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The dynamics of carbon dioxide evacuation from closed enclosures

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Abstract. The development of human society involves the growth and diversification of industrial activities in which asphyxiating substances such as carbon dioxide are produced or formed. The presence of this gas in closed or semi-closed spaces can seriously affect the human body and when the concentrations are close to 12% Vol., death can occur. In order to establish preventive measures, it is very important to know how carbon dioxide affects the human body and how it is evacuate. Also, in order to establish the necessary measures, it is necessary to know the dispersion dynamics of carbon dioxide both horizontally and vertically. The paper presents the experiment on establishing the evacuation dynamics of carbon dioxide in a closed enclosure.

1. Introduction

Carbon dioxide is an asphyxiating gas, which has no flammability and explosion properties, no oxidation properties, has a molar mass of 44.0099 g / mol, melting point at -56.6 ° C (5.3 bar), has a boiling point of -78.5 ° C with a solubility of 3.3 g / l at 0 ° C, 1.45 g / l at 20 ° C and 1013 hPa. It falls into the group of poorly soluble substances [11].

At a content of 0.5% vol. CO_2 in the air there is a slight increase in pulmonary ventilation; a person exposed to this percentage of CO_2 will breathe a little deeper and faster.

If the air contains up to 2% vol. CO_2, the ventilation of the lungs will increase by 50%, there is irritation and redness of the skin and mucous membranes, and if it contains 3% vol. CO_2 the ventilation of the lungs increases by 100%. If this content reaches 5% vol. CO_2, the ventilation of the lungs increases by 300% and breathing is difficult. Between 2-6% vol. CO_2, headaches, ringing in the ears, palpitations, increased blood pressure, mental arousal occur. Between 8-10% vol. CO_2, appear respiratory failure, convulsions, loss of consciousness, stop breathing with cyanosis. At 10% vol. CO_2 in the atmosphere cannot be supported only a few minutes. At 12% vol. CO_2, death occurs immediately by cardiac inhibition or asphyxia. The suffocating effect of CO_2 depends on the CO_2 content of the air and the residence time.

Accidental or occupational exposure to carbon dioxide may have long-term physiological effects, particularly in the eye by increasing the visual field that the black spots in the retina due to retinal ganglion cell damage. Carbon dioxide has these effects when the oxygen content remains almost normal and the subject is at rest. A person's respiratory capacity (the volume of air inhaled or exhaled) is several times greater than the actual volume of oxygen consumed by inhalation. The exhaled air contains approximately the following gases: 16% O_2, 79% N_2, 5% CO_2. The national mandatory occupational exposure limit is 9000 mg / m3 or 5000 ppm. for exposure at 8 hours.

2. Description of the problem

The presence of carbon dioxide in high concentrations in or near industrial premises, even in areas where domestic activities take place, carries with it a major risk of poisoning. [3, 8-10, 13]. Workers may be exposed to asphyxiating substances such as carbon dioxide, where they directly affect the human body through long-term effects or death may occur. The topic of gas dispersion has been studied extensively internationally [1, 5, 12, 16]. However, in particular, the dynamics of asphyxiating gas evacuation indoors has been less studied but can be analyzed through experiments. [4, 6, 7]. The results of the detailed analysis can be used to determine areas of refuge or escape routes in the event of an unintentional release of carbon dioxide into an enclosed industrial premises [14, 15, 17].

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3. Establishing the conditions for experimentation

The experimentation regarding the establishment of the formation and dispersion dynamics of the asphyxiating atmospheres was carried out in the industrial ventilation laboratory within INCD INSEMEX Petroșani [2]. The experimental system used consists of a data acquisition equipment and a monitoring system consisting of 6 pulleys to which are attached 6 multigase detectors of ALTAIR type, which can detect concentrations of O_2, CO_2, CO and CH_4. The pulley system can configure a variable spatial arrangement in order to establish the rate of gas dispersion as well as the dynamics of the formation of asphyxiating atmospheres. To ensure the safety and health conditions at work at the experimental site as well as to study the dynamics of asphyxiating gas evacuation, a complex ventilation system with variable structure is used to study the ventilation capacity of enclosed spaces with risk of formation of potentially explosive atmospheres / toxic / suffocating.

This ventilation system consists of a fan unit - 3 kW centrifugal motor and a network with several branches of rectangular pipes with dimensions of 300/400 mm that control the indoor atmosphere.

