, which can be taken to prevent an explosion timely or to minimize the possible consequences of an explosion.

The solving of the last problem (inhibition, use of shut-off devices, shutdown of equipment, evacuation of personnel, etc.) is defined by solving of three previous problems.

The fundamental possibility of the transition of combustion into an explosion is associated with the instability of the flame front [10, 18]. Instability of flames is investigated by different authors and in different formulations of the stability problem [12, 13], [17]. It is researched also in connections with deflagration-to-detonation transition in homogeneous (liquid and gas) media [19, 20], [21] and in heterogeneous (dust) media [22], but these scientific studies are based on numerical simulations of premixed gas combustion. Such numerical simulations are always connected with finite perturbations, while stability of flames should be researched in relation to small perturbations (Darrieus-Landau instability).

Mentioned above numerical simulations of the flame stability and deflagration-to-detonation transition have several disadvantages.

First of all, as it is mentioned before, the instability obtained in this way is instability in relation to finite (even if relatively small) perturbations, while a correct study of the internal stability of the flame requires the use of the mathematical apparatus of infinitely small perturbations.

Then it should be noted that the instability of combustion or detonation waves, obtained as a result of numerical simulation of these processes, can be due to the instability of the calculation scheme itself, while the real process can be stable.

And at last, mentioned above numerical simulations of the flame stability and deflagration-to-detonation transition require significant computer resources and time. Therefore they cannot be used for DSS in automated control systems for explosive objects, because the time for decision making is too limited.

The question of what kind of explosion (deflagration or detonation) can take place as a result of the development of flame instability has generally been little studied [10, 16], [23]. Most of researchers of combustion-to-explosion transition are focused on deflagration-to-detonation transition [19, 20], [21, 22]. The topic of transition from slow combustion to the deflagration explosion is practically not considered separately from the issue of deflagration-to-detonation transition in the modern scientific literature.

THE PURPOSE OF THE ARTICLE

The aim of the present research is to create mathematical and information models of combustion-to-explosion transition that makes it possible to create an adequate mathematical and information

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support for DSS of automated control systems for explosive objects.

Mathematical models should be sufficiently universal. They should provide opportunities for making simple analytical estimates for the explosive induction distance (a distance between the point of ignition and the initial shock wave front) and the time of the shock wave formation without working out phenomena in detail. These mathematical models should take into account both the possibility of transition from slow laminar combustion to a developed deflagration and deflagration explosion, and the possibility of deflagration-to-detonation transition. In addition, these models should be sufficiently versatile, that is, they should not be associated with specific types of explosive media (may be considered both explosive gas mixtures and condensed explosives such as nitroglycerin or liquid TNT, cast TNT, as well as heterogeneous media – aerosols, dusts, etc.). Such mathematical models make it possible to create information models of potentially explosive objects and develop appropriate software.

MATHEMATICAL MODELING OF COMBUSTION-TO-EXPLOSION TRANSITION

The starting point for constructing physical and mathematical model of the combustion-to-explosion transition is the assumption that the main reason for this transition is the hydrodynamic instability of the laminar flame [5, 16], [23].

Physical model for the combustion-to-explosion transition may be divided into the following stages:

1. There is possibility of the laminar flame instability [5, 12], [16, 23]. If there is no such possibility, that is the laminar flame is stable, then there is no possibility for the flame acceleration, and so there are no possibilities for deflagration explosions or detonations. But it should be borne in mind that laminar flames in premixed combustible gas mixtures are always instable under certain conditions [12, 17], [24, 25]. Combustible heterogeneous media in this sense are always explosive, since a dust particle or liquid droplet is itself an in homogeneity that turbulizes the flame. Diffusion flame is always stable [17, 24], [25].

2. The one-dimensional flame instability leads to the combustion damping or just strong fluctuations if there is no multidimensional flame instability [26]. The result of multidimensional flame instability is strong distortion of the flame front and large space-time pulsations [12, 27]. These factors lead to turbulent combustion.

3. Flame accelerates because the combustion surface area increases [18].

4. There are two possibilities for the accelerating flame:

a) the accelerating flame transits to the turbulent combustion mode with a constant average speed that is greater than the propagation velocity of the laminar flame (this mode can be called quasi-stationary): in this case, the explosion does not occur; the vast majority of researchers do not take this possibility into account at all;

b) the turbulent flame accelerates continuously.

5. If the flame accelerates continuously it accelerates till it generates shock wave. There are also two different possibilities:

a) the shock wave is intensive enough to ignite gas behind it: in this case there is detonation;

b) the shock wave is not intensive enough to ignite gas behind it: in this case there is no detonation, but there is deflagration explosion, i.e. explosion without detonation.

6. The result of multidimensional detonation instability is strong distortion of the detonation front and large space-time pulsations [10, 15]. The one-dimensional detonation instability leads to the detonation damping or the galloping detonation regime if there is no multidimensional detonation instability [10, 15].

The flame stability problem is considered by us in various settings (for a viscous incompressible medium, an ideal incompressible medium and ideal compressible medium; for open space, flat channels and round cylindrical tubes).

In the case of a viscous incompressible medium, the flow is described by the incompressibility equation and the Navier-Stokes equations. These equations are linearized and their particular solutions are constructed [12].

As boundary conditions, the laws of conservation during the gas transition through the flame zone, as well as the conditions for the damping of perturbations at infinity are used [12].

For symmetry reasons the problem of flame stability in an open space is considered as a plane (two-dimensional) problem [12].

In the two-dimensional case perturbations are set by proportional $\exp(ihy - i\omega t)$, where $h = 2\pi/\lambda$, λ is wave length, and i is unit imaginary number ($i^2 = -1$), ω is complex number, y is spatial coordinate, t is time.

In the case of a flat channel, the boundary condition of the impermeability of its walls imposes an additional condition on the perturbations, namely: an integer number of half-wavelengths must fit along the diameter of the channel [5].

Assessment of the stability of combustion is carried out as a result of solving the problem of eigenvalues. Such a problem arises as a result of substituting expressions for perturbations (solutions of the linearized equationsin) to boundary conditions.

The value of z is considered as a dimensionless eigenvalue:

$$z = -\frac{i\omega}{hu_1}, \quad (1)$$

where u_1 is normal flame speed [17].

