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DOCTORAL THESIS

RESEARCH ON THE FORMATION OF POLLUTING ATMOSPHERE IN RELATION TO VENTILATION SYSTEMS

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CONTENTS

1. KEY WORDS

Next, for a better understanding of the following exposition, it is necessary to enumerate some notions specific to the field addressed: industrial ventilation systems, dispersion gradient, toxic/explosive/asphyxiating atmosphere, experiments, gas dispersion, CFD modeling.

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

At the European and national level, the proactive activity regarding work accidents and occupational diseases occupies an important place in terms of the concerns of decision-makers.

Proactive activity is based on risk assessment at the level of the economic unit.

Risk assessment is based on two elements: frequency and severity.

The obligation to assess workplace risks is provided for in European legislation - Council Directive no. 89/391/EEC and aims to dimension and optimize worker protection.

The identification of risks as well as their elimination is based on the support of all participants in the work process.

The responsibility for ensuring OSH conditions rests with the heads of economic units, according to Law no. 319/2006.

Law no. 319/2006 provides that workplaces and equipment used must be safely built, used and maintained.

Economic activities involve the presence of risks that may result in economic losses, equipment failures, minor or major accidents and environmental pollution.

By assessing risks, economic agents have the necessary tools to improve working conditions.

Also, the risk assessment allows the leaders of the economic agents to act in order to reduce the level of risk from high to acceptable.

The risks generated by the occurrence of gaseous atmospheres with combustible, toxic or asphyxiating properties are very important because they can create the conditions for the occurrence of explosion, toxic or asphyxiating phenomena.

Avoiding or eliminating the risks of explosive, asphyxiating or toxic atmospheres requires the application of an efficient ventilation system at the level of industrial enclosure, a ventilation system that represents the primary protection used against the formation of these types of atmospheres.

The previously presented elements highlight the need for scientific research on the analysis of explosive, toxic, asphyxiating atmospheres, the dynamics of their formation, as well as the ventilation capacity of closed or semi-closed enclosure in order to identify the optimal evacuation routes for workers in case of imminent danger.

The doctoral thesis highlights ideas and results applicable by personnel specialized in the field of OSH at the level of economic units that have responsibilities regarding the proper functioning of technological processes that are carried out in closed or semi-closed enclosure.

The objectives of the thesis

The general objective

The main objective of the thesis is the establishment of the formation of polluting atmospheres in relation to ventilation systems for the purpose of dimensioning proactive measures, respectively for ensuring OSH.

The identification of the specific elements of explosive, toxic and asphyxiating atmospheres is the desired result of the research activity. At the same time, the intended result involves the manner and dynamics of the formation of explosive, toxic, asphyxiating atmospheres, as well as the establishment of the mathematical tools necessary to establish the dynamics of the formation of explosive, toxic, asphyxiating atmospheres. At the same time, the role of the ventilation systems is taken into account, respectively their ventilation capacity in the conditions where the risk of explosive, toxic, asphyxiating atmospheres is present.

Specific objectives

Identification of terotechnological principles usable in the field of industrial ventilation.

Establishing methods and techniques for determining air condition parameters, analyzing the microclimate of industrial enclosure.

Identification of local ventilation installations used within closed or semi-closed industrial enclosure.

Analysis of flow laws through the lens of fluid dynamics in order to establish the mathematical equations for establishing the movement of real fluids.

Thorough evaluation of gas dispersion simulation capabilities using specialized simulation programs.

Carrying out experiments in the laboratory to identify the dynamics of the formation of explosive, toxic or asphyxiating atmospheres and their interaction with industrial ventilation systems.

Realization of CFD modeling regarding the dispersion of methane, carbon monoxide and carbon dioxide in a closed enclosure.

3. THESIS STRUCTURE

The doctoral thesis presents in the beginning a part intended to present the importance, purpose and objectives of the research. The basic body is structured in nine chapters through which the methodology and the results of the scientific research are presented within 134 pages, respectively an annex.