The network of rectangular pipes intended for the suction of air consists of short and long branches intended for the ventilation of the enclosures in which gases of low, medium or high specific weight can be found.

4. Laboratory experiments

In the experimental laboratory, the dynamics of the formation of the asphyxiating atmosphere through the use of carbon monoxide, CO_2 were analyzed.

The measuring instruments used are of the MSA - ALTAIR type and have the following series: Apparatus no. 1: 000 6011 454 MSA; Apparatus No. 2: 000 6010 119 MSA; Apparatus No. 3,000 6011 456 MSA; Apparatus No. 4: 000 6011 457 MSA; Apparatus No. 5,000 6010 120 MSA; Apparatus No. 6: 000 6011 455 MSA. The ground section of the experimental enclosure is 5.8x5.62 m. The height of the enclosure is 3.65 m. Consequently, the total volume of the experimental enclosure is 118.9754m^3. Considering the fact that other experimental systems are located in the enclosure, the free volume of the enclosure is 116 m^3.

For the ventilation of the experimental enclosure was used "complex experimental system with variable structure for the study of the ventilation capacity of closed enclosures with risk of formation of potentially explosive / toxic / asphyxiating atmospheres" which has 18 flow variators and 15 suction mouths. At the level of the experimental enclosure this system has 6 flow variators and 5 suction mouths. The suction openings are arranged as follows: 3 suction openings with horizontal suction respectively 2 suction openings with vertical suction. The centrifugal drive fan is type V20 - 450D - 3kW. The flow rate achieved by this type of fan is 2800m^3/h. The average flow achieved at the level of a suction mouth was 3.11 m^3/min. At the level of the experimental enclosure, the average flow achieved was 15.55 m^3/min. The initial test conditions were as follows: Temperature: T = 22.3 ° C; Atmospheric pressure: B = 9,450 da Pa; Relative humidity: RH = 63.5%. The system for introducing the gas into the enclosure is shown in fig. 1.

Fig. 1. Intake gas system

The system consists of a cylinder of carbon dioxide compressed at a pressure of 200 bar and a concentration of 100% Vol., A pressure reducer and a flow meter.

The MSA - ALTAIR detection devices were positioned on the 6 pulleys at a low level and the height at which the suction and detection area of the devices was positioned was 0.25 m of the floor presented in fig. 2.

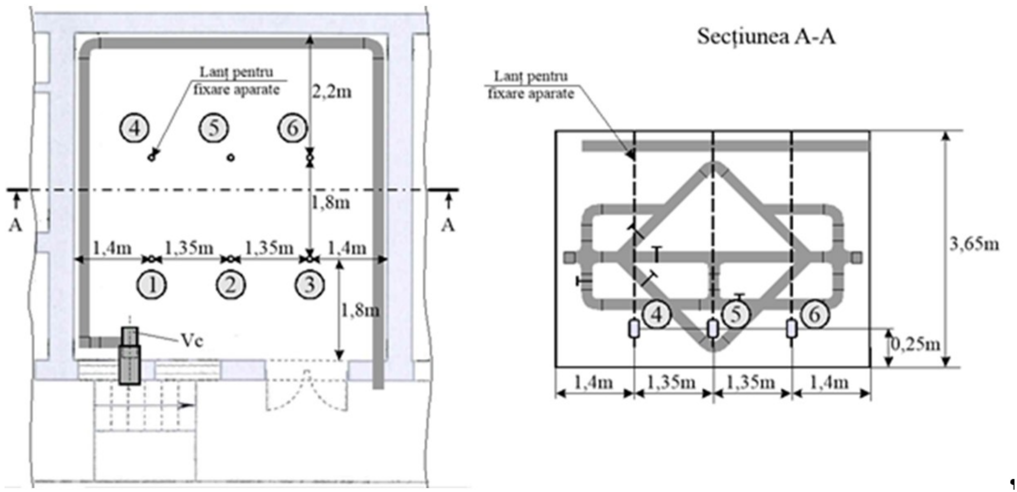

Fig. 2. Location of the detection system

The ventilation system of the enclosure was structured with the help of flow variators. The ventilation system as well as the flow variators were operated by the SCADA type command and control system. As a result of the experiment, the following results were obtained in tables 1-6:

Table 1. At the level of the MSA ALTAIR device no. 1

Date **Altair 5X -1**	COMB	O_2		CO	H_2S	CO_2	°C
	Peak	Min	Max	Peak	Peak	Peak	
8/10/2020 12:24:30 PM	0	20.8	20.8	0	0	1.2	28
8/10/2020 12:27:30 PM	0	20.8	20.8	0	0	1.2	28
8/10/2020 12:30:30 PM	0	20.8	20.8	0	0	0.91	28
8/10/2020 12:33:30 PM	0	20.8	20.8	0	0	0.77	29
8/10/2020 12:36:30 PM	0	20.8	20.8	0	0	0.44	29
8/10/2020 12:39:30 PM	0	20.8	20.8	0	0	0.42	29
8/10/2020 12:42:30 PM	0	20.8	20.8	0	0	0.34	29
8/10/2020 12:45:30 PM	0	20.8	20.8	0	0	0.24	29
8/10/2020 12:48:30 PM	0	20.8	20.8	0	0	0.19	28
8/10/2020 12:51:30 PM	0	20.8	20.8	0	0	0.11	29
8/10/2020 12:54:30 PM	0	20.8	20.8	0	0	0.09	29
8/10/2020 12:57:30 PM	0	20.8	20.8	0	0	0.05	29
8/10/2020 13:06:30 PM	0	20.8	20.8	0	0	0.03	29

Table 2. At the level of the MSA ALTAIR device no. 2

Date **Altair 5X -2**	COMB	O_2		CO	H_2S	CO_2	°C
	Peak	Min	Max	Peak	Peak	Peak	
8/10/2020 12:25:45 PM	0	20.8	20.8	0	0	1,27	31

8/10/2020 12:28:45 PM	0	20.8	20.8	0	0	1,27	31
8/10/2020 12:31:45 PM	0	20.8	20.8	0	0	1,11	31
8/10/2020 12:34:45 PM	0	20.8	20.8	0	1	0.68	31
8/10/2020 12:37:45 PM	0	20.8	20.8	1	0	0.64	31
8/10/2020 12:40:45 PM	0	20.8	20.8	0	0	0.48	31
8/10/2020 12:43:45 PM	0	20.8	20.8	0	0	0.49	31
8/10/2020 12:46:45 PM	0	20.8	20.8	0	0	0.4	31
8/10/2020 12:49:45 PM	0	20.8	20.8	0	0	0.36	31
8/10/2020 12:52:45 PM	0	20.8	20.8	0	0	0,35	32
8/10/2020 12:55:45 PM	0	20.8	20.8	0	0	0.14	32
8/10/2020 12:58:45 PM	0	20.8	20.8	0	0	0.17	32
8/10/2020 13:07:45 PM	0	20.8	20.8	1	0	0.03	33

Table 3. At the level of the MSA ALTAIR device no. 3

Date **Altair 5X -3**	COMB	O_2		CO	H_2S	CO_2	°C
	Peak	Min	Max	Peak	Peak	Peak	
8/10/2020 12:22:00 PM	0	20.8	20.8	1	0	1,09	28
8/10/2020 12:25:00 PM	0	20.8	20.8	1	0	1,09	28
8/10/2020 12:28:00 PM	0	20.8	20.8	1	0	1,09	28
8/10/2020 12:31:00 PM	0	20.8	20.8	1	0	0.87	28
8/10/2020 12:34:00 PM	0	20.8	20.8	0	0	0.75	28
8/10/2020 12:37:00 PM	0	20.8	20.8	0	0	0.87	28
8/10/2020 12:40:00 PM	0	20.8	20.8	1	0	0.74	28
8/10/2020 12:43:00 PM	0	20.8	20.8	1	0	0.72	28
8/10/2020 12:46:00 PM	0	20.8	20.8	1	0	0.34	28
8/10/2020 12:49:00 PM	0	20.8	20.8	0	0	0.25	28
8/10/2020 12:52:00 PM	0	20.8	20.8	0	0	0,15	29
8/10/2020 13:01:00 PM	0	20.8	20.8	0	0	0.03	29

