MINISTRY OF EDUCATION AND RESEARCH

UNIVERSITY OF PETROȘANI

DOCTORAL SCHOOL

DOCTORAL FIELD: INDUSTRIAL ENGINEERING

Eng. MATEI ADRIAN

DOCTORAL THESIS

CONTRIBUTIONS ON THE THREE-DIMENSIONAL ANALYSIS OF POTENTIAL EXPLOSIVE ENVIRONMENTAL INTERMEDIARIES WITH INDUSTRIAL VENTILATION SYSTEMS

Scientific leader

Univ. prof. habil Ph.D. eng. MORARU ROLAND

Petroșani
2020

CONTENTS

1. KEY WORDS

Furthermore, for a better understanding of the following exposure, it is necessary to enumerate some notions specific to the approached field: flammable / explosive environment, risk, danger, 3D modeling of the explosive mixture, explosiveness diagram, explosiveness prism, industrial ventilation system, critical time forecast, generalized Ex distance, PCMEX computer program.

2. THE IMPORTANCE AND NECESSITY OF THE TOPIC. OBJECTIVES AND STRUCTURE OF THE THESIS

The risks encountered in the industry in the form of potential hazards can generate, in case of materialization of the potential of specific danger, work accidents, occupational diseases and loss of life, as a result of an unexpected disruption in the work process.

The need to identify the risks encountered at industrial level and in particular the risk of explosion, is an urgent need for the following reasons:

- one of the most important risks is the risk of explosion;
- in the continuous operation of the economic objectives related to the active industries, substances are used or appear in the form of gases, mists, dusts or dusts that can create potentially explosive or toxic atmospheres;
- in order to avoid the risk of explosion, it is necessary to eliminate the damage situations that can lead to the loss of human lives, material losses, respectively the closure of some industrial objectives;
- avoiding or reducing the risk of explosions by establishing the behavior of explosive environments, as a proactive measure, is a priority;
- the main measure to prevent explosions is to achieve adequate ventilation at the level of isolated or closed premises;
- the issue of explosion risk in industrial premises must be addressed not only in terms of achieving an optimal ventilation system, but also in terms of monitoring the atmospheres of industrial premises with the help of specific tools such as explosiveness diagrams;
- the associated danger and risk of explosion, which is permanently present in certain industrial premises and which expose workers during work processes, is an extremely strong motivation for identifying new means and ways to prevent explosion-type phenomena.

The probability of the formation of an explosive medium in the case of the availability of a mixture of flammable gases depends on the degree of flammability of these substances when mixed with air. The explosive medium is formed when the required degree of dispersion is reached with the simultaneous condition of the concentration of flammable substances in the analyzed mixture within the limits of explosion. By their very nature, gases and vapors are characterized by a sufficient degree of dispersion. The specialized literature in the field of occupational risk analysis in the industrial environment describes numerous and varied methods and tools applicable in the field of risk assessment, for example in order to identify sources of danger (checklists, analysis failure modes, effects and criticality, command error analysis, study HAZOP, preliminary risk analysis) or intended for quantitative or semi-quantitative estimation (event analysis, analysis based on failure or event trees, cause-andeffect diagrams, Tripod-Beta method, etc.), but in case of explosion protection, they do not they are useful only in exceptional situations, for example for determining ignition sources in complex technical installations. All these aspects support the importance and opportunity of scientific research dedicated to the three-dimensional analysis of potentially explosive environments that interact with industrial ventilation systems in order to reduce the risk of explosion. The research results from the doctoral thesis can be directly used by all specialists / decision makers in the field of Occupational Health and Safety within the industrial units.

The objectives of the thesis

The general objective

The main objective of the PhD research is based on the idea to define a methodological approach *completely new and inventive* in terms of analyzing three-dimensional potentially explosive environments and tools specific application in order to establish permanent point defining the atmosphere of industrial premises in relation in terms of explosiveness.