The chapters are sized and have appropriate graphics and the doctoral thesis includes 102 figures, 15 tables and 134 bibliographic references cited in the thesis. The results of the experimentation activity regarding the experiments carried out at the level of a closed enclosure regarding the dynamics of the formation of asphyxiating, toxic and explosive atmospheres, the ventilation capacity of the enclosures, as well as the simulation using the CFD technique of the formation of explosive, toxic and asphyxiating atmospheres in a closed enclosure and especially the activity of analysis, synthesis and conception necessary to achieve the established objectives are systematically presented in the work. The scientific approach is carried out in a unitary manner and is based on the scientific analysis of fluid dynamics, laboratory experiments and CFD modeling, and ends with the establishment of the dynamics of the formation of explosive, toxic, asphyxiating atmospheres in relation to industrial ventilation systems.

In ***chapter I***, titled **„The atmosphere of the enclosures**”, the ventilation equipment that has the role of ensuring the optimal microclimate at the level of industrial enclosure is presented. The ventilation system adopted must take into account the technological process, the density of the sources and the way of propagation of harmfulness, respectively the intensity of harmful emissions. In order to maintain the atmospheres of the industrial enclosure at an appropriate level for carrying out the necessary activities by the workers, they assume the control of the factors that ensure the quality of the environment, within acceptable limits at the level of the closed enclosure (indoor air temperature, relative humidity, speed of movement, average radiation temperature).

Chapter II, which bears the title **„Local ventilation installations and flow calculation method”** presents the local capture systems. The local ventilation installations used depend on the nature of the harmful agents, on the specifications of the equipment, on the type of technological processes, on the characteristics of the enclosure and can be made by devices under depression, overpressure or depression and overpressure.

Local installations through depression control the dispersion of harmful substances and ensure the development of technological processes in optimal conditions. The harmfulness capture equipment can be: open, semi-closed or closed.

Auxiliary ventilation installations by overpressure represent a method of ventilation of the workplace, applied to technological processes with high temperatures, workplaces with emissions of harmful substances.

Auxiliary ventilation installations by overpressure and depression are used within industrial enclosure of extended widths, tunnels for painting, drying, vats for electrolysis and for all sources of harmful, gaseous or powdery substances that have a tendency to propagate at the level of the enclosure using auxiliary ventilation systems.

The substantial section on the methodology for establishing the air flow rate is dedicated to determining the air flow rate in ventilation installations made of tube columns and installations for general and local ventilation.

To stabilize the air flow achieved by ventilation installations, the speed of the air current is measured, the speeds measured at the same measuring point are averaged and the necessary relationships are applied. For large sections we have to take into account the section coefficient.

The chapter ends with a synthesis of the relationships that determine the required air flow.

In ***chapter III***, **„Explosive, toxic and asphyxiating gases”**, the composition of the atmospheric air is presented in a succinct manner. The composition of the atmospheric air varies depending on the place, altitude, time of year as well as other factors. The main constituents of air are: nitrogen, oxygen, argon and carbon dioxide. Gases in the atmosphere have other constituents in the mix as follows: dust, pollen, bacteria, viruses, mold spores, smoke particles and residues from industrial activities such as SO_2, H_2 and S. Volcanic activity also brings various gases and dust in the atmosphere.

Atmospheric air during the ventilation of industrial enclosure changes both physically and chemically. Thus, the constituents that can appear in the composition of the air discharged from industrial enclosure can be grouped into four categories: toxic, suffocating, explosive and radioactive.

Most of the disasters and accidents that have occurred and continue to occur in industrial enclosure are due to the poisonous, suffocating and explosive effects of these gases.