The value of z for long-wave perturbations ($\xi \equiv hL \equiv \frac{2\pi L}{\lambda} \ll 1$), where L is the laminar flame thickness) can be represented by a series expansion

$$z = z_0 + z_1\xi + \ldots, \quad (2)$$

where only the first two terms in the expansion play a significant role [12].

If to take the perturbation wavelength λ as the characteristic size in the stability problem, then the Reynolds number Re can be represented as

$$\mathrm{Re}_\lambda = \lambda u_1 / \nu_1, \quad (3)$$

where ν_1 is viscosity of combustible gas mixture.

It follows from the thermal theory of flame [17, 25] that the extent of the flame zone can be determined as

$$L \approx \chi_1 / u_1, \quad (4)$$

where χ_1 is thermal diffusivity of combustible gas mixture. Since viscosity and thermal diffusivity are quantities of the same order [25], then

$$L \approx \nu_1 / u_1. \quad (5)$$

It follows from the formulas (3) and (5) that

$$\mathrm{Re}_\lambda = \lambda / L. \quad (6)$$

But since it is assumed above that

$$\xi \equiv hL \equiv \frac{2\pi L}{\lambda}, \quad (7)$$

then

$$\xi = \frac{2\pi}{\mathrm{Re}_\lambda}. \quad (8)$$

Thus the values Re_λ and ξ are mutually inverse. The case of long-wave perturbations ($\xi \ll 1, \lambda \gg L$) corresponds to large Reynolds numbers Re_λ, at which autoturbulization (turbulization due to internal causes) of the flame can be achieved. This justifies the remark made immediately after the equation (2). That is, to solve the problem of autoturbulization of the flame, only long-wave perturbations should be considered.

The main formulas for evaluating the stability of combustion of a viscous gas are the formulas [12]:

$$z_0 = \frac{\delta_2}{\delta_2+1}\left(-1+\sqrt{\delta_2+1-\frac{1}{\delta_2}}\right), \quad (9)$$

$$-(1+\frac{\delta_2}{\delta_2+1})z_0 z_1 = \frac{z_0}{2}((1+\frac{z_0}{2})(2\delta_2+1)+ + (\frac{\delta_2}{\delta_3}-1)+\delta_2^m(\frac{\delta_2+1}{\delta_2}z_0+\delta_3+3))+ + \frac{1}{2}(\delta_2-1)(1+2z_0+\frac{z_0^2}{\delta_3}), \quad (10)$$

where

$$\delta_2 = \frac{\rho_1}{\rho_2}, \quad (11)$$

ρ_1 is the initial inflammable mixture density, ρ_2 is density of combustion products,

$$\delta_3 = \delta_2 - \frac{\delta_2 - 1}{e}, \quad (12)$$

$m = const$ $(0,5 \le m \le 1)$ is exponent in dependence of dynamic-viscosity coefficient on temperature [12, 25].

It is obvious that $z_0 > 0$ (unstable expansion term of Landau [24]) and $z_1 < 0$ (stabilizing expansion term, which is a result of viscosity stabilizing effect [12]).

Solving the inequality

$$z_0 + z_1\xi > 0, \quad (13)$$

makes it possible to find the wavelengths range for unstable perturbations. The wavelength λ_m of the perturbation that grow most rapidly with time [12] is also determined as

$$\lambda_m = -\frac{4\pi L z_1}{z_0}. \quad (14)$$

Parameter λ_m can be considered an estimate of the average size of the flame cells, if the flame has a cellular structure as a result of the development of instability [12, 25], [27].

The critical Reynolds number Re_{λ_m} corresponding to the parameter λ_m is calculated as follows

$$\mathrm{Re}_{\lambda_m} = -\frac{4\pi z_1}{z_0}. \quad (15)$$

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The theoretical value of the critical Reynolds number Re_{λ_m} obtained by the method described above, $\mathrm{Re}_{1\lambda_m} = 7{,}16 \cdot 10^2$ for fast-burning gas mixture of acetylene and oxygen ($37{,}5\%\ C_2H_2 + 62{,}5\%\ O_2$ by volume).

The theoretical value of the critical Reynolds number Re_{λ_m} for slow-burning gas mixture of propane with air ($5\%\ C_3H_8$ by volume) is $\mathrm{Re}_{2\lambda_m} = 2{,}96 \cdot 10^2$.

The data of experimental measurements [25] leads to the following values of the Reynolds number calculated from the size of the flame cell: $\mathrm{Re}_1 = (7{,}5 \pm 2{,}5) \cdot 10^2$ for a mixture of acetylene and oxygen ($37{,}5\%\ C_2H_2 + 62{,}5\%\ O_2$) by volume); $\mathrm{Re}_2 = (2{,}8 \pm 0{,}4) \cdot 10^2$ for a mixture of propane with air ($5\%\ C_3H_8$ by volume).

The achieved quantitative agreement between the theoretical and experimental results for both fast-burning (oxygen) and slow-burning (air) mixtures is a convincing argument in favor of the constructed theory.

This theory is suitable not only for the combustion of gas mixtures, but also for the combustion of liquids and, in some cases, heterogeneous media [16, 27].

Parameter λ_m may be considered as an estimate for the average size of the flame cells, if the flame has a cellular structure as a result of the development of instability [12, 17], [25].

The wavelength λ_m gives possibility to estimate [5, 16] the acceleration of the flame g_f as

$$g_f = \frac{4\pi z_0 u_1^2 (1 - M_1)}{\lambda_m M_1}, \qquad (16)$$

or, in accordance to equation (14),

$$g_f = -\frac{z_0^2 u_1^2 (1 - M_1)}{2 z_1 L M_1}, \qquad (17)$$

where $M_1 = \frac{u_1}{a_1}$ is Mach number for the laminar flame propagation ($M_1 \ll 1$).

As noted above, the main factor stabilizing the process of normal combustion is viscosity. However, the compressibility of the medium also has a stabilizing effect on the flame [23, 26], [27]. Joint consideration of the influence of viscosity and compressibility of the medium on the process of propagation of small perturbations of the stationary flame is not possible due to the extreme mathematical complexity of the problem. Therefore, the influence of compressibility must be considered separately.