Table 4. At the level of the MSA ALTAIR device no. 4

Date **Altair 5X -4**	COMB	O_2		CO	H_2S	CO_2	°C
	Peak	Min	Max	Peak	Peak	Peak	
8/10/2020 12:24:30 PM	0	20.7	20.8	0	0	1.4	30
8/10/2020 12:27:30 PM	0	20.7	20.8	1	0	1.4	30
8/10/2020 12:30:30 PM	0	20.8	20.8	0	0	1,05	30
8/10/2020 12:33:30 PM	0	20.8	20.8	0	0	0.74	30
8/10/2020 12:36:30 PM	0	20.8	20.8	0	0	0.61	30
8/10/2020 12:39:30 PM	0	20.8	20.8	1	0	0.49	30
8/10/2020 12:42:30 PM	0	20.8	20.8	0	0	0.47	30
8/10/2020 12:45:30 PM	0	20.8	20.8	1	0	0.35	30
8/10/2020 12:48:30 PM	0	20.8	20.8	0	0	0.27	30
8/10/2020 12:51:30 PM	0	20.8	20.8	0	0	0,19	30
8/10/2020 12:54:30 PM	0	20.8	20.8	0	0	0.15	30
8/10/2020 12:59:30 PM	0	20.8	20.8	1	0	0.03	31

Table 5. At the level of the MSA ALTAIR device no. 5

Date **Altair 5X -5**	COMB	O_2		CO	H_2S	CO_2	°C
	Peak	Min	Max	Peak	Peak	Peak	
8/10/2020 12:16:30 PM	0	20.8	20.8	0	0	1.04	28
8/10/2020 12:19:30 PM	0	20.8	20.8	0	0	1.04	28
8/10/2020 12:22:30 PM	0	20.8	20.8	0	0	0.98	28
8/10/2020 12:25:30 PM	0	20.8	20.8	0	0	0.91	28
8/10/2020 12:28:30 PM	0	20.8	20.8	0	0	1.06	28
8/10/2020 12:31:30 PM	0	20.8	20.8	0	0	0.88	28
8/10/2020 12:34:30 PM	0	20.8	20.8	0	0	0.48	29
8/10/2020 12:37:30 PM	0	20.8	20.8	0	1	0.42	29
8/10/2020 12:40:30 PM	0	20.8	20.8	0	0	0.29	29
8/10/2020 12:43:30 PM	0	20.8	20.8	0	0	0.26	29
8/10/2020 12:46:30 PM	0	20.8	20.8	0	0	0.16	29
8/10/2020 12:49:30 PM	0	20.8	20.8	0	0	0.13	28
8/10/2020 13:04:30 PM	0	20.8	20.8	0	0	0.03	29

Table 6. At the level of the MSA ALTAIR device no. 6

Date **Altair 5X -6**	COMB	O_2		CO	H_2S	CO_2	°C
	Peak	Min	Max	Peak	Peak	Peak	
8/10/2020 12:22:30 PM	0	20.8	20.8	0	0	1.2	29
8/10/2020 12:25:30 PM	0	20.8	20.8	0	0	1.18	29
8/10/2020 12:28:30 PM	0	20.8	20.8	0	0	1.18	29
8/10/2020 12:31:30 PM	0	20.8	20.8	0	0	0.99	29
8/10/2020 12:34:30 PM	0	20.8	20.8	0	0	0.62	29
8/10/2020 12:37:30 PM	0	20.8	20.8	0	0	0.52	29
8/10/2020 12:40:30 PM	0	20.8	20.8	0	0	0.32	29
8/10/2020 12:43:30 PM	0	20.8	20.8	0	0	0.29	29
8/10/2020 12:46:30 PM	0	20.8	20.8	0	0	0.2	29
8/10/2020 12:49:30 PM	0	20.8	20.8	0	0	0.16	29
8/10/2020 12:52:30 PM	0	20.8	20.8	1	0	0.12	29
8/10/2020 13:07:30 PM	0	20.8	20.8	0	0	0.03	30

The duration of the experiment was 40 min. The volume of Carbon Dioxide introduced into the enclosure was 868.5 liters or 0.8685 m^3. The time allotted for ventilation was 50 min.

The dynamics of the Carbon Dioxide discharge at the closed enclosure is shown graphically in fig. no. 3.

