Use of explosibility diagrams in potentially explosive atmospheres

Adrian Matei^{}, Răzvan Drăgoescu, Nicolae Ianc, Emeric Chiuzean, and Florin Rădoi*

National Institute for Research and Development in Mine Safety and Protection to Explosion – INSEMEX, 32-34 G-ral Vasile Milea street, 332047, Petrosani, Hunedoara county, Romania

Abstract. Although the first research in the field was carried out by Davy in 1816, the first discovery emerged in 1891 when Le Chatellier defined the law for determining the explosive limits. Lower Explosive Limit (LEL) represents the lowest concentration of gas or vapours in air which is able to generate the explosion in the presence of an efficient ignition source. It is considered to be the same as the Lower Flammability Limit (LFL). Upper Explosive Limit (UEL) represents the highest concentration of gas or vapours in air which is able to generate the explosion in the presence of an efficient ignition source. It is considered to be similar with the Upper Flammability Limit (UFL) [1]. For the optimal management of underground or surface industrial environments, confined, obstructed or open environments, is required to know the point which defines the monitored atmosphere in relation with the explosion triangle. For confined underground environments, monitoring the atmosphere and using the explosibility diagrams are required during the closure process and also for re-opening the area. For underground environments specific to active mine workings and for industrial environments located on the surface, monitoring the atmosphere and using explosibility diagrams are required permanently.

1 Use of explosive diagrams

For the optimal management of the underground or surface industrial environments, semi-closed or open closed environments, it is necessary to know the position of the point that defines the monitored atmosphere in relation to the explosive triangle [2-4].

For the underground environments specific to the active mining works as well as for the industrial surfaces from the surface, the monitoring of the atmosphere as well as the use of explosive diagrams are permanently required [5-8]. For example, a gas composition specific to the closed industrial environments for which explosive diagrams are used is given and analysed.

2 Coward - Jones explosion chart

- For a closed area we have the following composition:

^{*} Corresponding author: adrian.matei@insemex.ro

- X: CH₄= 6% vol.; CO = 1 % vol.; O₂ = 16 % vol.; H₂ = 0.5 % vol.; CO₂ = 2% vol.; N₂ = 79 % vol.
- Fuel gases with figures from 1 to 3 are noted, and their percentage concentration with P₁-CH₄; P₂- CO; P₃ - H₂. The total concentration of P_i fuel gases will be given by the expression:

$$\begin{aligned}
 P_t &= P_1 + P_2 + P_3 \text{ \%} \\
 P_t &= 6 + 1 + 0,5 = 7,5\%
 \end{aligned}
 \tag{1}$$

The explosive limits of the mixture are calculated with the ratio:

$$\frac{P_t}{L_t} = \frac{P_1}{L_1} + \frac{P_2}{L_2} + \frac{P_3}{L_3}
 \tag{2}$$

in which:
Lt - explosive limit
L_{1...3} - Properties of gases ar shown in the Table 1.

Table 1. Properties of gases

The name of the gas	Explosive limits		Minimum combustion limits	
	lower	higher	Gas	Oxygen
Methane	5.0	15.0	5.9	12.2
Carbon monoxide	12.0	74.0	13.8	6.1
Hydrogen	4.0	74.0	4.3	5.1

The minimum burning limit of the L_{min} mixture is determined by the relation:
Where L_{min 1...3} the minimum combustion limits corresponding to each combustible gas in the mixture.
The excess N_{ex} nitrogen required is given by the relation:

$$N_{ex} = \frac{L_{min}}{P_t} (N_1^+ P_1 + N_2^+ P_2 + N_3^+ P_3)
 \tag{3}$$

wherein: N⁺ 1,2,3 - represent the m³ of N⁺ that must be added for each m³ of combustible gas in order for the blending of the mixture to cease, these values are shown in Table 2.

Table 2. Parameters for combustion ceasing.