Consideration of the compressibility influence on the stability of the combustion process seems to be especially important in those cases when the flame propagates at a sufficiently high speed and neglecting values of the order M_1^2 may lead to serious mistakes. For such high-speed combustion regimes, the role of the viscosity factor in stabilizing flame propagation decreases, since viscosity (internal friction) is due to the transfer of momentum by molecules from one gas layer to another, which in itself is a very “slow” process. On the other hand, the role of the stabilizing influence of the compressibility of the medium increases.

At a sufficiently high flame propagation speed, it is the compressibility of the medium, and not its viscosity, that can become the main stabilizing factor. However, it should be noted that such high-speed combustion regimes take place, as a rule, not for laminar, but for turbulent flames [17, 25], and in these cases it is impossible to talk about the stability of “normal” combustion. However, even if the flame propagates in a turbulent regime, but the turbulence is small-scale, i.e. the scale of turbulence is much smaller or even comparable to the thickness of the (laminar) flame zone (but the thickness of the flame zone itself is much smaller than the characteristic size of the problem – width of the flat channel, pipe diameter, radius of the flame sphere for a spherical flame), then the entire combustion process can be considered as quasi-laminar and, accordingly, the problem of the stability of a quasi-laminar flame have to be considered. Thus, the following solution for the problem of the stability of a flame propagating in an ideal (nonviscous) compressible medium primarily refers to high-speed turbulent combustion with a relatively small turbulence scale, and makes it possible to answer the question of whether (in the case of stability) this turbulent regime takes place. This turbulent regime means combustion with an averaged (without taking into account small pulsations) flame propagation velocity u_1 (which can no longer be called the normal combustion velocity). In the case of instability the turbulence scale changes and the average flame propagation velocity increases, i.e. the flame continues to accelerate.

In the case of an ideal compressible medium, the flow is described by the equations of continuity, Euler, and energy balance. The last equation takes into account the heat release at the flame front.

These equations are linearized and their particular solutions are constructed [15, 16], [26, 27].

As boundary conditions, the laws of conservation on the flame front, as well as the conditions for the damping of perturbations at infinity are used [15, 16], [27].

Assessment of the stability of combustion again is carried out as a result of solving the problem of eigenvalues. This problem is a result of substituting expressions for small perturbations into boundary conditions.

The value of the dimensionless eigenvalue z in this case ($M_1 < 1$ or even $M_1 \ll 1$) can be represented by a series expansion

$$z = z_0 + z_1 M_1^2 + \dots , \qquad (18)$$

where only the first two terms in the expansion play a significant role [15, 16, 27].

As a result of solving the characteristic equation for the eigenvalue z, the values z_0 and z_1 are found.

Mathematical expression for z_0 is the same as the expression (9). That is z_0 is the instable root of Landau [24].

For value z_1 it can be proved that $z_1 < 0$.This indicates a stabilizing effect of compressibility.

The instability criterion is

$$M_1^2 < -\frac{z_0}{z_1} \quad (z_0 > 0,\ z_1 < 0) , \qquad (19)$$

or

$$M_1^2 < \left|\frac{z_0}{z_1}\right| . \qquad (20)$$

The value

$$M_{1cr} = \sqrt{\left|\frac{z_0}{z_1}\right|} , \qquad (21)$$

may be called the critical Mach number, the excess of which means the possibility of flame stabilization.

Calculation of the critical Mach number for a fast-burning mixture of acetylene and oxygen ($37{,}5\%\ C_2H_2 + 62{,}5\%\ O_2$ by volume) according to the experimental data [10, 25], leads to $M_{1cr} = 0{,}295$.

It means, that at the initial stages of the development of instability, the stabilizing effect of compressibility is very weak, while the stabilization of the high-speed turbulent combustion regime with a relatively small scale of turbulence (this regime can be called quasi-laminar – see above) should have manifested itself at $M_1 \geq M_{1cr} \approx 0{,}295$. However, at such large values of the Mach number, the flame creates a rather powerful shock wave in front of it, which ignites the mixture of acetylene with oxygen, i.e. even before the supposed moment of stabilization, the transition from combustion to detonation occurs, which was observed experimentally [10, 25].

Similar calculation of the critical Mach number for a slow-burning mixture of propane and air ($5\%\ C_3H_8$ by volume) according to the experimental data [25], leads to $M_{1cr} = 0{,}335$. This again means a very weak stabilizing effect of compressibility at the initial stages of the development of flame instability and the impossibility of stabilizing the quasi-laminar high-speed combustion regime before its transition to an explosive process.

Thus, the stabilizing effect of the medium compressibility on the development of the laminar flame instability at the initial stages of the instability development is insignificant compared to the effects of viscosity (for homogeneous media), the finite length of the flame zone, and the change in the length of the flame zone under the influence of disturbances. This conclusion is confirmed experimentally for both fast-burning and slow-burning gas mixtures.

Quantitative estimates of the critical Mach number lead to conclusion that the transition of an unstable self-accelerating combustion process into a developed deflagration or detonation is inevitable for gas mixtures. That is the explosive process is practically inevitable in case of ignition of a combustible gas mixture. Prevention of this combustion-to-explosion transition is possible either due to external causes not taken into account in the problem of internal stability (external stabilizing factors, various energy losses in the combustion process, flame extinction), or in the case when the process of auto-turbulization and self-acceleration of the flame itself is rather "slow" and the detonation induction distance exceeds the length of the channel or pipe filled with a combustible medium (in other words, when burnout occurs before the transition of combustion to an explosion). It must be emphasized once again that the conclusion about the inevitability of the transition of unstable combustion into an explosion applies only to gas mixtures, but not to condensed or heterogeneous media.

Quantitative estimates of the critical Mach number also make it possible, to a certain extent, to estimate what kind of explosive process – deflagration or detonation – occurs as a result of the development of instability, self-turbulization, and self-acceleration of the flame. If $M_{1cr} < 0{,}15$, then

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for a detonation-capable medium, the explosive process is probably of a deflagration nature.

To research fully the problem of the quasi-laminar (or even turbulent) flame stabilization it may be useful to apply fractal theory [28, 29] and theory of strange attractors [13], but it is not the aim of present work.