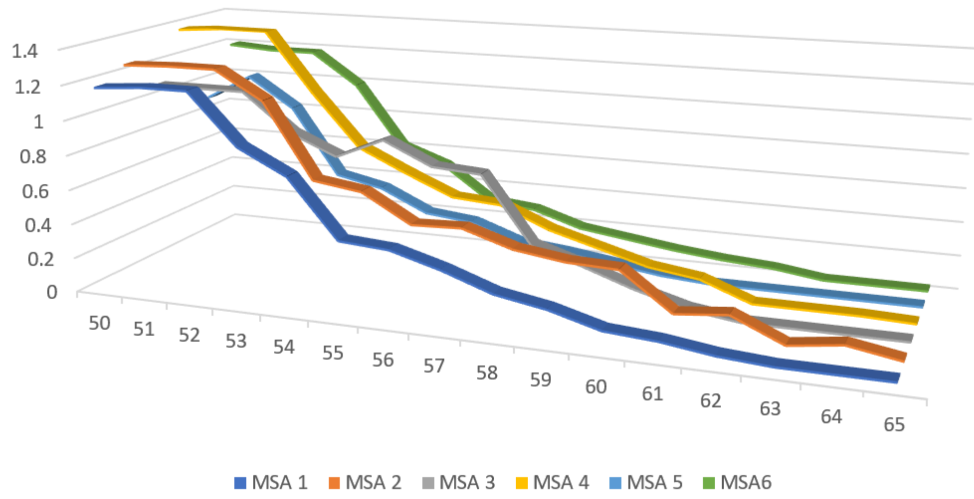

Fig. 3. Dynamics of carbon dioxide evacuation indoors

5. Discussions

From the experimentation regarding the evacuation of asphyxiating gases in the closed enclosure by using Carbon Dioxide, the following conclusions can be drawn:

The process of evacuating carbon dioxide indoors comprises the ventilation period in which the gas is discharged by means of the ventilation system with variable structure;

The evacuation process is characterized by a variable evolution both horizontally and vertically. This aspect is proved by the different values of the gas concentrations at the level of the detection devices, in the same time interval;

The period of ventilation and progressive dilution of the gas showed different evolutions depending on the position of the detectors in the plan as follows: The period of ventilation and progressive dilution of the gas was long at the level of the detectors located in points 3, 4 and 6 being 39 ; 35 and 36 min, respectively; The period of total aeration and progressive dilution of the gas was very long at the level of the detection devices located in points 1, 2 and 5 being 39 min .;

The maximum gas concentration showed different evolutions depending on the position in the plane of the detection devices as follows: The maximum gas concentration of the gas was reduced at the level of the detection devices located in points 3 and 5 being 1.09 and 1.06% Vol .; The maximum gas concentration was average at the level of the detection devices located in points 1, 2 and 6 being 1.2; 1.27 and 1.2% vol . The maximum gas concentration of the gas was high at the level of the detection device located in point 4 being 1.4% vol .

The gradient of dispersion and progressive dilution of the gas in the closed enclosure, Gd, showed a variable evolution depending on the position in the plane of the detection devices as follows: The gradient of dispersion and progressive dilution of gas at the enclosure, Gd, showed reduced value at the detection apparatus located in point 5 being 1,631% Vol. / h. The gradient of dispersion and progressive dilution of the gas at the enclosure level, Gd, presented average values at the level of the detection devices located in points 1 and 3 being of 1.846 respectively 1.816% Vol. / h. The gradient of dispersion and progressive dilution of the gas at the enclosure level, Gd, presented a high value at the level of the detection devices located in points 2 and 6 being of 1,954 respectively 1.999% Vol. / h. The gradient of dispersion and progressive dilution of the gas at the enclosure level, Gd, presented a very high value at the level of the detection device located in point 4 being of 2,333% Vol. / h;

Asphyxiating gas - carbon dioxide, accumulated in the closed enclosure, showed a phenomenon of dilution and heavy and uneven evacuation compared to the geometric shape of the enclosure. The average ventilation time in relation to the indications of the detection devices, respectively with the shape of the enclosure, was over 37 min. which gives the carbon dioxide a reduced capacity for total evacuation from closed enclosures.

6. Conclusions

For the study of the formation dynamics of toxic or asphyxiating explosive atmospheres, in the experimental laboratory for the study of industrial ventilation systems, experiments were performed on the dynamics of the asphyxiating atmosphere evacuation using carbon dioxide, CO2.

The process of evacuating carbon dioxide inside the enclosure includes the period of ventilation of the enclosure.

