MINISTRY OF EDUCATION AND RESEARCH
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DOCTORAL THESIS

- SUMMARY -

RESEARCH ON TESTING AND IMPLEMENTATION OPPORTUNITIES OF EXPLOSION PROTECTION FOR LARGE EQUIPMENT

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TOPIC IMPORTANCE AND NECESSITY
THESIS OBJECTIVES AND STRUCTURE

Explosion hazards can occur in all activities involving flammable substances and can include many of the raw materials, intermediate products, final products and waste from usual production processes. Virtually all branches are affected, because hazards caused by explosive atmospheres occur in a wide range of processes and operations.

Large technical equipment intended for use in spaces where combustible substances in form of gases, vapours, mists are present but not continuously, can be effectively protected against explosion by pressurized casings type of protection.

Operation of electrical equipment protected by pressurized casings type of protection, in spaces posing risk of explosive atmosphere, involves maintaining the regime of overpressures and dilutions required by the use of pressurized enclosures "p" type of protection [59].

Approaching a possible scenario of an explosion, simulation and calculated analysis of the dispersion of hazardous (toxic or explosive) substances released into the environment following a potential event are necessary steps to highlight virtual consequences.

The use of simulation software to understand certain phenomena and determine essential parameters is common in all industries, regardless of the nature of services provided. Computer simulations are used in design, production, transport and operation phases to optimize processes on the one hand, but also to discover, based on well-argued scenarios, valuable information regarding the effects of analysed physical processes.

The use of computer simulations offers clear advantages in understanding phenomena and analysing parameters influencing a complex process.

Such computational simulations can be useful for taking proactive and predictive measures to increase the level of safety and health at work for evaluated activities. In this sense, results of computer simulations can be integrated in the development of emergency response plans aimed at minimizing dangerous effects of toxic/explosive gas emissions on workers and surrounding atmosphere.

Such a software package used in the analysis of phenomena generated by explosions and their consequences is the CFD (Computational Fluid Dynamics) software.

The CFD simulation method is becoming more and more used for modelling systems that include fluid flow in many fields. CFD codes make it possible to numerically solve fluid transport, mass and energy balances in systems having very complicated geometry. The results obtained describe special patterns of flow and transfer, difficult to be obtained experimentally or by conventional modelling methods.

The use of CFD numerical analysis environments in researching the conformity of equipment protected by pressurised casings, allows the determination of important parameters such as: distribution of pressure and velocity field inside the casing; determination of supplying current’s flow lines and many other parameters.

This allows the evaluation of studied equipment’s performance, without considerable expenses, with minimal effort and maximum efficiency.

In industrial environments, where flammable and/or combustible substances are processed, transported or stored, the presence of an explosive atmosphere is likely, thus the danger of explosion is present.

When no method can describe a dangerous phenomenon, risk assessment and optimization of safety measures become a difficult task.

Through computer analytics, retrospective knowledge can be successfully turned into forward-looking actions.

Thesis objectives

Research carried out in order to develop the current paper aimed at several essential objectives:

- Highlighting the regulations for the use of technical equipment in explosive atmospheres;
- Study of safety requirements regarding explosion protection for large pressurized equipment operating in potentially explosive environments;
- Analysis of requirements for testing large equipment protected by pressurized casing;
- Simulation of dilution processes in pressurized enclosures by using CFD (Computational Fluid Dynamics) techniques;
- Testing in real conditions specific to the type of pressurized casing protection.

Research activities

In order to achieve the targeted objectives, the following research activities were carried out:

- Description of legal aspects regarding the use of technical equipment in the context of explosion risk;
- Analysis of explosion’s initiation sources, mechanisms of combustion processes, as well as explosion protection of technical equipment;
- Description of protection types for technical equipment used in potentially explosive atmospheres but also of the principles underlying explosion protection;
- Description of safety requirements for large pressurized equipment;
- Highlighting specific type tests for pressurized equipment;
- Analysing the algorithm for pressurization operation and creating the logigram;
- Completing the test procedure’s revised edition, detailing the stages for identification of concentration sampling points through CFD (Computational Fluid Dynamics) simulation;
- Description of the simulation model for dilution processes specific to filling and purging tests for pressurized enclosures;
- Synthetising the results of the simulation of dilution processes specific to filling and purging tests for pressurized enclosures;

- Describing the computer system for running the simulation and the time required for simulation;
- Description of the test stand and tested pressurized equipment;
- Analysis of test results.