Solutions for the detonation induction distance X_s and the deflagration-to-detonation transition time τ_s are obtained by H. Jones and M. Nettleton [10] for different types of the flame acceleration g_f. Estimating the detonation induction distance X_s, M. Nettleton defines this distance as a distance between the point of ignition and the shock wave front, whether the shock wave initiates detonation or not. Thus in fact the value of X_s is the explosive induction distance.

Under the assumption that $g_f = const$, i.e. that the flame acceleration is constant, distance X_s between the point of ignition and the point, where the flame is situated during the shock wave formation, can be estimated as [2]

$$X_s = \frac{2{a_1}^2}{g_f \beta_f (\gamma_1 + 1)}, \tag{22}$$

where $\beta_f = const$ ($0 < \beta_f \le 1$, $\beta_f = 0{,}9$ in most real cases), a_1 is sonic speed for combustible gas mixture, γ_1 is the ratio of specific heats for this mixture.

Substitution of (17) into (22) leads to

$$X_s = -\frac{4 z_1 L}{(1 - M_1) M_1 {z_0}^2 \beta_f (\gamma_1 + 1)} . \tag{23}$$

For the time of the shock wave formation τ_s such approximate estimate takes place [5]:

$$\tau_s = \frac{X_s}{u_1}. \tag{24}$$

Thus analytical estimates for the explosive induction distance (23) and the time of the shock wave formation (24) are obtained. Calculating by these algebraic formulae is very simple and needs a minimal computer time, but such calculating does not describe the deflagration-to-explosion transition phenomena and its nature in detail as it is done in [19, 20], [21]. But a detailed analysis of the transition of slow combustion to explosion is just not required for creating of DSS on the explosion safety problems. And simple algebraic formulas (10) and (11) are just fit for this purpose.

All the conclusions made above can only be attributed not only directly to the combustion of homogeneous gas mixtures, but also for dust-air mixtures [5].

As follows from the dynamics of a two-phase medium, this seems quite possible if the dust-air mixture is a monodisperse system, since the general form of the equations for combustion and shock-detonation processes at a low concentration of the solid phase differs little from those for a homogeneous mixture. The fine dispersion of industrial dust testifies to the fact that a solid substance (flour, etc.) is “smeared” in the gas phase, which allows to consider the medium as quasi-homogeneous, replacing the air parameters with some effective averaged mixture parameters. The finer the dust particles are, the closer the dust-air mixture to the gas-air mixture according to the kinetics of chemical reactions is [5].

Since the length of the flame zone in the gas-air mixture is much greater than the corresponding length of the combustion zone in a homogeneous gas mixture, the ratio of the perturbation wavelength to the width of the flame zone is much smaller. Correspondingly, the size of the flame front inhomogeneity, which is also an indicator of large-scale turbulence, is smaller (at least in a relative sense). Thus, in the dust-air mixtures instability and large-scale flame turbulence are achieved much more often and faster than in homogeneous mixtures [5].

The detonation stability problem is also considered by us in various settings for an ideal compressible medium: for open space, flat channels and round cylindrical tubes) [5, 15], [30].

In this case the flow is described by the equations of continuity, Euler, energy balance and chemical kinetics. These equations are linearized and their particular solutions are constructed [15, 30].

In the case of flame propagation in a round cylindrical tube, perturbations are specified by proportional $\exp(-i\omega t + in\varphi) J_n(\zeta_{nk} r r_0^{-1})$, where r_0 is tube radius, r and φ are cylindrical coordinates, n is the azimuthal wave number (n = 0, 1, 2, ...), $J_n(\zeta)$ is the cylindrical functions of the 1-st kind of order n, ζ_{nk} is the k th root of the equation $dJ_n(\zeta)/d\zeta = 0$, y_{jk} $(k = 1, ..., 4)$ – dimensionless function of z. Thus, the boundary conditions of the impermeability of the tube walls are also satisfied.

The proposed method of analysis for development of perturbations of detonation waves that spread in flat channels and cylindrical tubes makes it possible to calculate the pulsating structure of gas detonation with sufficiently high reliability [15, 30]. Along the diameter of the tube or along the width of the channel an integer number of non-uniformities can be placed. That number can be found precisely (in such a way the solutions for single-head, double-head and multi-head detonations are obtained) [15, 30].

From various experiments [10] it is known that the critical diameter of the tube d_{cr}, at which the reconstruction of detonation during its entrance into the tube of a larger section takes place, can be calculated as $d_{cr} = n \times \Delta S$, where ΔS is the size of non-uniformities (the distance between transverse waves in a detonation wave with regular multifront structure [10, 24]**),** n is integer number, which is constant for each kind of gas mixture (for example [10], $n = 13$ for stoichiometric mixture of acetylene and oxygen).

For its turn, the minimum diameter $d_{\min}$ of the gas cloud capable of detonation is proportionate to $d_{\min}$. Thus, the definition of the size of non-uniformities and their number along the diameter of the tube from the solution of the stability problem makes it possible (using experimental data) to solve the problem of initiating detonation in a specified explosive volume.

As the solution of the stability problem is produced for arbitrary kinetics of chemical reaction and the general equations of the state of two-parameter media, it is quite suitable for estimating stability and structure for detonations of condensed (solid and liquid) explosives and for heterogeneous media. In particular, it was a success to prove stability of detonation of cast trotyl, confirmed experimentally [31] (the calculation is based on kinetics, proposed in [32]).

Thus the stability of detonation of powerful solid explosives with "fast" kinetics is shown on the example of cast TNT. This fact indicates the impossibility of suppressing such a detonation after its initiation. Thus, in this case, the prevention of an explosion is achieved in the only way – by ensuring the absence of an initiating effect. True, accidental explosions of solid explosives are practically impossible (such explosions are almost always deliberate).

It is shown also that detonation waves in liquid explosives can be both stable and unstable [30]. For this reason, it is very difficult to make general a priori estimates of the explosion safety of systems, containing liquid explosives, although such estimates are possible in each specific case [30].

Thus, a simple mathematical model of the transition of combustion to explosion is constructed.

This model is universal: it is applicable to the combustion of both homogeneous gas mixtures and heterogeneous media (dust-air mixtures, aerosols and sprays).

