Fuzzy Logic in Control Systems for Potentially Explosive Objects

Victor Volkov[1], Natalia Makoyed[2]

[1]*Odessa I.I.Mechnikov National University, Dvoryanskaya str.,2, Odessa, 65082, Ukraine*
[2]*Odessa National Academy of Food Technologies, Kanatnaya str., 112, Odessa, 65039, Ukraine*

Abstract

Main principles of the decision-making on hazards of industrial explosions are formulated. Classical mathematical models often are not applicable for the decision-making on hazards of industrial explosions, because explosive objects in most cases are very complicated systems. The model of decision-making under risk, that is based on the probability theory and the probability logic, is not effective also. Thus application of the model of decision-making under uncertainty, that is based on the fuzzy-set theory and fuzzy logic, is preferable for complicated industrial and transport potentially explosive objects. Application of the fuzzy logic is the first basic principle of the decision-making on hazards of industrial explosions. But fuzzy logic in this case has to be used in combination with the exact mathematical theory of combustions and explosions combined with correct application of experimental data. That is the second basic principle of the decision-making on hazards of industrial explosions. This approach provides an opportunity to avoid involvement of evaluators (experts) and thus to avoid all problems connected with evaluators and their interaction and cooperation with decision-makers. Mathematical model for decision-making in decision support systems (DSS) for automated control of potentially explosive objects is developed. This model is based on combination of the fuzzy logic and classical mathematical methods from the mathematical theory of combustions and explosions (primarily the theory of stability of combustion and detonation waves). That makes it possible to create an adequate mathematical support for the mentioned above DSS. Suitable DSS is developed for the enterprises of the grain storing and processing, which are explosive objects.

Keywords

Decision-making, uncertainty, fuzzy logic, mathematical model, fuzzy logic, explosion, explosive object, combustion, detonation

1. Introduction

The explosion prevention is one of the most topical and most difficult problems of the present-day industry and up-to-date transport. There are lots of reasons for such state of affairs. Among these reasons there are the complications of technological processes, the emergence of new combustible materials and explosives, the chemicalization of industry, etc. But one of the main reasons is the insufficient efficiency of automatic and automated systems for preventing and suppressing explosions [1].

Nowadays the progress in computing machinery and telecommunicational equipment enlarged greatly the human potentialities in sphere of making of the high-quality decisions for solving different problems. It concerns also the problems of hazards, prevention and mitigation of industrial and transport explosions.

The basic idea of the present-day organization of explosion protection is to prevent the occurrence of accidental fires [2-4]. Naturally, if a fire does not occur, then an explosion is impossible. Therefore, in the process of solving the fire safety problem, the problem of explosion safety is simultaneously fully solved. Thus, the

ISIT 2021: II International Scientific and Practical Conference «Intellectual Systems and Information Technologies», September 13–19, 2021, Odesa, Ukraine
EMAIL: viktor@te.net.ua (A.1); natamakoyed@gmail.com (A.2)
ORCID:0000-0002-3990-8126(A.1); 0000-0002-4591-555X(A.2)

problem of explosion safety is not solved as a separate problem, but only within the fire safety problem. Thereby modern automated control systems for explosive objects are aimed at the prevention or suppression of accidental fires and spontaneous combustion [3-5]. But this approach has at least two significant drawbacks:

- For a relatively low probability of ignition, the possibility of an explosion in the case of fire may be great [1,2,6]; this is true first of all for enterprises where explosive dust-air mixtures are formed during the production process [6,7], as well as for coal mines [6,8,9];
- It is not always possible to detect and suppress a fire on time [4, 7, 10].

So for lots of enterprises and for many kinds of equipment the fire safety problem sometimes can't be solved properly, i.e. it is impossible to guarantee almost complete absence of fires. This is critical if there is a danger of explosion.

These cases have to be specifically diagnosed, because the damages and personnel casualties from explosions are much greater than from fires. In such cases it's necessary to have additional safety "mechanism" to prevent explosions. One of the main parts of such mechanism should be a decision support system (DSS) for the decision-making on the explosion safety problems.