Thesis structure

- The thesis has a total of 193 pages, structured in 4 chapters, Introduction, Conclusions and personal contributions, References and 4 Appendixes.
- The first chapter, entitled "**Requirements for technical equipment intended for explosion hazard spaces**", is a summary of the fundamental concepts of explosion prevention and explosion protection of technical equipment, as well as of regulations in force regarding equipment, systems and protection devices intended for use in potentially explosive atmospheres.
- The principle of the equipment's explosion protection type, as well as the requirements for equipment selection, in accordance with the category and level of protection were also highlighted in this chapter.
- The second chapter, "**Considerations on studying safety requirements for large pressurized equipment**", deals with the principle of the "p" type of protection and with the constructive requirements for pressurized casings and for large pressurized equipment. At the same time, aspects regarding testing large equipment protected by a pressurized casing were also described.
- The dynamics of states specific to pressurization operation were presented.
- Completing the project of the test procedure's revised edition "Test procedure for large pressurized casings", detailing the stages for identification of gas sampling points by CFD (Computational Fluid Dynamics) simulation.
- The third chapter, "**Simulation of dilution processes in pressurized enclosures**", presents the test stages according to protection type requirements and standards in force.
- By using the CFD simulation technique, the following processes were achieved: filling, purging and highlighting the critical points (points where the concentration of test gas lastly reaches the value prescribed by test procedures).
- Simulation stages for equipment protected by pressurized enclosures and for rooms protected by pressurization have been established.
- Boundary conditions and simulation parameters have been established.
- The fourth chapter, "**Tests in real conditions specific to the type of protection**", summarizes and presents test results.
- Composition of the test stand and the tested sample were described.
- A classification model of measurement points, based on purging time metric, was used, which highlighted the critical points for purging after filling with carbon dioxide and respectively after filling with helium.
- A model for indirect determination of test gas concentration by using the oxygen

concentration value was presented and used.

- The variation model of oxygen concentration's indication, as a result of environmental factors, pressure and temperature influence, was presented.
- An alternative to measurement by means of oxygen concentration, based on the use of test gases containing an additive was demonstrated. On this occasion, the following were analysed: the distribution of decimal logarithm values for the range of values and the distribution of the decimal logarithm values for the value resolution.
- In the last chapter, "**Conclusions and personal contributions**", among other, possible future research directions were presented.

CHAPTER 1
REQUIREMENTS FOR TECHNICAL EQUIPMENT INTENDED FOR EXPLOSION HAZARD SPACES

Protective systems and equipment may "be placed on the market and/or put into operation only if they do not endanger health and safety of individuals or, as the case may be, domestic animals or goods, when installed, maintained and used in accordance with the intended purpose" [33].

Explosive atmospheres, characteristics, built-up and classification

In the operating conditions of installations and equipment that use flammable gases, the possibility of flammable cloud(s) (mixtures) built-up, in the form of a fine dispersion of gases, cannot be a priori excluded.

Explosive clouds, following direct contact with ignition sources, generate explosions. These explosions, which occur in fractions of a second, release a large amount of heat and, at the same time, generate flames that cause fires, high temperatures, vertiginous increases in pressure, shock fronts, etc.

Explosive atmospheres are mixtures of flammable substances and air, in the form of fine dispersions of gases under normal atmospheric conditions, in which, after ignition, combustion propagates violently (explosively) from initiation source to the entire mixture volume.

In initiation reactions, free radicals are formed generating primary chains. If the series of elementary reactions leads to the occurrence of more free radicals than those initially present, new chains are formed, the chain branches and the reaction accelerates.

The explosion is an extremely fast exothermic reaction, caused by chain branching. The branching chain reaction can be of two types: long chains with scattered branching and chains with continuous branching, branching occurring at each cycle.