The intended result is the development of a 3D system for the analysis of explosive atmospheres and, explicitly, refers to the construction and practical use of the prism of explosiveness in industrial work environments. Also, the intended result consists in identifying, developing and making the necessary mathematical tools in order to establish the critical time required for a point that defines the atmosphere in the industrial precinct until it reaches the prism of explosiveness, extremely important parameter for sizing and determining the application. of prevention measures, among which the most important are: pre-alarm, alarm and evacuation of personnel.

Specific objectives

I. carrying out a documentary study on the atmosphere of the industrial premises, of the specific risks and of the applicable ventilation techniques;
II. study of plane graphical systems usable for the analysis of explosive atmospheres.
III. validation of the use of explosiveness diagrams;
IV. elaboration of an original method, with novelty character at national level, of three-dimensional analytical research of explosive atmospheres;
V. establishing the mathematical basis from a descriptive-geometric, respectively analytical-geometric perspective of the explosive atmospheres in a three-dimensional system;
VI. elaboration of a computer tool for forecasting the behavior of explosive environments in order to establish the critical time.

3. THESIS STRUCTURE

The doctoral thesis is composed of IX chapters and includes 132 pages dedicated to the scientific approach itself and 13 pages corresponding to the 2 annexes, 79 figures, 10 tables and 141 bibliographical references.

The composition of the thesis by chapters follows a logical, procedural approach, each chapter presenting aspects that were introduced in the design and elaboration of the method of three-dimensional analysis of explosive media and - subsequently - in the development of PCMEX computer application for predicting explosive media behavior.

In the paper are presented synthetically and systematically personal research, representing the results of efforts to document, collect and process data and - especially - design. The doctoral thesis is conceived as a unitary whole that starts from the documentary study and ends with the methods and tools necessary for the innovative analysis in three-dimensional system of explosive environments.

Chapter I entitled ***"The atmosphere of the industrial premises. Specific risks and ventilation techniques ",*** aims at delimiting the conceptual framework of the research, including notions regarding the external atmosphere of industrial premises, with direct reference to air pollution, classification of pollution modes, pollution sources and inorganic pollutants of the atmosphere, respectively regarding the emissions of air pollutants. Also, information specific to the indoor atmosphere of industrial premises is synthesized, where the risks due to pollution were analyzed, with special emphasis on the risks of intoxication and asphyxiation, the risk of explosion and the risk of exposure to extreme temperatures. Substances dangerous to the human body and occupational diseases that may occur as a result of exposure to the human body are analyzed. In addition, the elements of industrial ventilation are presented, with a direct focus on industrial ventilation techniques and potentially explosive or toxic environments. In this context, the local ventilation systems, the principles of achieving local ventilation, respectively the devices for capturing the noxious substances were analyzed. At the same time, the general ventilation systems were presented and analyzed, with emphasis placed on the general principles of implementation, respectively on the compensation air. It was pointed out that general ventilation accepts a certain degree of residual pollution, which is the main reason why it should be used only as an addition to local ventilation, in particular to ensure a minimum contribution of fresh air in the premises and to dilute pollutants not captured by the local suction system.

Chapter II entitled ***"2D system analysis of explosive atmospheres"*** is dedicated to the study of explosive atmospheres and their methods of graphical analysis; in this context, the flammability / explosiveness property of the explosive substances was analyzed in detail, respectively the factors that influence their flammability / explosiveness. Among the factors influencing the flammability of explosive substances were analyzed in particular: dependence on energy, temperature, chemical composition, explosive substances and pressure. Regarding the graphical analysis of the explosion phenomena, the explosiveness diagrams in 2 D system were studied, namely: Coward - Jones, Ellicott, USBM - Zabetakis, Kennedy Ternary or Triangular diagram and CCSM - Bardocz. It has been pointed out that after 1975, when Hertzberg tried to establish in depth the theory of flammability, but at an academic level, difficult to use by practitioners, this field was well deepened and new laws appeared that govern the phenomenon of flammability / explosiveness as well as the factors that influence it. Currently, professional methods in the field of flammable atmospheres consisting of gas mixtures or dilution gases are set out in ISO 10156/2010, which contains test methods and methods for determining the flammability of gas mixtures.