The main theoretical problems for this decision-making are:

1. Problem of the flame stability.
2. Finding of the explosion induction distance.
3. Finding the time of the explosion induction.

Solving of the flame stability problem allows to answer the question about the possibility of the combustion-to-explosion transition in principle. Only instable flames accelerate and generate shock or detonation waves [11]. This problem is solved analytically [1, 12] and numerically [10, 13]. The scientific studies [10, 13] are done first of all in connection with deflagration-to-detonation transition [10] and are based on numerical simulations of premixed gas combustion. But these numerical simulations are always connected with finite perturbations, while stability of flames should be researched in relation to small perturbations (Darrieus-Landau instability). Besides, deflagration explosions are more frequent than detonations, though detonations are more dangerous and destructive. In addition, numerical simulations of the flame stability [14] and deflagration-to-detonation transition [13,15,16] require significant computer resources and time. Therefore such numerical simulations cannot be used for DSS in automated control systems for explosive objects, because the time for decision making is strictly limited. Analytical criteria [1, 12] for the flame instability are also only very rough estimates [1, 17].

Finding of the explosion induction distance makes it possible to answer the question about the possibility of the combustion-to-explosion transition for almost all kinds of channels and tubes [1], which simulate a variety of potentially explosive and detonative objects [1, 18]. Algebraic formulae for estimations of the explosive induction distance and the time of the combustion-to-explosion transition are obtained analytically [1] and are in good agreement with some experimental data. 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 the computational time and computer resources. This is important for on-line control of potentially explosive objects and makes such control less expansive [1, 17]. But analytical estimations of the explosive induction distance are still too inaccurate because of wall roughness and obstacles in channels and tubes. These roughness and obstacles significantly reduce explosion induction distance X_s and the time of the shock wave formation (i.e. the time of the explosion induction) τ [1, 10, 17].

Finding the time of the explosion induction is closely related to finding of the explosion induction distance. Solving of this problem helps to decide, what measures can be taken to prevent an explosion timely or to minimize the possible consequences of an explosion.

Although a simple mathematical model of the transition of combustion to explosion is constructed [1, 10] and this model is simple (for calculations) and universal (it is applicable to the combustion of both homogeneous gas mixtures and heterogeneous media, i.e. dust-air mixtures, aerosols, sprays, etc.), 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 [1, 10, 17, 18], based on classical mathematical methods and rather primitive physical models.

The aim of the present research is the development of a mathematical model that is based on fuzzy logic and makes it possible to create an adequate mathematical support for DSS of automated control systems for explosive objects.

2. Main principles and mathematical modeling of the decision-making on hazards of industrial explosions

As shown above classical models for the decision-making [19] on hazards of industrial explosions often are not applicable.

2.1. Main principles

Thus for the constructing of DSS on the explosion-proof problems it is possible to use only two kinds of mathematical models:

- The model of decision-making under risk.
- The model of decision-making under uncertainty.

The model of decision-making under risk is based on the probability theory and the probability logic.

The model of decision-making under uncertainty is based on the fuzzy-set theory and fuzzy logic.

It is proved that application of the latter model is preferable for complicated industrial and transport systems [1, 17].

Thus application of the fuzzy logic is the first basic principle of the decision-making on hazards of industrial explosions.

As a matter of fact a lot of parameters, which are essential for the first model of decision-making, are determined under the statistics processing. But statistics for the explosive processes are absent or very imperfect in many cases. Moreover, these statistics sometimes are also fuzzy in a way. And though it is always possible to make the probability graph for conversions from the explosion-proof state to the dangerously/highly explosive one and to build up the probability matrix for such conversions, the efficiency of this methodology does not look high.

Decision-making under uncertainty should be implemented if all possible states of object (nature, medium) are known, but their probability distribution is not known [19]. Decision-making under uncertainty leads to robust, quasi-rational decision, that means making the best possible choice when information is incomplete. Theoretical base for such decisions is fuzzy-set theory and fuzzy logic [20]. This kind of decision-making uses uncertain estimates of evaluators (experts), based on their theoretical knowledges, practical experiences, their intuition and so on. Due to the large number of considerations involved in many decisions, computer-based DSS can be developed to assist decision makers in considering the implications of various courses of thinking. This may help to reduce the risk of different human errors.