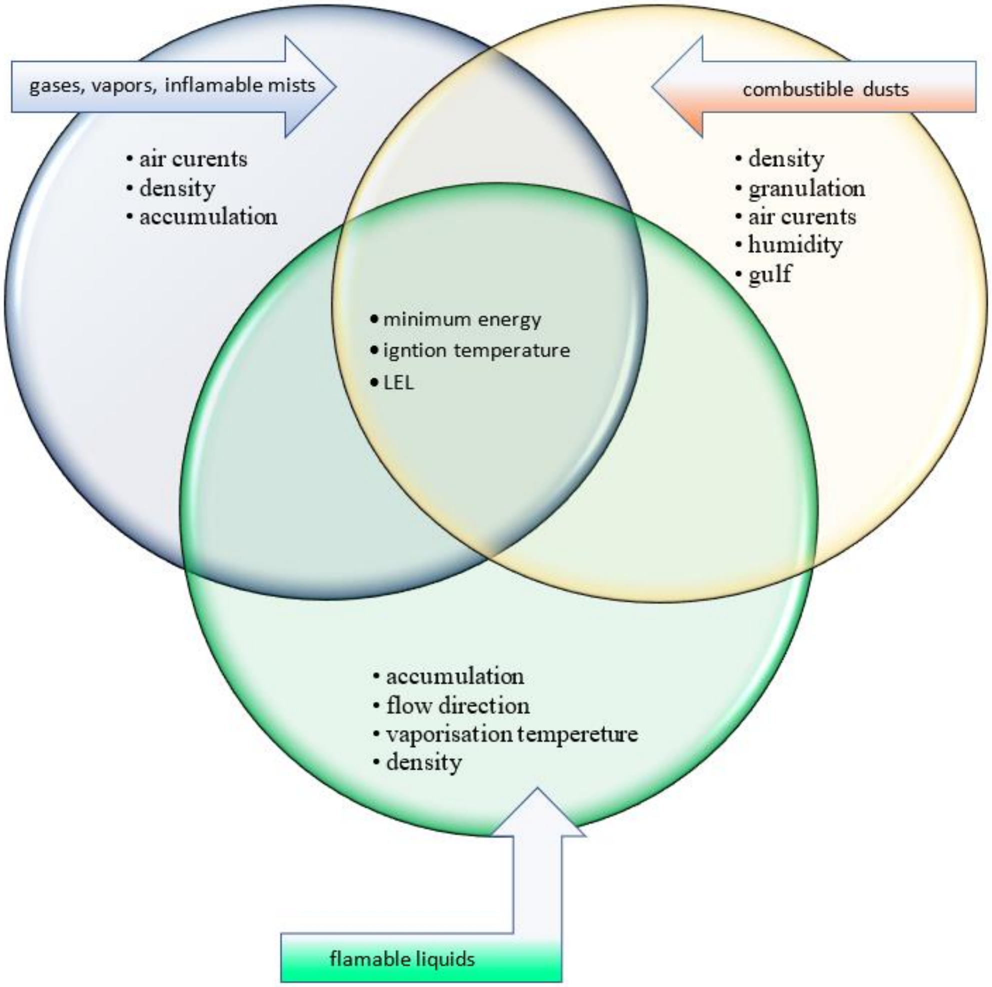

Figure ***Error! Use the Home tab to apply Titlu 1 to the text that you want to appear here.****.1 Factors influencing ignition phenomena*

Explosion protection [15] cumulates the specific, especially constructive, measures, which applied to electrical or non-electrical equipment make them eligible for use in atmospheres where flammable substances may occur [64].

The type of protection is based on providing overpressure with a protective gas inside an enclosure. Depending on functional characteristics of protected equipment, it is possible to opt for continuous circulation of the protective gas or for losses compensation. Protection levels provided by this type of protection are ***pxb, pyb*** and ***pzc***. This type of protection is generally applicable but not limited to large equipment, for gas, vapor and flammable dust atmospheres.

Explosion protection levels

Explosion protection aims at preventing the ignition of explosive atmospheres, i.e., preventing potential sources of ignition and limiting the occurrence of explosive atmospheres through protective measures (isolation, suppression and constructive limitation).

Protective measures aim at reducing the probability that (electrical and non-electrical) technical equipment will become a source of ignition, to an acceptable level.

If electrical equipment is to be installed in areas where dangerous concentrations and quantities of flammable gases, vapours, mists or dust may be present in the atmosphere, protective measures must be applied to reduce the likelihood of an explosion caused by arcing, sparks or hot surfaces occurred either during normal operation or under specific fault conditions.

Pressurization protection is justified only if it is coordinated with extraction of heat resulting from energy losses of installed electrical equipment. An enclosure that needs explosion protection is purged with inert gas. Thus, an overpressure is created, that is maintained during operation. This overpressure prevents environmental explosive gases and vapours from entering the enclosure (pressurization with loss compensation).