Chapter IV **„Fluid dynamics”.** Fluid dynamics studies the movement of fluids and their interaction with rigid bodies, taking into account the forces involved and the energy transformations produced during the movement. In fluid dynamics, the general principles of general mechanics, laws of variation and laws of conservation are applied. Fluid dynamics approaches the movement of fluids considering the intervening forces and the energy transformations produced during the movement. Fluid kinematics studies the movement of fluids without taking into account the forces that intervene and change the state of motion.

For the study of ideal fluid dynamics, we analyzed Euler's, Helmholtz's, and Gromeka-Lamb's equations, the impulse theorem and the kinetic moment theorem in the case of permanent fluid movement. The two theorems for a material point are defined as follows: the time variation of the impulse is the sum of the external forces, respectively the time derivative of the kinetic moment and is the resultant moment of the external forces.

The flow of real fluids can occur in two different regimes of movement established in relation to their physical structure: the laminar regime and the turbulent regime. The existence of these different regimes of motion was pointed out by the English physicist Reynolds.

It has been established experimentally and theoretically that in laminar motion, the liquid encounters a resistance proportional to the average speed, and in the turbulent regime, at high Reynolds numbers, the resistance is proportional to the square of the speed. The phenomenon is general for all fluids, therefore also for gases.

For the study of the movement of real fluids, the Cauchy, Navier-Stokes, Cauchy-Helmholtz equations were analyzed and it was determined that the Navier-Stokes equations best represent the laminar flow process of real fluids.

In ***chapter V*****, „Gases dispersion simulation”** programs or packages of specialized programs used for the simulation of gas dispersion are presented. An integrated tool is based on reproducing experimental tests by using simplified algebraic equations. In addition, semi-physical equations are added for the prediction of scenarios that are slightly different from the experimental tests.

The integrated tools are robust and extremely fast to use (simulation time is in the order of seconds). Built-in tools cannot include physical obstacle or terrain effects (there are parameters that can be used to mimic an average effect of buildings or trees).

The most common simulation programs are: PHAST, TRACE, FLACS and KFX.

The accidental presence of high concentrations of methane gas can occur both in industrial enclosure, underground or in living spaces.

In this chapter we have presented different simulations using the CFD technique carried out over the years for the leakage and diffusion of methane in an enclosure, the dispersion of carbon dioxide in a semi-closed enclosure and on complex terrains, respectively the dispersion of carbon monoxide in the atmosphere when a rocket is launched.

Chapter VI**, „Location description”.** In order to cover the needs for experimentation of ventilation systems usable in closed or semi-closed industrial enclosure, respectively for the study of the dynamics of the formation of explosive atmospheres, INCD INSEMEX Petroșani has allocated a dedicated space in this regard. The space is represented by a building intended for the experimentation of industrial ventilation systems.

Ensuring OSH conditions at the place of experimentation requires the use of a complex ventilation system intended for ventilating and ventilating enclosure with the risk of potentially explosive/toxic/asphyxiating atmospheres.

The power supply and automation panel includes protection equipment and frequency converters for controlling the electric power supply to the fans, including the drive fan for the complex ventilation system with variable structure.

The command and control system is provided by an automation system that allows the command and control of the equipment, both for the force equipment and for the flow variators.

Chapter VII**, „Experiments in the laboratory”.** In order to study the dynamics of the formation of explosive, toxic or asphyxiating atmospheres, the following experiments were carried out in the experimental laboratory:

- Experiments using methane, CH_4;
- Experiments using carbon monoxide, CO;
- Experiments using carbon dioxide, CO_2.

The experiments were carried out in a room with dimensions of 5.8x5.62 m, height 3.65 meters, therefore the total volume of the experiment enclosure is 118.9754 m^3. Considering the fact that other experimental systems are located in the enclosure, the free volume of the enclosure is considered to be 116 m^3.

This experiment system is composed of a data acquisition system, a monitoring system consisting of 6 pulleys on which 6 ALTAIR type multigas detectors are attached, which can detect concentrations of O_2, CO_2, CO and CH_4, and a monitoring system. The pulley system can configure a variable spatial layout in order to establish the speed of gas dispersion as well as the dynamics of the formation of explosive atmospheres.