Fuel gas	m ³ of N ⁺ necessary for the combustion to cease
Methane	6.07
Carbon monoxide	4.13
Hydrogen	16.59

The concentration of O₂ required at the minimum burning limit of the mixture is:

$$O_2 = 0.2093(100 - N_{ex} - L_{min})\%
 \tag{4}$$

Thus:

The lower explosive limit of the mixture is:

$$\frac{7.5}{L_i} = \frac{6}{5} + \frac{1}{12} + \frac{0.5}{4} \quad (5)$$
$$L_i = 5.30\%$$

The upper explosive limit of the mixture is:

$$\frac{7.5}{L_i} = \frac{6}{15} + \frac{1}{74} + \frac{0.5}{74} \quad (6)$$
$$L_i = 17.8\%$$

The excess N+ required is:

$$N_{ex} = \frac{6.22}{7.5} (6.07 \cdot 6 + 4.12 \cdot 1 + 16.59 \cdot 0.5) = 40.51 \% \quad (7)$$

The concentration of O₂ required at the minimum burning limit of the mixture is:

$$O_2 = 0.2093(100 - 40.51 - 6.22) = 11.15\% \quad (8)$$

As a result, the point that defines the monitored atmosphere X (Fuels, oxygen) in our case X (7, 5,16), is located inside the explosive triangle according to Figure 1.

Fig. 1. Coward - Jones explosion chart.

3 Ellicott explosion chart

To use the Ellicott diagram, there have to be calculated the X and Y coordinates in relation to the nose point coordinates. The peak point is defined by the point 0 (L_{min}, O_{2min}), in our case 0 (6,22; 11,15).

Thus, we have:

$$X = 7.5 - 6.22 = + 1,28 \% \text{ vol. } Y = 16 - 11.15 = + 4.85 \% \text{ vol.}$$

Consequently, the point that defines the monitored atmosphere X (Fuels, oxygen) in our case X (+1.28; +4.85), is located inside the explosive zone according to Figure 2.

Fig. 2. Ellicott explosion chart.

4 USBM explosion chart – Zabetakis

For constructing explosive triangles, the ratio R between methane and total fuels is used: Thus, we have:

$$R = \frac{CH_4}{CH_4 + H_2 + CO} \tag{9}$$

$$R = \frac{6}{6 + 1 + 0.5} = 0.8$$

The value corresponding to the inert gas concentration is determined. Inert cash = % excess N₂ + 1.5 (% CO₂) % vol.
Inert cash = 40.51 + 1.5 (2) = 43.51% vol.

The value corresponding to the concentration of the actual fuel gas is determined. Fuel efficiency =% CH₄ + 1.25% H₂ + 0.4% CO % vol.
Fuel efficiency = 6 + 1.25 · 0.5 + 0.4 · 1 = 7.025% vol.

As a result, the point defining the monitored atmosphere X (Effective inert, Effective fuels) in our case X (43.51; 7.03), is located outside the explosive areas A1 and A2 explosive according to the value of parameter R, in the area of non-explosive mixtures. but which can become explosive by the addition of air, Figure 3.

Fig. 3. USBM explosion chart – Zabetakis.

5 Ternare - Kennedy explosion chart

For the use of the Ternare or Kennedy explosive diagram, we must only consider the concentrations of methane, oxygen and nitrogen.

Thus, the point X (CH_4 , O_2 , N_2) that defines the monitored atmosphere must be identified, in the case of our X (6; 16; 79).

Consequently, the point that defines the monitored atmosphere X (CH_4 , O_2 , N_2) in our case X (6; 16; 79), is located inside the flammability zone according to Figure 4.

Fig. 4. Ternare - Kennedy explosion chart.