Based on the theoretical solutions of the problem of hydrodynamic flame stability, the processes of the flame autoturbulization and flame acceleration are analyzed. The possibilities of the transition of slow combustion to a deflagration explosion or to detonation are analyzed.

Algebraic formulae for estimations of the explosive induction distance and the time of the combustion-to-explosion transition are obtained. The calculations made using these formulas are in good agreement with experimental data and the results of other studies. The comparative simplicity of the formulas obtained makes it possible to evaluate the possibilities and time of the transition from combustion to explosion without significant expenditure of computer time and computer resources. This is important for on-line control of potentially explosive objects and makes such control less expansive.

FUZZY LOGIC FOR DECISION MAKING IN CONTROL SYSTEMS FOR POTENTIALLY EXPLOSIVE OBJECTS

Although a simple mathematical model of the transition of combustion to explosion is constructed and this model is simple (for calculations) and universal (it is applicable to the combustion of both homogeneous and heterogeneous media), it cannot be used directly in DSS for the decision-making on the explosion safety problems. That is because of roughness and inaccuracy of results, obtained by using this model, based on classical mathematical methods and rather primitive physical models [33].

Taking into account the foregoing, it's necessary to construct intellectual, universal enough DSS using the model of decision-making under uncertainty (i.e. under conditions of "fuzziness") on the explosion-proof problems [33]. But fuzzy logic in such DSS must be used in combination with the exact mathematical theory of combustions and explosions combined with correct application of experimental data (accounting sometimes on the "fuzziness" of those data) [5, 11], [33].

This approach provides an opportunity to avoid involvement of evaluators and to avoid all problems connected with evaluators and their interaction and cooperation with decision-makers [33, 34].

The basis for decision-making on hazards of industrial explosions have to use fuzzy estimates for such parameters as combustibility of medium, its abil-

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ity for deflagration explosion or detonation, possibility of initiation (by different ways) of combustion or detonation, possibility of transition of "slow" burning to explosive deflagration or detonation and so on. These estimates afford grounds for making decisions on prevention or mitigation of explosions. Some of those decisions should be implemented at the stage of projecting of the potentially explosive object, the others makes it possible to take operative actions such as the inhibitor injection, pressure relief, use of flame arresters and protective partitions, etc.

Let us consider for example the fuzzy estimate of the explosive ability of media [11, 33].

Data base of the detonation concentration limits and of the deflagration concentration limits is created. For the estimation of the explosive ability a decision maker has to indicate fuel, oxidizer (if any), fuel concentration, geometrical form (round tube, flat duct, etc.) for mixture or other explosive medium and geometrical sizes, physical parameters (first of all initial pressure and initial temperature) of explosive or mixture.

The combustion ability of such system is expressed by fuzzy logical variable (fuzzy statement) $\tilde{F}\tilde{A}$, which is the conjunction of three fuzzy statements, namely:

– fuzzy logical variable $\tilde{F}\tilde{C}$, expressing maintenance of the combustion (explosion) concentration limits (the combustion concentration limits and/or the detonation concentration limits) [10];

– fuzzy logical variable $\tilde{F}\tilde{D}$, expressing maintenance of the absence for the combustion suppressing distance [3,4];

– fuzzy logical variable $\tilde{F}\tilde{P}$, expressing exceeding of the initial pressure over the critical one [3, 4, 10].

That is

$$\tilde{F}\tilde{A} = \tilde{F}\tilde{C} \wedge \tilde{F}\tilde{D} \wedge \tilde{F}\tilde{P} \quad . (25)$$

Universal set (basic set, basic scale) for fuzzy logical variable $\tilde{F}\tilde{C}$ is set of values for the fuel volumetric concentration C, expressed by percentage ($0 \le C \le 100$). The characteristic function μ_C for fuzzy logical variable $\tilde{F}\tilde{C}$ is trapezoidal, expressed by formula

$$\mu_C = \begin{cases} \dfrac{C}{LCEL}, 0 \le C \le LCEL \\ 1 , LCEL \le C \le UCEL \\ 1 - \dfrac{C - UCEL}{100}, UCEL \le C \le 100 \end{cases} , (26)$$

where $LCEL$ is the lower concentration explosive limit, $UCEL$ is the upper concentration explosive limit. These limits are determined analytically [5, 11], [12] or experimentally [10, 17].

For a potentially explosive object the value of μ_C defines the degree of the belonging to the fuzzy subset A_C of those potentially combustible (explosive) objects, which are able for combustion (explosion) by the fuel concentration. It is a fuzzy subset of the accurate set U of all possible objects of this type with specified fuel and oxidizer. If $\mu_C = 1$, potentially explosive object may be estimated as undoubtedly able for combustion and explosion by the fuel concentration. In the case $\mu_C = 0$, potentially explosive object is estimated as undoubtedly disabled for combustion and explosion.

Universal set for fuzzy logical variable $\tilde{F}\tilde{D}$ is set of values for the duct width or the tube diameter $d\left(d \ \ge \ 0\right)$. The characteristic function μ_D for fuzzy logical variable $\tilde{F}\tilde{D}$ is piecewise-linear, expressed by formula

$$\mu_D = \begin{cases} \dfrac{d}{d_{cr}}, 0 \le d \le d_{cr} \\ 1 , d_{cr} \le d \end{cases} . (27)$$

Value of d_{cr} is less than the fire cell size or the detonation cell size [10, 17], [24]. These sizes are determined analytically [5, 12] or experimentally [10, 17], [24].

For potentially explosive object the value of μ_D determines the degree of the belonging of this potentially explosive object to the fuzzy subset A_D of the objects, which are able for combustion and explosion by the geometry of walls. It is a fuzzy subset of the accurate set U_1 of all possible potentially explosive objects with specified fuel and oxidizer and also with specified geometry of walls ($U_1 \subset U$). If $\mu_D = 1$, potentially explosive object may be estimated as undoubtedly able for combustion and explosion by the geometry of walls. In the case $\mu_D = 1$, potentially explosive object is estimated as disabled for combustion and explosion.