As for the experimentation on establishing the dynamics of the formation of explosive atmospheres by using methane, the system consists of a cylinder of compressed methane gas at a pressure of 200 bars at a concentration of 100% volume, a pressure reducer, respectively a flow meter with float. The gas was introduced into the enclosure by means of a hose with a diameter of 8 mm. The discharge of methane gas inside the enclosure was carried out by means of a support placed 0.25 meters from the floor on the eastern wall halfway down its base.

The gradient of dispersion and progressive dilution of the gas at the level of the closed enclosure, Gd was between 0.271 and 0.782% vol/h.

The methane gas pumped into the closed enclosure showed a phenomenon of uneven accumulation at the ceiling level, proven by the fact that gas concentrations were identified at the level of the detection devices between 0.4-1.15% volume compared to the value of the average concentration calculated in relative to the free volume of the enclosure of 0.36% volume.

As for the experimentation on establishing the dynamics of the formation of toxic atmospheres by using carbon monoxide, the system consists of a cylinder of carbon monoxide compressed to the pressure of 200 bars at a concentration of 230 ppm, a pressure reducer, respectively a flow meter with float. The gas was introduced into the enclosure by means of a hose with a diameter of 8 mm. The discharge of the carbon oxide inside the enclosure was achieved by means of a support placed 0.25 meters from the floor on the eastern wall halfway up its base side.

The gradient of dispersion and progressive dilution of the gas at the level of the closed enclosure, Gd was between 4.277 and 4.753 % ppm/h.

The carbon monoxide pumped into the closed enclosure showed a phenomenon of relatively uniform accumulation at the level of the enclosure, proven by the fact that gas concentrations between 16 and 18 ppm were identified at the level of the detection devices compared to the average concentration value calculated in relation to the free volume of the enclosure of 15.86 ppm.

With regard to the experimentation regarding the establishment of the dynamics of the formation of asphyxiating atmospheres by the use of carbon dioxide, the system consists of a cylinder of compressed carbon dioxide at the pressure of 60 bars at a concentration of 100% volume, a pressure reducer, respectively a flow meter with a float. The gas was introduced into the enclosure by means of a hose with a diameter of 8 mm. The discharge of carbon dioxide inside the enclosure was achieved by means of a support placed 0.25 meters from the floor on the eastern wall, halfway along its base.

The gradient of dispersion and progressive dilution of the gas at the level of the closed enclosure, Gd was between 0.3356 and 0.4552% vol/h.

The carbon dioxide pumped into the closed enclosure presented a phenomenon of relatively uneven accumulation in the floor, proven by the fact that maximum gas concentrations were identified at the level of the detectors between 1.06 and 1.4% by volume compared to the average concentration value calculated in relation to the free volume of the enclosure of 0.74% volume.

***Chapter VIII*, „CFD modeling".** To study the dispersion dynamics of explosive, toxic and asphyxiating gases, the CFD technique was used with the help of the ANSYS MULTIPHISICS software package for the dispersion of CO, CO_2, CH_4.

In order to carry out the simulations in a manner as close as possible to the experimental conditions, the topographic survey of the location within the experimental laboratory where the experiments were carried out in the laboratory was carried out, and the computerized model was made.

For the modeling of methane dispersion, the following aspects were established: concentration 100% volume, the flow of gas pumped inside the enclosure is 4.5 l/min and the simulation time set at 10 minutes. From the modeling regarding the dispersion of explosive gases in the closed environment using methane, the following aspects emerge: The modeling of the dispersion of methane gas in the closed environment presented a dispersion phenomenon oriented towards the flow direction of the compressed gas jet. The flow of methane gas has the form of a plane jet stuck to the floor up to the middle of the enclosure in the direction of flow, after which it detaches and tends to the opposite wall. The gas stream goes up the opposite wall and disperses unevenly at the ceiling level. The concentration of methane gas is maximum in the source area, gradually decreases by dilution as it moves away from the source, and becomes variable and low in the ceiling accumulation area. If the methane gas were continuously introduced for a longer period of time, the atmosphere in the room would be displaced starting from the ceiling towards the floor.