Chapter III entitled ***"Experimental research on the use of explosive diagrams"*** is devoted to conducting numerical case studies based on concrete data obtained by measurements in industrial premises, on the practical use of explosive diagrams Coward - Jones, Ellicott, USBM - Zabetakis, Ternara or Triangular Kennedy and CCSM - Bardocz, in order to detect their applicability in further research.

Chapter IV "Analytical research of the explosive atmosphere in 3D system" presents the results of the totally new theoretical and conceptual analysis on the approach of explosive atmospheres in three-dimensional system. In this regard, the Coward - Jones explosive triangle and the use of the explosive diagram are explained in detail. It has been shown that if the ventilation systems used become inefficient, either by improper use or by changing the functional parameters over time, then the dilution of explosive gases is achieved with low efficiency and consequently the explosive gas concentrations may exceed the lower explosive limits. Under these conditions, in the presence of an efficient source, there is an explosion phenomenon with devastating effects and which can create mechanical or environmental conditions incompatible with life. Based on the presented premises, a strictly necessary measure is to ensure the monitoring of the working atmosphere in order to identify at an early stage any trend to increase the concentration of explosive gases above the maximum limits allowed by current legislation. It also analyzes for the first time the construction and use of the explosive prism, which is a step forward in terms of the analysis of explosive atmospheres in terms of conceptual, visual, analytical and results.

Chapter V "Descriptive geometric analysis of explosive atmosphere in 3D system" is dedicated exclusively to establishing the descriptive-geometric mathematical basis for the representation of point, line and plane in order to analyze and understand how the explosive prism works to control explosive atmospheres. The specific case that represents the ratio between the plane in which the points defining the monitored atmosphere are located) and the plane generated by translating the line defined by the point specific to the lower explosive limit are elucidated.

Chapter VI "Analytical geometric modeling of the explosive atmosphere in 3D system" includes the conceptual mathematical apparatus, geometric analytical that was developed to understand how to operate the explosive prism in order to control explosive atmospheres. In this sense, the point and line in the plane system, respectively the point and the line in the space system, were analyzed analytically geometrically. In the case of the explosive prism, the developed model can be applied for the intersection of the line or space curve obtained by linear or nonlinear regression with the distribution plane, and the result is represented by a point through whose coordinates both oxygen and methane concentrations are obtained. the time at which the monitored atmosphere becomes explosive. The obtained results were used directly in the elaboration of the PCMEX computer program.

Chapter VII "Development of the PCMEX computer program for forecasting the behavior of explosive environments" is devoted to the development of a computer program, usable for viewing the evolution of any potentially explosive atmosphere, monitored and established critical time. In this sense, a mathematical model has been developed that uses the use of regression analysis as a tool to predict the evolution of the explosive atmosphere, with direct reference to linear and nonlinear mathematical regression. At the same time, the mathematical form for forecasting the critical time was made, which represents the period of time necessary for a point that defines the monitored atmosphere until the moment when it reaches the prism of explosiveness. Also, the computer program PCMEX was developed for predicting the critical time specific to explosive environments, using the programming language R. The language R allows the user, for example, to program instruction groups for the successive analysis of data sets. It is also possible to combine several statistical functions in a single program to perform more complex analyzes. While classical software immediately displays the results of an analysis, R stores these results in an "object", so that an analysis can be performed without displaying any results. Thus the user can extract only the part of the result he is interested in. For example, if someone runs a series of 20 regressions and wants to compare different regression coefficients, R can only display the estimated coefficients: so the result can have a single line, while a classic software can open 20 windows with results. The explosive prism has the advantage that the point X (), which defines the monitored atmosphere, allows, by projection in the planes CH4 - 0 - t or O2 - 0 - t and then on the line t, to determine the time in which the monitored area reaches the prism. of the explosive, the period of time inside the explosive prism, as well as the moment when it comes out of the explosive prism