CHAPTER 2

CONSIDERATIONS ON STUDYING SAFETY REQUIREMENTS FOR LARGE PRESSURIZED EQUIPMENT

The constructive solution of this ***p*** type of protection, consists in separating ignition sources from potentially explosive atmosphere by maintaining a higher pressure, inside the casing, by means of a protective gas (inert gas or air).

This type of protection is divided into three protection levels (pxb, pyb and pzc) that correspond to the EPL (Equipment Protection Level) appropriate to desired area equivalent category (Mb, Gb or Gc), but also if inside the casing a release is present or not, on one hand, and whether or not the inside equipment can initiate ignition of the Ex classified atmosphere.

If in normal operation pressures are likely to occur, potentially causing a deformation of pipes, casings, if any, or connecting parts, equipment must be provided with a suitable safety device to limit the maximum internal overpressure, to a value lower than that which could negatively affect the type of protection. If the manufacturer does not provide this safety device, the equipment must be marked with an "X" and the description documentation must contain all necessary information required by the user to ensure compliance with requirements of [59].

Openings and partitions should be located so that they provide effective ventilation.

Areas of poor dilution can be eliminated by proper location of the protective gas inlet and outlet and by considering the effect of partitions.

For gases or vapours heavier than air, the protective gas inlet should be located near the top of the pressurized enclosure and the outlet, near the enclosure bottom.

For lighter-than-air gases or vapours, the protective gas inlet should be located near the bottom of the pressurized enclosure, with the outlet near the enclosure top.

Placing the inlet and outlet ports on opposite sides of the casing facilitates cross-ventilation.

All safety devices (except static pressurization), used for minimizing the risk of ignition and explosion of pressurized electrical equipment must have protection types appropriate for their intended use or be installed in areas not classified as Ex.

Security devices must be provided by device manufacturer or user. If the manufacturer does not provide this safety device, the equipment must be marked with an "X" and the description documentation must contain all necessary information required by the user to ensure compliance with safety requirements.

All safety devices used to prevent electrical equipment protected by static pressurization from producing an explosion, shall not, themselves, be able of producing an explosion and, if the safety device is electrically actuated, it shall be protected by one of the protection types accepted by [64] or must be installed outside the hazardous area.

The protective gas must be inert. Oxygen concentration, after filling with inert gas, must be less than 1% by volume. No internal sources of release are allowed.

Study of test requirements for pressurized equipment

Type tests for pressurized equipment

a) Purging test for pressurized casings without any internal release source and filling test for static pressurization.

Pressurized casing having air as protective gas

The pressurized casing is prepared for the test as described in [3]. The pressurized casing is filled with gas until the concentration at any inside point is equal to or higher than 70%. After carrying out the filling operations, protective gas insertion is stopped and air is inserted, at the minimum flow indicated by the manufacturer to carry out the purging. The time required until there are no more sampling points where test gas concentration is above the specified concentration, i.e.:

- a value equivalent to 25% of the worst value at the lower flammability limit (LFL - Low Flammable Limit), when tests for specific flammable gases are applied;
- a value equivalent to 25% of the LFL, when a single specific flammable gas is contained;
- 1 % for the helium test and 0.25 % for the argon or carbon dioxide test, when all flammable gases are contained. Purge time should be measured and recorded.

If a second test is required, the pressurized enclosure shall be filled with a second test gas, representing an opposite value of the density range, to a concentration of at least 70 % in any point and purge time for the second test shall also be measured. The minimum purge time, specified by manufacturer, shall not be less than the measured purge time, or higher than the two purge times, measured when two tests are performed.

Tests represent a complementary stage to evaluation in the certification process of equipment protected by pressurized casing/chamber.

The purpose of tests is to demonstrate practical compliance with performance requirements included in the specific standard.

Depending on the pressurization method chosen for the equipment, certain type tests are applicable.

Large pressurized equipment is characterized by a larger volume and a high number of topological peculiarities.

This fact, through the traditional approach, requires a higher number of test gas concentration monitoring points for each test stage: filling and purging.

The higher number of points leads to a proportionally increased time of the measurement cycle. And as the measurement cycle time increases, the measurement accuracy of purge time decreases.

Based on these deficiencies, a procedure was developed for testing large pressurized casings.