6 CCSM - Bardocz explosion diagram

In order to construct the flammability diagram of an explosive gas mixture, the following steps are taken [9]:

The points corresponding to the lower explosive limit of the explosive mixture (5,3% vol.) and the upper explosive limit of the explosive mixture (17,8% vol.) are marked on the parallel abscissa;

From these points is drawn the parallel with the ordinate until it intersects the diagonal of the diagram, which represents the oxygen line, in points A and B;

From point A is drawn a straight line parallel to the abscissa to point C, which corresponds to the minimum required value of oxygen at which ignition is no longer possible (11,15% vol.);

The points A, B and C from which the flammable triangle of the explosive mixture results;

The oxygen concentration in the explosive gas mixture (16% vol.) is identified on the oxygen scale, from which a parallel is drawn to the ordinate to the point corresponding to the maximum concentration of flammable gases (7,5% vol.). This point is scored by 1, a point that characterizes the position of the mixture in relation to the flammability triangle. As a result, the point that defines the monitored atmosphere 1 (Oxygen, fuels) in our case 1 (16.0; 7.5), is located inside the explosive triangle, as presented in the Figure.

Fig. 5. CCSM - Bardocz Chart.

7 Conclusions

Human activity in general but industrial activity in particular, generates specific risks of underground fire, fire or explosion, which can result in human losses and significant material losses. All the listed risks can occur if three factors are overlapping in time and space, namely: fuel, oxygen and source of initiation.

Although the first research in the field was conducted by Davy in 1816, however, the first discovery came in 1891 when Le Chatelier discovered the law for determining explosive limits.

The lower and upper explosive limits define the explosive interval that is located inside a straight segment between the point characterized by 0% combustible gas and 100% air and the point 100% combustible gas and 0% air.

In 1952, H. F. Coward and G. W. Jones first presented the shape of the explosive triangle. Coward - Jones' explosive triangle was a 2D representation of the explosive atmosphere consisting of simple methane and air.

C. W. Ellicott modified the Coward-Jones diagram in 1981, in order to simplify it for easier practical use.

For this, Ellicott transformed the Coward - Jones explosive triangle into a CH_4 - 0 - O_2 system, in a diagram in X and Y, where X represents the relative concentration of combustible gases and Y represents the relative concentration of oxygen.

In 1959, M. G. Zabetakis, R. W. Stahl, and H. A. Watson, presented for the first time the USBM explosivity diagram or the Zabetakis diagram, for a mixture of methane, nitrogen, and air at 80 ° F and at atmospheric pressure.

K. Kennedy established in 1965 the method of making the triangular or ternary diagram. In the case of the construction of the Ternary or Triangular Kennedy diagram, for a mixture of combustible gas (methane) - oxygen - inert (nitrogen), it is positioned clockwise and rising on the sides of the triangle gas concentrations.

In 1977, V. Bardocz establishes the construction of the flammability triangle of a mixture of explosive gases consisting of oxygen, nitrogen, carbon dioxide, methane, carbon monoxide and hydrogen. Explosion diagram CCSM - Bardocz uses a binary system to represent flammable gas mixtures.

References

1. H.F. Coward, G.W. Jones, *Limits of flammability of gases and vapors*, (U.S. Bureau of Mines, Bulletin 503, Washington, USA, 1952).
2. C. Teodorescu, Z. Gontean, I. Neag, *Mining ventilation*, (in Romanian), (Technical publishing house, Bucharest, 1980).
3. D. Carson, Classification en zones explosives poussiéreuses, (INERIS Report, Paris, 2001). Available on <http://www.ineris.fr/centredoc/b.pdf>
4. J. Cheng, Y. Luo, Journal of Loss Prevention in the Process Industries, **26**, 714-722, (2013). 5. J. Cheng, Y. Luo, Arch Min Sci, **59**, (1), 25-40, (2014).
6. D.R. Echeverri, S. H. R. Cano, J. A. J. Builes, Revista Educacion en Ingenieria, **14**, (7), (2012).
7. R. I. Moraru, Research and results in industrial and occupational safety, (in Romanian), (Habilitation thesis, University of Petrosani, 2015).
8. V. Bardocz, G. Neac, I. Focşa, *Underground lignite gasification*, (in Romanian), (CCSM Petrosani research study, Petrosani, 1977).
9. XXXX- Guidelines on Explosive atmospheres – Protection to explosion, <http://www.materialeelectrice.ro/normalizari/Zone%20antiex%20co.pdf> (in Romanian).