Finally, universal set for fuzzy logical variable $\tilde{F}\tilde{P}$ is set of values for the initial pressure p. The characteristic function μ_P for fuzzy logical variable $\tilde{F}\tilde{P}$ is piecewise-linear, expressed by formula

$$\mu_P = \begin{cases} \dfrac{p}{p_{cr}}, 0 \le p \le p_{cr} \\ 1\ , p_{cr} \le p \end{cases} \quad . (28)$$

Parameter p_{cr} is the minimal initial pressure, when combustion and explosion are possible. It is determined analytically or experimentally [10, 17].

For potentially explosive object the value of μ_P defines the degree of the belonging to the fuzzy subset A_P of the objects, which are able for explosion by the initial pressure. It is a fuzzy subset of the accurate set U_2 of all possible systems of such type with specified fuel and oxidizer and also with specified geometry of walls initial pressure ($U_2 \subset U$). If $\mu_P = 1$, potentially explosive object may be estimated as undoubtedly able for explosion by the initial pressure. If $\mu_P = 0$, potentially explosive object is estimated as disabled for combustion and explosion.

As mentioned above for each $\tilde{F}\tilde{A}$ the explosion induction distance X_s [10] may be calculated. It is well known [10, 24] that wall roughness and obstacles in channels and tubes significantly reduce explosion induction distance X_s and the time of the shock wave formation τ_s (in some cases in several times, up to 20-50 times [10]). But, of course, it is impossible to take all these factors into account analytically, and the numerical solutions of such problems require a lot of computer time. For this reason fuzzy logic must be used again.

Suppose that an elementary potentially explosive object (a flat channel or a round cylindrical pipe) has length L, and the estimate of the explosion induction distance is X_s.

Then the fuzzy variable $\tilde{L}$ may be considered:

$$\tilde{L} = \begin{cases} \dfrac{L}{X_s}, 0 \le L \le X_s \\ 1\ , X_s \le L \end{cases} \quad (29)$$

If $\tilde{L} = 1$, potentially explosive object may be estimated as undoubtedly able for explosion. If $\tilde{L} = 0$, potentially explosive object is estimated as disabled for explosion [5, 11].

The value $\tilde{F}\tilde{A}$ expresses the fire hazard of the potentially explosive object.

The value $\tilde{L}$ expresses the relative explosiveness of the potentially explosive object, i.e. its explosiveness without taking into account the fire hazard.

Thus the explosive ability of the potentially explosive object is expressed by fuzzy logical variable $\tilde{F}$, which is the conjunction of two fuzzy statements, namely $\tilde{F}\tilde{A}$ and $\tilde{L}$.

That is

$$\tilde{F} = \tilde{F}\tilde{A} \wedge \tilde{L} \quad (30)$$

It should be worth noting that value L is the maximum length of the object (silo height, length of the gas pipe, etc.).

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

INFORMATION MODEL FOR POTENTIALLY EXPLOSIVE OBJECT

To construct suitable DSS for the decision making on the explosion safety problems it is necessary to compose general information model for potentially detonative object of arbitrary type [11, 35].

An arbitrary potentially explosive object is a complex system [5, 16], [35]. This system may be viewed from the standpoint of system analysis. The architecture of this complex system consists of some components (subsystems) and of the hierarchical relationships between these components. As a matter of fact, hierarchy is the main feature of a complex system, since only systems with a hierarchical structure can be studied in principle [36].

The first stage for the development of an information model of every system is its structuring [35].

The complex explosive object is considered a potentially explosive object of the zero level with the number 0 (PEO_0). This object can be divided into subsystems; those subsystems are potentially explosive objects of the 1st level (PEO _1), each of which has its own individual number n_1 ($1 \le n_1 \le m_1$), where the general number of PEO _1 is equal to m_1; these potentially explosive objects of the 1st level are marked as PEO_1_1, PEO _1_2, ..., PEO _1_ m_1 .

Some of the PEO_1 (for example, PEO _1_ i_1, PEO _1_i_2, ..., PEO _1_$i_к$, where $1 \le i_1 \le ... \le i_k \le m_1$) can also be divided into subsystems – potentially explosive objects of the 2nd level (PEO_2), which are numbered as follows: PEO_2_ 1_i_1_1, PEO_2_ 1_i_1_2, ..., PEO_2_ 1_i_1_ $m_{2,1}$; PEO-_2_ 1_i_2_1, PEO_2_ 1_i_2_2, ..., PEO_2_ 1_i_2_$m_{2,2}$; …; PEO_2_ 1_i_k_1, PEO_2_ 1_i_k_2, ..., PEO-_2_ 1_i_k_$m_{2,k}$. The general number of PEO_2 is equal to $m_2 = m_{2,1} + m_{2,2} + \ldots + m_{2,k}$.

Some of the PEO_2 can also be divided into subsystems – potentially explosive objects of the 3rd level (PEO_3) in the general number of m_3, and so on [35].

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The total number of sublevels in a complex potentially explosive object (which itself is considered an object of the zero level) is not limited in principle and is determined by the developer of the information model. The developer, in turn, focuses on the specifics of the object and features of the formulation of the explosion safety ensuring problem. The numbering of the levels is "top-down", i.e. the lower level has a larger number.

It is quite obvious that the generalized structure of a complex potentially explosive object can be represented by an oriented tree (a connected directed acyclic graph) [37] with a root corresponding to PEO_0. This graph (tree) can be sorted [37]; the outgoing degrees of all vertices, except the external ones (i.e., except the terminal nodes or leaves) are at least 2.

It is obvious that terminal vertices can be in any level, except zero level. The subsystems corresponding to the terminal nodes of the graph in the graph representation of the structure of a potentially detonative object, considered as a complex system, are the elementary components of the system. These components are called elementary potentially explosive objects (EPEO) [16, 35].

According to [16, 35], the choice of elementary components of the system under study is relatively arbitrary and is largely determined by the researcher himself. However, such arbitrariness in the choice of the researcher is actually always limited: such a restriction is primarily dictated by the need to have all the information required for solving the task set about each of the elementary components of the system – its characteristics, possible states and reactions to the effects of other components of the system or external influences.