The carbon dioxide evacuation process is characterized by a variable evolution both horizontally and vertically. This aspect is proved by the different values of the gas concentrations at the level of the detectors, in the same time interval.

The ventilation period showed evolutions between 36 and 39 minutes.

The maximum gas concentration showed a variable evolution with values between 1.06 and 1.4% Vol.

The gradient of dispersion and progressive dilution of gases at the level of the closed enclosure, G_d, presented a variable evolution being between 1,631 - 2,333% Vol. / h.

The average ventilation time in relation to the indications of the detection devices and the shape of the enclosure was over 37 minutes which gives the carbon dioxide a reduced capacity for total evacuation from closed enclosures.

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References

1. G. Chiodini, A. Costa, D. Rouwet, F. Tassi, - *Modeling CO_2 air dispersion from gas driven lake eruptions,* Geophysical Research Abstracts, Vol. 18, EGU2016-17572, 2016, EGU General Assembly (2016).
2. D. Cioclea - *The superior valorization for energy purposes of coal deposits under the conditions imposed by environmental strategies (VSMET),* INSEMEX Petroșani Study - NUCLEU Project, (2023).
3. H. Goodfellow, E. Tahti - *Industrial ventilation design guidebook*, Academic Press, San Diego, California, USA, (2001).
4. V. Guillemaud, - *Modélisation et simulation numérique des écoulements diphasiques par une approche bifluide à deux pressions,* Université de Provence - Aix-Marseille I,Français, Thèse pour obtenir le grade de Docteur, (2007).
5. T. Kletz - *Learning from Accidents - Third edition* - First published as Learning fromAccidents in Industry (1988), Reprinted 1990, Second edition 1994, Third edition 2001, British Library Cataloguing in Publication Data, Library of Congress Cataloguing in Publication Data, ISBN 0 7506 4883 X.
6. P. Lauret - *Modelisation de la dispersion atmospherique sur un site industriel par combinaison d'automates cellulaires et de reseaux de neurones,* l'École Nationale Supérieure des Mines de Saint-Étienne, Thèse pour obtenir le grade de Docteur, (2014).
7. B. Liu, X. Liu, C. Lu, A.R. Godbole, G. Michal - *Computational fluid dynamics simulation of carbon dioxide dispersion in a complex environment*, Journal of Loss Prevention in the Process Industries, 40 419-432, (2016). Research Online is the open access institutional repository for the University of Wollongong.
8. O. Loison, A. Fauveau - *Le Risque chimique et la grande distribution, Ecole Nationale Supérieure des Officiers de Sapeurs Pompiers,* RCH 4 – Session (2007).
9. S. Mannan - *Lees' Loss Prevention in the Process Industries,* Imprint Butterworth -Heinemann, ISBN 978-0-7506-7555-0, (2005).
10. T. Robertson, J. Dunbar - *Guidance for evaluating landfill gas emissions from closed or abandoned facilities,* U.S. Environmental Protection Agency Office of Research and Development, Washington, EPA-600/R-05/123a, (September 2005).
11. M. J. Suess, S. R. Craxford - *Manuel de gestion de la qualite de l'air des villes,*Organisation Mondiale de la Sante, Bureau Regional de l'Europe, Copenhague, ISBN 92 9020 201 7, (1978).
12. M. Zhang, W. Song, Q. Li, Z. Chen - *FDS Simulation and Consequences Forecasting of LPG Storage Tank Pool Fire and Explosion,* Applied Mechanics and Materials, ISSN: 1662-7482, Vols. 353-356, pp 2412-2418, doi:10.4028/www. scientific.net/AMM.353-356.2412, © Trans Tech Publications, Switzerland, (2013).
13. xxxx – *Air contaminants*, ASHRAE Handbook Fundamentals, (2013).
14. xxxx – *Ventilation of the industrial environment*, ASHRAE Handbook HVAC Applications, (2015).
15. xxxx – *ABS Guidance notes on gas dispersion studies of gas fueled vessels,* American Bureau of Shipping Incorporated by Act of Legislature of the State of New York 1862, (2019).
16. xxxx - *Drager – Gas Dispersion,* Lübeck, Germany, (2010).
17. xxxx - *Guidance on evaluation of development proposals on sites where methane and carbon dioxide are present*, The National House-Building Council - NHBC, RSK Group PLC, Report edition No.: 04, (March 2007).