Chapter VIII entitled "Validation of PCMEX: case study on determining the critical time", represents an applicative quintessence of the research results undertaken during the doctoral internship, materializing the realization of a case study developed starting from real data on explosive gas and oxygen concentration. , at the level of an industrial premises and running the PCMEX program in order to establish the critical time. The results obtained provide a clear picture of the dynamics of the formation of explosive atmospheres, respectively a trajectory of the point that defines the monitored atmosphere in relation to the prism of explosiveness.

Chapter IX "Conclusions, personal contributions and future research directions" summarizes the main aspects of the study and conceptual analysis of the phenomena, methods, applications and results obtained. The presentation of their own contributions in the area of the topic studied in the doctoral thesis, highlighted the original theoretical and applied contributions, a much higher interest being given to the way in which they can be integrated and capitalized.

Starting from the highlighting of certain inherent limits of the research undertaken, the main research directions in which future efforts to reduce the risk of explosion should be directed have also been identified.

The degree of novelty of the doctoral thesis consists in the progressive, procedural approach, based on the latest knowledge, theoretical foundations, principles and hypotheses in the field of explosive atmospheres, in a form that allows understanding of two-dimensional and three-dimensional concepts, phenomena and analyzes. of the monitored industrial premises with risk of formation of explosive atmospheres. The method proposed in Chapter IV can be appreciated as having a novelty at national and international level, as well as the application materialized through the PCMEX software. The issue of the thesis was structured so that the scientific novelty and the practical value of the paper reside in several elements highlighted in the final chapter.

Degree of complexity: given the nature of the systems approached, the importance of the legislative complex and regulations, the multitude of information sources and the evolution of scientific research in the field, for conceptualizing the system and theoretical basis of methods used for three-dimensional analysis of potentially explosive environments interacting with industrial ventilation, knowledge from several fields of knowledge was required (industrial ventilation, mining aeration, aerodynamics, thermotechnics, mathematics, computer science, automation, etc.) which gives the doctoral thesis a pronounced inter-disciplinary and multi-disciplinary character.

4. PERSONAL CONTRIBUTIONS

In this doctoral thesis we have described original tools and solutions to support specialized personnel in the field of Occupational Safety and Health and other factors interested in fulfilling the obligations provided in the national legislation on explosion prevention.

It is considered that the theoretical part, the methodological part and the applied part that we developed during the doctoral internship summarized below, are original contributions in the field of research aimed at preventing and controlling potentially explosive atmospheres.

Personal contributions in this field include both theoretical and practical aspects.

From the point of view of bibliographic research and analysis of the current state of the topic:

We performed an analysis of the atmosphere of industrial premises with emphasis on the outer atmosphere and their inner atmosphere. Starting from the fact that ventilation is the primary protection against the formation of explosive or toxic atmospheres, we analyzed and deepened the industrial ventilation systems, respectively the general principles of their realization.

From the point of view of research objectives:

We have identified on the basis of the studies carried out, the difficulties and problems that lead to the risk of explosion in industrial premises and we have established accordingly the research objectives in this thesis.

We detected the specific objectives and we clearly established the directions of action for fulfilling the mediating objectives circumscribed to the theme of the paper based on carefully selected principles.

We have identified the possibility of developing a computer application, practicable for users without advanced knowledge in the computer field.

From the point of view of theoretical research:

For the analysis in 2D system of explosive atmospheres we analyzed the flammability and explosiveness of explosive substances.

We also deepened and analyzed the factors that influence the flammability and explosiveness of explosive substances.

For the analysis in 2 D system of the explosiveness phenomenon we analyzed and deepened the different explosiveness diagrams made in plan plane.

Regarding the analysis of explosive atmospheres, we detailed the explosive triangle, its meaning and how to use it.