For modeling the dispersion of carbon monoxide, the following aspects were established: concentration of 230 ppm, gas flow rate inside the enclosure is 4.5 l/min and simulation time set at 10 minutes. From the modeling regarding the dispersion of toxic gases in the closed environment using carbon monoxide, the following aspects emerge: The modeling of the dispersion of carbon monoxide in the closed environment presented a phenomenon of dispersion oriented in the direction of flow of the repressed gas jet. The flow of carbon monoxide takes the form of a flat jet sticking to the floor up to the level of the opposite wall. The gas flow rises vertically on the opposite wall and disperses uniformly at the ceiling level.

The concentration of carbon monoxide is maximum in the source area, gradually decreases by dilution as it moves away from the source, and becomes relatively uniform and reduced in the accumulation area throughout the enclosure. If carbon monoxide were continuously introduced for a longer period of time, the atmosphere in the enclosure would present relatively uniform concentrations throughout the enclosure.

For modeling the dispersion of carbon dioxide, the following aspects were established: concentration 100% volume, the gas flow rate inside the enclosure is 4.5 l/min and the simulation time set at 10 minutes. From the modeling regarding the dispersion of asphyxiating gases in the closed environment using carbon dioxide, the following aspects emerge: The modeling of the dispersion of carbon dioxide in the closed environment presented a dispersion phenomenon oriented towards the flow direction of the repressed gas jet. The flow of carbon dioxide takes the form of a plane jet attached to the floor up to the level of the opposite wall. The gas disperses unevenly vertically from the floor level. The concentration of carbon dioxide is maximum in the source area, gradually decreases by dilution as it moves away from the source, and becomes relatively uniform and reduced in the accumulation area at the level of the floor. If carbon dioxide were continuously introduced for a longer period of time, the atmosphere in the room would be displaced starting from the floor towards the ceiling.

Chapter *IX* „Conclusions, personal contributions and future research directions" presents the results obtained from the synthesis of concepts, methods and experimental research.

The theoretical plan and the pragmatic plan, both with an emphasis on how they can be applied, are interconnected.

At the end of the chapter, some essential research directions that can be researched in perspective are presented.

The author believes that these directions could contribute to increasing the understanding and knowledge of the formation of polluting atmospheres of an explosive, toxic, asphyxiating nature in relation to industrial ventilation systems. It includes a chapter that summarizes the results and provides a detailed description of the contributions to the research field.

4. PERSONAL CONTRIBUTIONS

In my opinion, the doctoral thesis brings a series of original contributions to the development of knowledge in the field of the formation of polluting atmospheres, in relation to ventilation systems, having an important potential to contribute to the reduction of occupational diseases, respectively the prevention of work accidents and of occupational diseases in numerous branches and industrial units.

In the following I will highlight some of the most significant personal contributions.

From the point of view of theoretical and methodological research:

- Elaboration of the system of specific objectives of the research, in interdependence with the general objective of the doctoral thesis;
- Highlighting, based on the analyzes carried out, the theoretical aspects and practical tools that further substantiated the unitary and interdependent approach to the specific aspects of the formation of polluting atmospheres in relation to ventilation systems;
- I made a synthesis regarding the microclimate of industrial enclosure both with regard to the applicable ventilation systems and with regard to the particularities of the environmental factors in the industrial field;