Taking into account the foregoing, it’s necessary to offer effective methodology for constructing intellectual, universal enough DSS using the model of decision-making under uncertainty (i.e. under conditions of “fuzziness”) on the explosion-proof problems. 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). That is the second basic principle of the decision-making on hazards of industrial explosions.

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 [21, 22].

2.2. Main principles

The basis for decision-making on hazards of industrial explosions must use fuzzy estimates for such parameters as combustibility of medium, its ability for detonation, possibility of initiation (by different ways) of combustion or detonation, possibility of transition of “slow” burning to explosive deflagration or even 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 allow for the possibility of taking operative actions such as the inhibitor injection, pressure relief, use of flame arresters and protective partitions, etc.

Let us consider the fuzzy estimate of the explosive ability of media.

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 explosive ability of such system is expressed by fuzzy logical variable (fuzzy statement) *FA*, which is the conjunction of three fuzzy statements, namely:

- Fuzzy logical variable *FC*, expressing maintenance of the explosion concentration limits (the combustion concentration limits and the detonation concentration limits).
- Fuzzy logical variable *FD*, expressing maintenance of the absence for the explosion suppressing distance.
- Fuzzy logical variable *FP*, expressing exceeding of the initial pressure over the critical one.

That is

$$FA = FC \ \& \ FD \ \& \ FP \qquad (1)$$

Universal set (basic set, basic scale) for fuzzy logical variable *FC* is set of values for the fuel volumetric concentration *C* , expressed by percentage (*0 ≤ C ≤ 100*). The characteristic function μ_C for fuzzy logical variable *FC* is trapezoidal (Figure 1), expressed by formula

$$\mu_C = \begin{cases} \dfrac{C}{LCEL}, 0 \le C \le LCEL \\ 1 , LCEL \le C \le UCEL \\ 1 - \dfrac{C - UCEL}{100}, UCEL \le C \le 100 \end{cases} \qquad (2)$$

where *LCEL* is the lower concentration explosive limit, *UCEL* is the upper concentration explosive limit. These limits are determined analytically [1, 17] or experimentally [10, 11].

For a potentially explosive object (PEO) the value of μ_C defines the degree of the belonging to the fuzzy subset A_C of those PEO, which are able for 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 $\mu_C = 1$, PEO may be estimated as undoubtedly able for explosion by the fuel concentration. In the case $\mu_C = 0$, PEO is estimated as undoubtedly disabled for explosion.

Universal set for fuzzy logical variable *FD* is set of values for the duct width or the tube diameter *d* (*d ≥ 0*). The characteristic function μ_D for fuzzy logical variable *FD* is piecewise-linear (Figure 2), expressed by formula

$$\mu_D = \begin{cases} \dfrac{d}{d_{cr}}, 0 \le d \le d_{cr} \\ 1 , d_{cr} \le d \end{cases} \qquad (3)$$

Value of d_{cr} is less than the fire cell size or the detonation cell size [10,11]. These sizes are determined analytically [1, 12] or experimentally [10, 11].

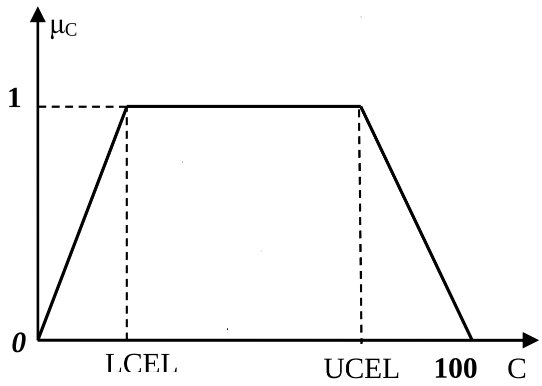

Figure 1: The characteristic function μ_C for fuzzy logical variable *FC*

For PEO the value of μ_D determines the degree of the belonging of this PEO to the fuzzy subset A_D of the objects, which are able for explosion by the geometry of walls. It is a fuzzy subset of the accurate set U_1 of all possible PEO with specified fuel and oxidizer and also with specified geometry of walls ($U_1 \subset U$). If $\mu_D = 1$, PEO may be estimated as undoubtedly able for explosion by the geometry of walls. In the case $\mu_D = 0$, PEO is estimated as disabled for explosion.