As another novelty, in my scientific approach, I performed the analysis of the explosive atmosphere in 3D system. For this, we modified the Coward - Jones explosiveness diagram in a 2 D system and transformed it into an explosive prism, a 3 D system, by attaching the time coordinate axis.

We also explained how to make and use the explosive prism. In order to broaden the theoretical scope of the explosive atmosphere, we performed a descriptive geometric analysis of the explosive atmosphere in the 3 D system.

We geometrically analyzed the representation of the point, the line, and the plane in the 3 D system. In addition, we performed the geometric analytical treatment of the explosive atmosphere in the 3 D system.

In the first phase, we performed the geometric analytical treatment in planar system, after which we performed the geometric analytical treatment in spatial system. In order to mathematically determine the point in space that defines the atmosphere in an industrial precinct in relation to the explosive prism and the evolution of the point in the 3D system, we analyzed the characteristics of linear mathematical regression given that the trajectory of the point is linear.

Additionally, we developed a program for predicting critical explosion time in R language.

In terms of practical and applied contributions:

To illustrate the practical application of explosive diagrams we conducted a case study on the use of explosive diagrams.

In order to visualize the applicative nature of the explosive prism, we conducted a case study on determining the critical time.

In order to ensure the applicative character of the explosive prism, we analyzed and developed the mathematical apparatus necessary to determine the critical time in order to cover the point that defines the atmosphere in an industrial precinct, in the initial phase and when the explosive prism is reached.

In terms of disseminating the results:

During the doctoral internship and the previous documentations, I published as first author and co-author a number of 18 articles and scientific papers, 11 books and 4 patent applications as follows (details in annex 4):

- 3 articles published in indexed journals Clarivate Analytics Web of Science - WoS (ISI);
- 6 scientific papers published in the volumes of scientific events indexed Clarivate Analytics Web of Science-WoS (ISI) Proceedings;
- 3 scientific papers published in BDI indexed specialized journals;

• 9 Papers published in the volumes of international scientific events;
• 11 books;
• 4 patent applications.

5. LIMITATIONS OF THE STUDY AND FUTURE RESEARCH DIRECTIONS.

5.1 Limitations of the study

The ubiquity of uncertainty about the knowledge and reliability of the data used, the measures to be taken to limit the consequences or minimize the likelihood of materialization, the degree of subjectivity of assessments make it particularly difficult, according to experts, a precise formalization of explosive risk assessment procedures and decisions. applied. Moreover, we often find that the very level of expertise that exists is a space for experimentation.

The main limits of the research presented in the doctoral thesis aimed at three-dimensional analysis of potentially explosive environments that interact with industrial ventilation systems, can be summarized as follows:

Approaching for the first time at national level the modality of three-dimensional analysis on the dynamics of explosive atmospheres formation using the explosive prism correlated with the objective of developing a method applicable by designated workers in the field of Occupational Safety and Health, respectively internal services and prevention and protection services, required that the theoretical and applied study focus on a simplified system consisting of an explosive atmosphere containing a single flammable gas.

At the same time, the complexity of the field approached in the doctoral thesis led to the simplification of the way of analyzing the evolution of the explosive prism in relation to time.

5.2 Future research directions

As a result of the deepening of the knowledge in the research field targeted by the doctoral thesis and of the personal contributions brought, the following main research directions can be proposed towards which to direct the efforts aiming at the continuation of the researches and the completion / improvement of the proposed methods:

• Generalization of the use of the explosive prism as a means of controlling explosive atmospheres that may occur underground and on the surface.

• Analysis of the behavior as well as the trajectory of the point that defines the atmosphere of the workplace in mono-gas system, with different gases.

• Analysis of the behavior as well as the trajectory of the point that defines the workplace atmosphere in a multi-gas system.

• Improving occupational safety and health methods by setting pre-alarm, alarm and evacuation times in relation to critical time.

• Realization of a functional system that allows the real-time use of the explosive prism, respectively the determination of the critical time, etc.