- I synthesized the local ventilation installations usable in industrial enclosure, by which we highlighted the local exhaust ventilation installations, the local suction ventilation installations, respectively the local exhaust and suction ventilation installations;
- I performed a synthesis of the methodology for establishing the air flow through the lens of the equipment and the way of working;
- I analyzed the explosive, toxic and asphyxiating gases that can enter the composition of the air from the perspective of toxicological aspects;
- I made a synthesis on fluid dynamics in the field of ideal fluids using Euler's equations, the momentum theorem and the kinetic momentum theorem, respectively diffusion in gases and free diffusion at low pressures;
- I also carried out a systematic analysis of the movement of real fluids through the prism of laminar movement, the state of tension in the fluid, the Cauchy equations of motion, respectively through the Navier-Stokes equations;
- I have thoroughly analyzed gas dispersion simulation programs such as PHAST, TRACE, FLACS and KFX;
- At the same time, I carried out a brief analysis regarding the simulation of gas dispersion using the CFD technique regarding the dispersion of methane, the dispersion of carbon dioxide, respectively the dispersion of carbon oxide;
- For the in-depth knowledge of gas dispersion phenomena in order to establish the dynamics of the formation of explosive, toxic or asphyxiating atmospheres, I created an experiment system equipped with a security system for the protection of workers;
- I have developed a completely new and innovative methodological approach in terms of experimentation, respectively simulation regarding the formation of explosive, asphyxiating or toxic atmospheres;

From the point of view of practical and applied contributions:

- I have systematically highlighted the way to identify and establish the mathematical tools necessary to establish the way of formation of asphyxiating, toxic or explosive atmospheres.
- I contributed to the realization of the experimentation system for the study on the formation of asphyxiating, toxic or explosive atmospheres, I also contributed to the realization of the security system which included a ventilation system with variable structure, a force equipment automation system, respectively a system command and control type SCADA.
- I carried out experiments on the dynamics of the formation of explosive atmospheres regarding the use of methane, CH_4.
- I carried out experiments on the dynamics of the formation of toxic atmospheres regarding the use of carbon monoxide, CO.
- I carried out experiments on the dynamics of the formation of asphyxiating atmospheres regarding the use of carbon dioxide, CO_2.
- Using the CFD technique, I modeled the dispersion of methane in a closed enclosure.
- Using CFD techniques, I modeled the dispersion of carbon monoxide in a closed enclosure.
- Using the CFD technique, I modeled the dispersion of carbon dioxide in a closed enclosure.
- I carried out a mathematical and graphic analysis of the dispersion of explosive/toxic and asphyxiating gases in closed enclosure.
- I designed, in a completely new vision, a parameter: Gd - the gas dispersion gradient that reflects the formation of asphyxiating, toxic or explosive atmospheres.

In terms of disseminating the results:

During the period of conducting doctoral activities, I published as the first author/co-author a number of 14 articles and scientific works, and I was part of the collectives for the development of 3 books and 6 applications for invention patents as:

- 2 scientific papers published in BDI indexed specialized journals;
- 12 papers published in the volumes of international scientific events;
- 3 books with ISBN;
- 6 patent applications.

5. Future research directions

Any scientific endeavor is perfectible and may involve improvements, refinements and additions.

For the prospective development of the addressed field, namely "The way polluting atmospheres are formed in relation to ventilation systems", research directions can be developed as follows:

- The introduction in the occupational health and safety regulations of economic agents that use closed or semi-closed enclosure, of the need for conducting experimental tests with the aim of establishing the way of formation of asphyxiating, toxic or explosive atmospheres;
- Analysis of the mode of interdependence of ventilation installations operating in closed/semi-closed enclosure in relation to the mode of formation of asphyxiating, toxic or explosive atmospheres;
- Creation of tools for real-time monitoring of the formation of asphyxiating, toxic or explosive atmospheres in relation to the explosive range or dangerous ranges specific to each gas;
- Use of specialized programs for the analysis, design and optimization of industrial ventilation systems that operate, circulate or control potentially explosive/toxic/asphyxiating atmospheres.