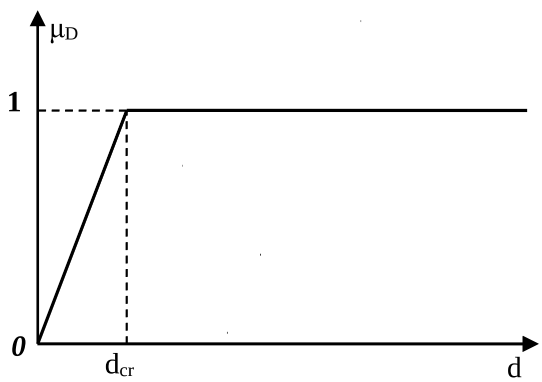

Figure 2: The characteristic function μ_D for fuzzy logical variable *FD*

Finally, universal set for fuzzy logical variable *FP* is set of values for the initial pressure *p*. The characteristic function μ_P for fuzzy logical variable *FP* is piecewise-linear (Figure 3), expressed by formula

$$\mu_P = \begin{cases} \frac{p}{p_{cr}}, 0 \le p \le p_{cr} \\ 1\ , p_{cr} \le p \end{cases} \quad (4)$$

Parameter p_{cr} is the minimal initial pressure, when explosion is possible. It is determined analytically or experimentally [10, 11].

For PEO 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 $\mu_P = 1$, PEO may be estimated as undoubtedly able for explosion by the initial pressure. If $\mu_P = 0$, PEO is estimated as disabled for explosion.

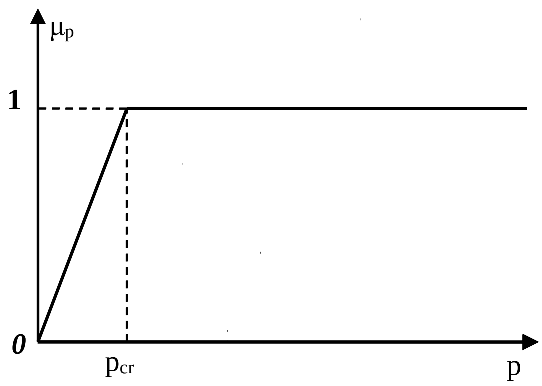

Figure 3: The characteristic function μ_p for fuzzy logical variable *FP*

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

3. Conclusions

Mathematical model for DSS of automated control systems of explosive objects is developed. This model is based on combination of the fuzzy logic and classical mathematical methods. That makes it possible to create an adequate mathematical support for these mentioned above DSS. Suitable DSS is developed by us for the enterprises of the grain storing and processing.

4. References

[1] V. Volkov, Y. Kryvchenko, Transition of combustion to explosion and decision support systems for explosion protection, in: Lecture Notes in Computational Intelligence and Decision Making, Advances in Intelligent Systems and Computing, volume 1246, Springer, Cham. 2021, pp. 437-447. doi: 10.1007/978-3-030-54215-3.

[2] Zarko V.E., Weiser V., Eisenreich N., Vasil'ev A.A. Prevention of Hazardous Fires and Explosions. The Transfer to Civil Applications of Military Experiences, Springer Netherlands – Kluwer Academic Publishers, 1999. doi: 10.1007/978-94-011-4712-5.

[3] Pekalski A.A., Zevenbergen J.F., Lemkowitz S.M., Pasman H.J., A Review of Explosion Prevention and Protection Systems Suitable as Ultimate Layer of Protection in Chemical Process Installations, Process Safety and Environmental Protection, volume 83, issue 1, 2005. doi:10.1205/psep.04023.

[4] Nolan D. P., Handbook of Fire and Explosion Protection Engineering Principles for Oil, Gas, Chemical and Related Facilities. William Andrew-Elsevier, 2011. doi:10.1016/B978-1-4377-7857-1.00033-1.