Within this procedure, computer simulation methods are used for the purpose of determining the critical points.

These critical points are those regions within the pressurized equipment that reach the pre-set concentration lastly.

Afterwards, a test in real premises is performed, which involves monitoring concentrations in critical points. In this test, the points where the test gas concentration will be monitored are precisely the critical points previously determined by the simulation processes.

Without the use of simulation methods for the filling and purging processes, testing pressurized equipment in real premises becomes very cumbersome, because of the many monitoring points required.

Using simulation methods reduces the subjectivity in setting concentration monitoring points, even if it is based on practical in situ experience.

The oxygen analyser is commonly used for (indirect) monitoring of test gas concentrations.

The process of indirectly determining test gas concentration based on indications of the oxygen analyser, involves a mathematical model that increases measurement uncertainty. Thus, the method of determining uncertainty for indirectly measured concentrations was also introduced in the procedure.

An alternative to indirect determination of test gas concentrations has also been introduced, for information purposes.

The test procedure of large pressurized casings is presented in Appendix 1.

CHAPTER 3

SIMULATION OF DILUTION PROCESSES IN PRESSURIZED ENCLOSURES

Computational fluid mechanics (MFC), or computational fluid dynamics, is a branch of fluid mechanics that relies on algorithms, numerical methods and computational systems to model and solve fluid flow problems.

Test simulation follows the same steps of performing type tests for equipment protected by pressurized casings and for chambers protected by pressurization.

Simulation model of dilution processes specific to filling and purging tests for pressurized enclosures

Considering these aspects, the usefulness of the process of simulating the filling and purging test using computerized techniques is highlighted.

By using the filling and purging process simulation, through the CFD technique, it is possible to highlight the critical points. At these critical points, the concentration of test gas reaches the value prescribed by test procedure lastly.

Highlighting these critical points brings along the advantage of reducing the number of measurement points to a minimum. This constitutes the premise of accurately determining the filling time and, at the same time, the possibility of accurately determining the purging time.

Taking into account the complementarity of test gases densities, carbon dioxide and helium respectively argon and helium, it can be assessed that the critical point, when filling for the test with the denser gas, is the critical point for the purge test with the less dense gas and vice versa.

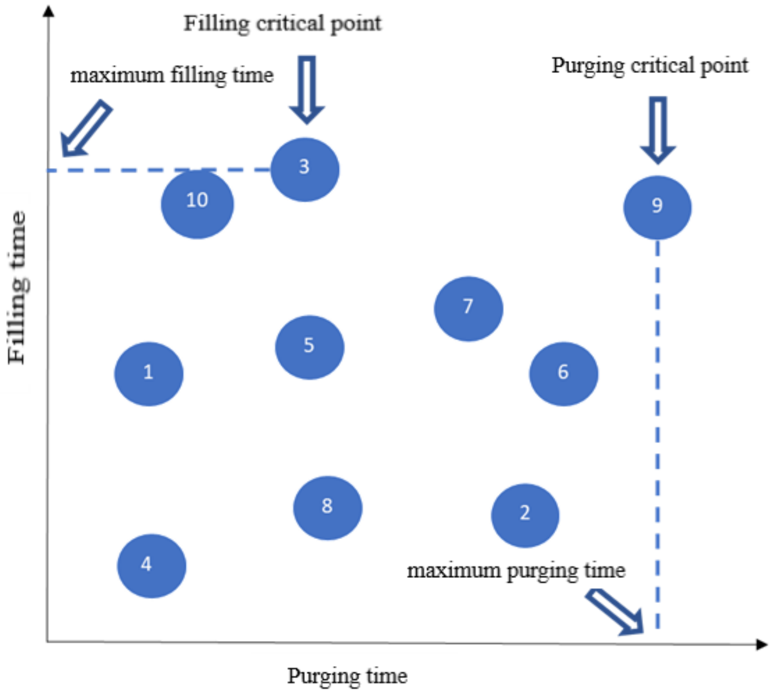

Figure ***Error! Use the Home tab to apply Titlu 1 to the text that you want to appear here.****.2 Critical points*

CHAPTER 4

TESTS IN REAL CONDITIONS SPECIFIC TO THE TYPE OF PROTECTION

Test stand configuration allows the following tests to be performed:

- Maximum overpressure test;
- Loss testing;
- Purging test for pressurized casings without any internal release source and the filling test for static pressurization;
- Purging and dilution tests for a pressurized casing with an internal release source;
- Checking the minimum overpressure;
- Overpressure test for a limited release container system.