In the case of modeling a potentially explosive object of an arbitrary nature, one of the following objects should be considered as an EPEO (model of a real object) [16, 35]:

1) Open space;

2) Flat channel: a) infinite (unlocked), b) of the finite length, half-open (closed at one end), c) of the finite length, closed (closed at both ends), d) of the finite length, open (open at both ends);

3) Round cylindrical tube: a) infinite (open), b) of the finite length, half-open (closed at one end), c) finite length, closed (closed at both ends), d) finite length, closed (closed at both ends).

The choice of such potentially explosive objects as elementary [16, 35] is due to the fact that for these objects mathematical models are developed. These models allow evaluating the possibility of the explosion developing in each of such objects. And almost any real potentially explosive object can be virtually modeled by a composition (combination) of these elementary potentially detonative objects.

Real potentially explosive objects or their components (subsystems) are easily identified as the above mentioned elementary explosive detonative objects [16, 35].

Any PEO is characterized by physicochemical properties (dynamic properties) and geometry of its borders/walls (static properties). It is the type of boundary geometry that gives possibility to identify and simultaneously classify EPEO. The above classification of EPEO may be considered as a topological classification (as opposed to other types of classification – systemic and parametric). Thus, 9 classes are distinguished. The object of each of these 9 classes of EPDO may be a model of some element (subsystem) of a real explosive system. The details about 9 classes of types 1-3 are outlined before [35].

It is necessary to note that EPDO of class 2 and class 3 can simulate not only channels of rectangular cross section and pipes of circular cross section, respectively, but also pipes of elliptical cross section. Moreover, if the length of the major semiaxis of the ellipse in the section of the pipe slightly exceeds the length of its minor axis, then the pipe can be modeled with a circular section pipe with a radius of a circle equal to the length of the major axis of the ellipse, i.e. potentially explosive class 3 facility; if the length of the major semiaxis of the ellipse in the section of the pipe significantly exceeds the length of its minor semiaxis, then the pipe can be modeled with a rectangular channel with a rectangle within which this ellipse can be inscribed, and such a channel, in turn, is modeled as one of the potentially explosive objects of class 2 [35].

There is a problem of the completeness of the EPDO classification.

It is quite obvious that the only often-observed common element of real PEO not covered by the 9 classes mentioned above is a round tube with a bend.

The explosion hazard for a pipe with a bend is significantly higher than the explosive hazard for a straight pipe even if the bend is small and smooth.

The detailed consideration of this problem shows [10] that the analysis of the explosion hazard of an object, if this object simulated by a curved circular tube, in one way or another, comes down to an analysis of the explosion hazard of an object that is simulated by a straight circular tube, i.e. one of the PEO of class 3. But at the same time, the obtained estimates of the explosion hazard in this case are very approximate [10, 35].

So the first stage of development of the information model for real PEO is its decomposition, which has to be done by the rules described above. The advantages of such decomposition are its naturalness and the possibility of obtaining, along with the assessment of the explosion hazard for a complex PEO as a whole, the explosion rating of each of its subsystems. However, such a multi-level decomposition of PEO as a complex system is not necessary in most cases.

In fact, if one particularly evaluates the explosion hazard of each technological or technical subsystem of a complex PDO, then this object can be considered as a simple set of EPDO. It should proceed from a simple postulate that the level of the explosion ability of a complex PDO as a whole is equal to or not less than the maximum explosion ability among all the EPDO that this PDO contains. Then a complex PDO (PDO_0) is represented by a system with only one sublevel containing "equal" EPDO, denoted as EPDO_1, EPDO_2, ... , EPDO_*m*, where m is the total number of such objects.

Thus, the hierarchical structuring of a complex detonative system is carried out.

The next step after structuring in the information model developing is the identification of conceptual entities, or objects, which constitute the subsystem for analysis.

In the case of PDO, first of all it is necessary to identify the EPDO (with their attributes and relationships) [36].

It is done with the use of notions (and attributes) **Explosion hazard** and **Relative explosion hazard** [35].

Explosion hazard is in the above terms the fuzzy variable $\tilde{F}$ for estimation of the possibility of explosion (deflagration or detonation). Algorithm for calculating this estimation is described above.

Relative explosion hazard is the fuzzy variable $\tilde{L}$ for estimation of the possibility of explosion when ignition already takes place. Algorithm for calculating of this estimation is also developed above.

Fuzzy variables $\tilde{F}$ and $\tilde{L}$ are connected by equation (30), where fuzzy variable $\tilde{F}\tilde{A}$ from the equation (25) is the notion **Fire hazard**.

All kinds of EPEO are described with their attributes and with the relationships between them and with the complex PEO. Information structure diagram [36] for complex PEO is composed for the most general case [35].

MODELING OF GRAIN RLEVATOR AS POTENTIALLY EXPLOSIVE OBJECT

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 [38, 39].

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.

The most explosive elements in the system of grain enterprises are silos and bunkers.

To prevent explosions, the automated elevator control system must be equipped with DSS for explosion safety.

Appropriate mathematical and information models of a grain elevator as PEO is developed by the described above scheme [39] .

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

1) Each separate object of the grain elevator (bucket elevator, silo, over-silo floor, sub-silo floor, working building, etc.) is considered as an 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).

2) For each EPEO, the concentration limits of ignition and explosion are determined separately, as well as the explosion induction distance X_S. These parameters are calculated as described above. 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 above.

3) Certain fuzzy logical variable corresponds to each EPEO. For a given moment in time 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)

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is calculated. The largest of these values (i.e. the value of the disjunction of these fuzzy logical variables) is an estimate of the explosiveness of the entire complex potentially explosive object as a whole, i.e. an estimate of the explosion hazard of the grain elevator itself.

4. 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 as mentioned above.

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 [36]. Information structure diagrams are also built.

On the base of mathematical and information models in the decision-making on hazards of grain elevator explosions the corresponding software is developed [39] and calculations are done.

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. These calculations are also useful also from the point of view of the grain elevator designing and the grain elevator control.

The results of the calculations are summarized in the following conclusions [39]:

1) If the humidity rises, then both the explosion hazard and the fire hazard of the grain elevator decrease.

2) Temperature fluctuations within a few tens of degrees have little effect on the fire hazard and explosion hazard of the grain elevator.

3) 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.