[5] Wei Lu, Ying-Jiazi Cao, Jerry C. Tien, Method for prevention and control of spontaneous combustion of coal seam and its application in mining field, International Journal of Mining Science and Technology, volume 27, issue 5, 2017. doi:10.1016/j.ijmst.2017.07.018.

[6] Lemkowitz S.M., Pasman H.J., A Review of the Fire and Explosion Hazards of Particulates, KONA Powder and Particle Journal, No. 31, pp. 52-81, 2014. doi:10.14356/kona.2014010.

[7] Eckhoff R. K., Dust Explosion Prevention and Mitigation, Status and Developments in Basic Knowledge and in Practical Application, International Journal of Chemical Engineering, volume 2009, pp. 1-12, 2009. doi:10.1155/2009/569825.

[8] Burgherr P., Hirschberg S., Assessment of severe accident risks in the Chinese coal chain, International Journal of Risk

Assessment and Management, No.7, pp. 1157-1175, 2007. doi: 10.1504/IJRAM.2007.015299.

[9] du Plessis J.J.L., Active explosion barrier performance against methane and coal dust explosions, International Journal of Coal Science and Technoogy, volume 2, issue 4, pp. 261–268, 2015. doi:10.1007/s40789-015-0097-7.

[10] Nettleton M. A., Gaseous detonations: their nature and control (1st. ed.), Springer, 1987. doi:10.1007/978-94-009-3149-7.

[11] Liberman M., Introduction to Physics and Chemistry of Combustion. Springer, Heidelberg, 2008. doi:10.1007/978-3-540-78759-4.

[12] Aslanov S., Volkov V., The integral method of studying the hydrodynamic stability of laminar flame, Combustion, Explosion and Shock Waves, volume 27, 1991,pp.553-558. doi:10.1007/BF00784941.

[13] Liberman, M., Sivashinsky, G.I., Valiev, D., Eriksson L.E., Numerical simulation of deflagration-to-detonation transition: the role of hydrodynamic instability, Int. J. Transp. Phenomena, volume 8(3), 2006, pp. 253-277.

[14] Buckmaster J., The structure and stability of laminar flames. Ann. Rev. Fluid Mechanics, volume 25, 1993, pp. 21-53. doi:10.1146/annurev.fl.25.010193.000321.

[15] Oran, E.S., Gamezo, V.N.: Origins of the deflagration-to-detonation transition in gas-phase combustion. Combustion and Flame volume 148, 2007, pp. 4-47. doi:10.1016/j.combustflame.2006.07.010

[16] Koksharov A., Bykov V., Kagan L., Sivashinsky G., Deflagration-to-detonation transition in an unconfined space, Combustion and Flame, volume 195, 2018, pp. 163-169. doi:10.1016/j.combustflame. 2018.03.006

[17] V. Volkov, Decision support systems on hazards of industrial explosions, in: Seventh International Symposium on Hazards, Prevention and Mitigation of Industrial Explosions: Thirteenth International Colloquium on Dust Explosions and Eighth Colloquium on Gas, Vapor, Liquid, and Hybrid Explosions, St. Petersburg, Russia, 7–11 July 2008, volume 3, pp. 343–347, 2008.

[18] A. Kovalenko, V. Volkov, Information Model for Potentially Detonative Object, in: CEUR Workshop Proceedings, volume 2683, pp. 50-52, 2019.

[19] Enta Y. A., Measure for the Discriminative Effect of Information, Proceedings of the 1978 Joint Automatic Control Conference, volume 3, pp.69-80,1978.

[20] Zadeh L., Fuzzy Sets Information and Control, volume 8, pp.338-353, 1965.

[21] P.H. Ross, M.W. Ellipse, H.E. Freeman, Evaluation: A systematic approach (8th ed.), Sage Publications, 2021.

[22] M. Hurteau, S. Houle, S. Mongiat, ().How Legitimate and Justified are Judgments in Program Evaluation, in: Evaluation, volume 15 (3), 2009, pp. 307-319. doi:10.1177/1356389009105883