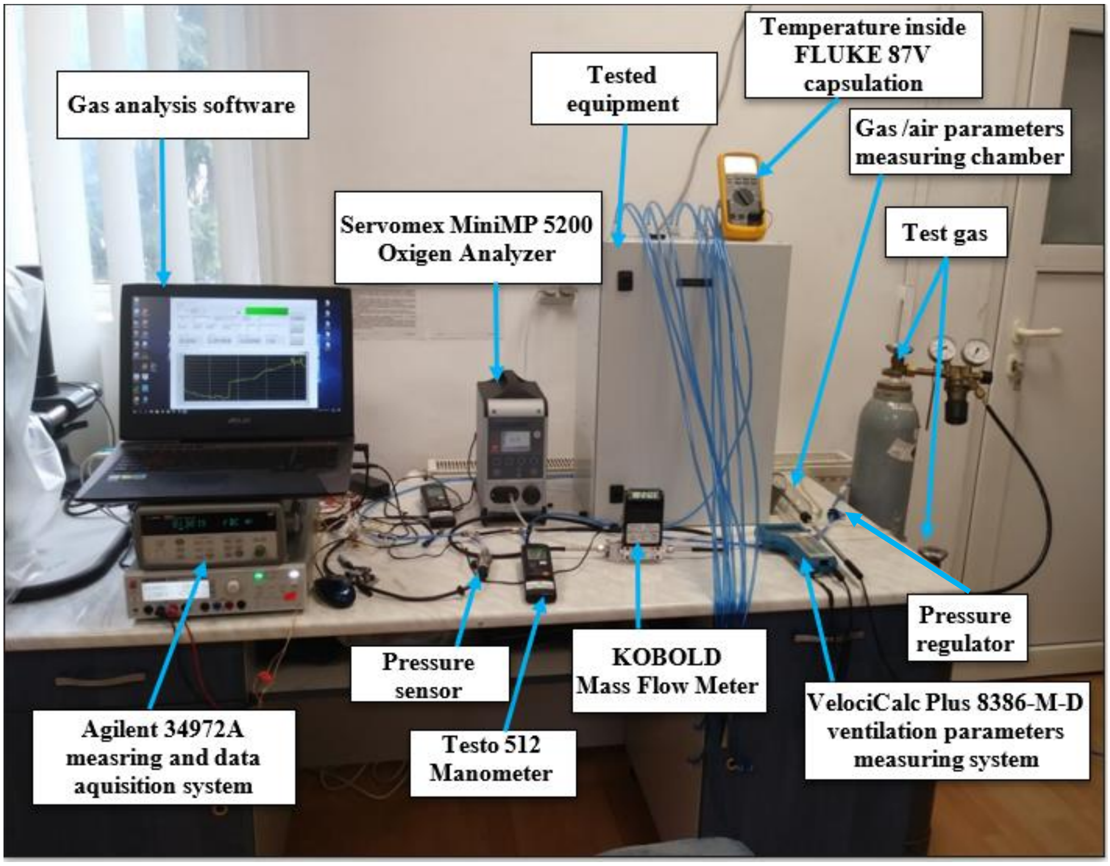

Figure 4.1 Test stand configuration

Gas concentration is measured using an oxygen analyser (Servomex, Type MiniMP 5200 for O_2), a pressure sensor (SIEMENS, Type 7MF 1565-3BA10 4AA1), a flow meter (KOBOLD, MAS-3008C2) and a manometer (Testo 512, 0-2000 mbar). A LabView software, prepared for this purpose, was used for data acquisition and measurement.

The critical point in the tested equipment was selected using a value corresponding to the metric distance to the origin, for each point considered in a coordinate system, having the three purging times as axis values.