4) Monolithic reinforced concrete silos are noticeably less explosive than prefabricated reinforced concrete silos. This is due to the condition of the inner walls of the silos. Metal silos are much more explosive than reinforced concrete ones.

5) Increasing of the height of the silo inevitably leads to the magnification of its explosion hazard.

6) A low degree of fire hazard does not always correspond to a low degree of its explosiveness.

EXPERIMENTS, RESULTS AND DISCUSSIONS

To verify the proposed mathematical model of combustion-to-explosion transition calculations of the explosion induction distance X_s and of the time of the shock wave formation τ_s are done for different combustible media [5].

For combustible gas mixtures near stoichiometry value X_s varies from 10 mm to 50 cm. Value τ_s accordingly varies from 0,001 s to 5 s.

For gas mixtures near concentration combustion limits value X_s varies from 50 cm to 5 m and value τ_s varies from 5 s to 15 s.

For fine-dispersed aerosols and dust suspensions value X_s changes from 1 m to 10 m and value τ_s varies from 5 s to 1 min.

For usual aerosols and dust suspensions X_s changes from 5 m to 15 m and value τ_s varies from 15 s to 2 min.

For aerosols and dust suspensions near concentration combustion limits value X_s is more than 15 m and value τ_s is more than 2 min.

Those results are in good agreement with experimental data and numerical researches for open spaces, wide channels and wide tubes with smooth walls [2, 3], [4, 5], [6, 7], [8, 9], [10]. These results are the basis for designing explosion-proof objects, as well as for making decisions that ensure explosion safety in the operational control mode.

It is obvious that for combustible gas mixtures the control system of PEO has to be only automatic control system. The speed of the explosive process development simply does not leave a person any time for the decision making.

It is also obvious that in the overwhelming majority of real cases for aerosols and dust suspensions, the control system of PEO may be an automated (not automatic) control system. This exactly corresponds to the case of the grain elevator discussed above.

CONCLUSIONS

Thus mathematical modeling of combustion-to-explosion transition of is done. The mathematical model of the process is simple and universal. This model is applicable to the combustion of both homogeneous gas mixtures and heterogeneous media (primarily dust-air mixtures). It is applicable also for detonations of condensed explosives.

Descriptions of the processes of autoturbulization and flame acceleration are based on the theoretical solutions of the problem of hydrodynamic flame stability. All the possibilities for the transition of slow (laminar or turbulent) combustion to a deflagration explosion or detonation, as well as the possibilities of the detonation wave propagation and development, are analyzed.

Algebraic formulae for estimations of the explosive induction distance and the time of the combustion-to-explosion transition are obtained. The calculations made using these formulas are in good agreement with experimental data and the results of other studies.

The comparative simplicity of the formulas obtained makes it possible to evaluate the possibilities and time of the transition from combustion to explosion without significant expenditure of computer time and computer resources. This is important for on-line control of potentially explosive objects and makes such control less expansive.

The application of fuzzy logic makes it possible to use the proposed mathematical model of the combustion-to-explosion transition for the mathematical support and software of decision support systems on the issues of explosion safety and explosion protection of the real industrial objects and transport facilities.

The advantage of the decision support system of this type is that it allows the decision makers to do without experts. This is especially important, since it is well known that working with experts has always been and remains a weak link in decision support systems.

The development of this study is associated with construction and use of the nonlinear theory of the flame instability. It is connected also with the possible application of the theory of fractal combustion and strange attractors for the analysis of autoturbulization of the laminar flame and the process of the possible combustion-to-explosion transition. In this case, the basis for the research should still be taken from the results of the analysis of the hydrodynamic stability of the flame in the classical sense of Darrieus-Landau.

It would also be interesting to try to extend this theory to polydisperse dust-air mixtures, which would significantly expand the capabilities of the corresponding decision support system.

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Математичні та інформаційні моделі в системах прийняття рішень з вибухозахисту

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АНОТАЦІЯ

Дану статтю присвячено питанню математичного та інформаційного моделювання переходу від горіння до вибуху, що дає змогу створити адекватне математичне та інформаційне забезпечення систем підтримки прийняття рішень (СППР) для автоматизованого керування вибухонебезпечними об'єктами. Побудовано просту математичну модель переходу горіння у вибух. Ця модель базується на розв'язанні математичних задач гідродинамічної стійкості полум'я та хвиль детонації. Ці задачі в свою чергу зводяться до розв'язання задач на власні значення для лінеарізованих диференціальних рівнянь газової динаміки. Математична модель досить універсальна. Це надає можливість робити прості аналітичні оцінки довжини зони переходу повільного горіння до вибуху та часу формування ударної хвилі. Розглянуто можливості переходу повільного горіння як у дефлаграційний вибух, так і в детонаційну хвилю. Отримано теоретичні оцінки довжини зони переходу повільного горіння до вибуху та часу такого. Ці оцінки виражаються алгебраїчними формулами, використання яких економить ресурси комп'ютера і не потребує значних витрат комп'ютерного часу. Застосування нечіткої логіки дає можливість використовувати запропоновану математичну модель переходу від горіння до вибуху для реальних вибухонебезпечних об'єктів у промисловості та на транспорті. Математичні моделі вибухонебезпечних об'єктів базуються на поєднанні нечіткої логіки та класичних математичних методів. Ці математичні моделі дають можливість створювати відповідні інформаційні моделі. Таким чином розроблено математичне та інформаційне забезпечення СППР для автоматизованих систем керування вибухонебезпечними об'єктами. Основна перевага цих СППР полягає в тому, що вони дають можливість особам, що приймають рішення, обходитися без експертів.Зокрема, розроблені математичні та інформаційні моделі створюють основу програмного забезпечення СППР вибухобезпеки зернових елеваторів. Розроблено відповідне програмне забезпечення та проведено деякі розрахунки. Ці розрахунки корисні не тільки з точки зору апробації запропонованого методу математичного моделювання елеватора як вибухонебезпечного об'єкта або тестування самого програмного забезпечення, але й з точки зору проектування елеватора.

Ключові слова: вибух; дефлаграція; детонація; пожежа; полум'я; система підтримки прийняття рішень; вибухобезпека; математична модель; інформаційна модель; потенційно вибухонебезпечний об'єкт

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