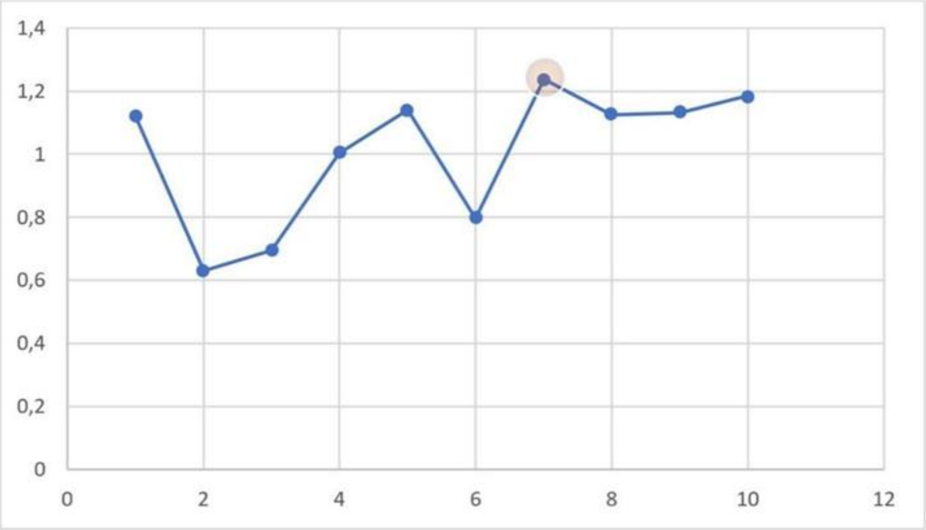

Figure 4.16 Metric graph for CO2 as a function of the analysed point index

The theoretical model resulting from the concentration balance of gaseous substances present in the equipment's casing, during the purging test, was used for determining the concentration of test gases.

CHAPTER 5
CONCLUSIONS AND PERSONAL CONTRIBUTIONS

Conclusions

Detailed specifications in terms of objectives regarding the practical fulfilment of essential requirements should be used as a guide for users of equipment and protective systems and components, included in the reference standards.

Flammable substances' state of aggregation induces different particularities of generated explosive atmospheres.

Due to various spectrum of constructive and functional requirements, protection types show different affinities for equipment's functional roles.

Protection types have various degrees of suitability for explosive atmospheres. Thus, some can only be used in atmospheres of gases, vapours and mists, others only for explosive atmospheres made of dust, lint and fibres and others for both types of atmospheres.

Pressurized casing/chamber explosion protection is also compatible with flammable dust atmospheres.

Large size equipment implies the use of pressurized casing/chamber explosion protection.

Performance of explosion protection, highlighted by the level of protection, respectively the ATEX category, provided by the pressurized casing is comparable to that provided by other types of protection.

The disadvantage of energy consumption to ensure explosion protection is compensated by the benefit of explosion protection for equipment of large dimensions or having a complex structure, for which another type of explosion protection cannot be applied.

The protective gas, in addition to its function of ensuring pressurization, can also be used for other functional purposes, such as taking over the excess heat (cooling) generated by the protected equipment, during operation.

Inter-laboratory competency tests showed that performance of tests specific to pressurized casing protection, provided within the laboratory, is at the level of European and international practice.

The use of critical points brings along the advantage of minimizing the number of measurement points. This fact constitutes the premise for precise determination of purging time.

With the development of CFD simulation techniques, came along the advantages that they offer, namely reduction of time and costs related to new projects, the possibility of studying systems in dangerous conditions and beyond normal performance limits, the possibility of studying systems in which controlled experiments are difficult or impossible to be performed, as well as a practically unlimited level of results' details.

CFD codes are structured around numerical algorithms that can address fluid flow problems. These codes contain three main elements: the pre-processor, the solver and the post-processor.

Some of the most important numerical solution methods are: the finite difference method, the finite element method and the finite volume method.

Performing a computer simulation requires the following: some input data of a mathematical model, a numerical solution, the selection of variables and their monitoring points and the post-processing of results.

The mathematical model is made up of: the boundary conditions and the governing equations of fluid flow. The mathematical model starts from the constructive characteristics of geometry, and the definition of boundaries is important in CFD applications, because these surfaces are associated with the input data.

The geometry, respectively the analysed domain, is divided into finite elements or finite volumes, creating a discretization network.

The governing equations are based on the laws of mass, momentum and energy conservation, but are applied differently for the finite element method and the finite volume method.

Equations obtained for a fixed finite volume in space, in integral or partial differential form, are called the conservation form of governing equations.

Equations obtained from the finite volume moving with the fluid, in integral or partial differential form, are called the non-conservation form of governing equations.

If the finite element method solves the algebraic equations for the discretization network's nodes, the finite volume method calculates these algebraic equations for the centre points of cells, this last method being also adopted by the Fluent application.

It is necessary to transpose the governing equations into a system of algebraic equations (linearization) that can be solved for each node of the discretization grid (in case of finite elements).

Minimizing discretization errors can be solved by refining the discretization network, thus increasing the number of nodes and implicitly, equations of the algebraic system.

The output data of a computer simulation is post-processed for an efficient exploitation of results and their visualization.

The last stage consists in checking and validating the final results, by comparison with those obtained from physical experiments.

The use of the CFD technique for simulating the filling and purging process has proven to be effective for highlighting the critical points (where the concentration of the test gas reaches the value prescribed by the test procedure, lastly).

Tests of pressurized equipment show potential for improvement, modernization.

Using the oxygen concentration value for indirect determination of test gases concentration (He, Ar, CO_2) remains a reference method.

The resolution of test gas concentration value, using oxygen measurement, shall not fall below approximately 0,05 % v/v.

The use of test gases with additives has the potential to be at least as effective as the indirect method, based on oxygen measurement.

In case of repeated tests, the model of metric distance of purging times is an effective means of classifying measurement points, for the purpose of determining critical points.

Calculation of measurement uncertainty, through the uncertainty budget, emphasized that the environmental parameters: relative humidity, ambient temperature, atmospheric pressure do not contribute to the concentration measurement uncertainty, for the analysed case.

Personal contributions

Presenting regulations applicable to equipment intended for use in locations where flammable substances may be present.

Analysis of explosions’ initiation sources and of combustion processes’ mechanisms, as well as of explosion protection of technical equipment.

Highlighting the basic principles of protection types.

Highlighting the principle of protection type p and the constructive requirements for pressurized casings and for large pressurized equipment.

Presentation of temperature limits for protection type p and security requirements for large pressurized equipment.

Highlighting specific type tests for pressurized equipment.

Presentation of the dynamics of pressurization operating states through the logigram and algorithm for pressurization operation.

Completing the project of the test procedure’s revised edition “Test procedure for large pressurized casings", detailing the stages for identification of gas sampling points by CFD (Computational Fluid Dynamics) simulation.

Introducing the concept of critical point, as the point inside the geometry that reaches the concentration pre-set value, lastly. The use of these critical points, in the test stage in real premises, contributes to increasing the accuracy of determining purging times but also reducing the effort implied by the test process.

Highlighting the importance of choosing the mathematical model for a successful solution of fluid flow cases and the contribution of each component of the model, respectively the boundary conditions and the governing equations to the final results of simulations.

Analysis of the linearization process of partial differential equations, by transposing them into algebraic equations, showing how flow characteristics are obtained in nodes of the elements, in case of finite elements, respectively in the centres of cells, in case of finite volumes.

Showcase of the possibility of reducing errors, to obtain higher accuracy results and the need for a post-processing for a complete visualization of the problem and its results, as well as of the stages of verifying the correctness of results.

Presentation of test stages according to protection type requirements and standards in force.

Establishing simulation stages for equipment protected by pressurized enclosures and for rooms protected by pressurization.

Establishing boundary conditions and simulation parameters.

Highlighting the effectiveness of the simulation process for the purpose of identifying critical points in pressurized casings.

Synthesizing and presenting the results of tests in real conditions.

Completing a classification model of measurement points based on purging time metric.

Implementing the classification model created and highlighting the critical points for the case of purging after filling with carbon dioxide and respectively after filling with helium.

Showcase of the model of indirect determination of test gas concentration, using the oxygen concentration value.

Showcase of the variation model of oxygen concentration's indication, as a result of the influence of environmental factors, pressure and temperature.

Presenting an alternative to measurement by means of oxygen concentration, based on the use of test gases containing an additive. For this situation, the possible range of values and the resolution value were analysed. The distribution of decimal logarithm values for the range of values and the distribution of the decimal logarithm values for the value resolution were analysed.

Completing the project of the revised test procedure, "Test procedure for large pressurized casings", in which the stages for identification of gas sampling points by CFD (Computational Fluid Dynamics) simulation and the possibility of using additive test gases are detailed.

The contribution of the following environmental parameters was analysed: relative humidity, ambient temperature, atmospheric pressure and it was found that they do not contribute to the concentration measurement uncertainty, for the analysed case.

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