Modelling of Consequences of Biogas Leakage from Gasholder

Modelování následků úniku bioplynu z plynojemu

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Abstract

This paper describes modelling of consequences of biogas leakage from a gasholder on agricultural biogas station. Four scenarios were selected for the purpose of this work. A rupture of gasholders membrane and instantaneous explosion of gas cloud, blast of gas with delay, emptying of whole volume of gas (without initiation) and initiation of gas with Jet-Fire. Leakage of gas is modelled by special software and consequences are determined on the basis of results. The first scenario was modelled with help of equations because used software does not include an appropriate model. A farm with high building density was chosen as a model case. Biogas is replaced by methane because used software does not support modelling of dispersion of mixtures. From this viewpoint, a conservative approach is applied because biogas contains “only” approximately 60% of methane (in dependence on technology and processed material).

Keywords: accident, agriculture, biogas, station

Abstrakt

Práce se zabývá modelováním možných následků úniku bioplynu na zemědělské bioplynové stanici. Pro účel této práce byly vybrány celkem čtyři havarijní scénáře. První scénář předpokládá poškození plynojemu a okamžitý výbuch plynného mraku. Druhý scénář předpokládá výbuch bioplynu se zpožděním, třetí scénář únik veškerého objemu bioplynu ze zásobníku bez následné iniciace a poslední scénář předpokládá iniciaci uniklého bioplynu a následný Jet-Fire. Scénáře byly modelovány s pomocí speciálního software. Následky jednotlivých scénářů byly poté určeny na základě výstupů z tohoto software. Jako modelový příklad byla zvolena zemědělská bioplynová stanice s vysokou hustotou zástavby. Pro účely modelování byl bioplyn nahrazen methanem. Z tohoto hlediska byl tedy zvolen konzervativní přístup, protože bioplyn v závislosti na technologii a zpracovávaném materiálu obsahuje přibližně 60% methanu.

Klíčové slova: bioplyn, havárie, stanice, zemědělství

Introduction

Biogas stations form a very dense network in some European countries. The highest number of biogas stations in Europe is in Germany (9035 in 2014). However, a lot of biogas stations are also in other countries such as Italy (1391 in 2014), Switzerland (620 in 2014) or Czech Republic (554 in 2014) (European Biogas Association, 2014). The amount of biogas systems increases in Europe. However, this growth is not as dramatic as in previous years. For example, in the following years, stagnation is expected in Germany or Czech Republic. Contrarily, countries such as Romania, Bulgaria and Poland still have a high potential and in these countries, further growth of biogas stations can be expected in the following years.

A growing number of units increase a probability that in the future an extraordinary event can occur on the biogas station. For this reason, an adequate attention must be paid to safety of equipment. In principle, four main risks exist on biogas stations: deflagration, poisoning, asphyxiation, and environmental damage due to leakage of liquid material (Schroeder et al., 2014).

Deflagration, poisoning and asphyxiation can occur in the case that biogas releases out of technological installations. This leakage of biogas is often associated with death due to H_2S or CO_2 poisoning or explosion. The appropriate knowledge about spread of gaseous cloud can help to estimate the consequences of accidental leakage. The present article is focused on biogas dispersion and determination of consequences caused by its deflagration. Software ALOHA (Areal Locations of Hazardous Atmospheres) by EPA (US Environmental Protection Agency) and NOAA (National Oceanic and Atmospheric Administration) was used for mathematical modelling of biogas dispersion and biogas deflagration. ALOHA is a relatively simple tool, which is used for modelling of accidents with potential leakage of dangerous gaseous substance. This tool was utilized in many works and studies (Shao and Duan, 2012; Tseng et al., 2012; SWCA, 2010). The main objective of this work is the calculation of consequences in the case accident leakage of biogas in biogas station. Total four scenarios were selected for this purpose. These scenarios were selected with respect to experiences with accidents on hydrocarbon gasholders.

Materials and methods

Locality

An agricultural farm was chosen as a model case. Placement of the reactor with gasholder and locations of other buildings are shown in Figure 1. Building density in the area is relatively high. The buildings near the gasholder are used for storage of materials and livestock breeding.

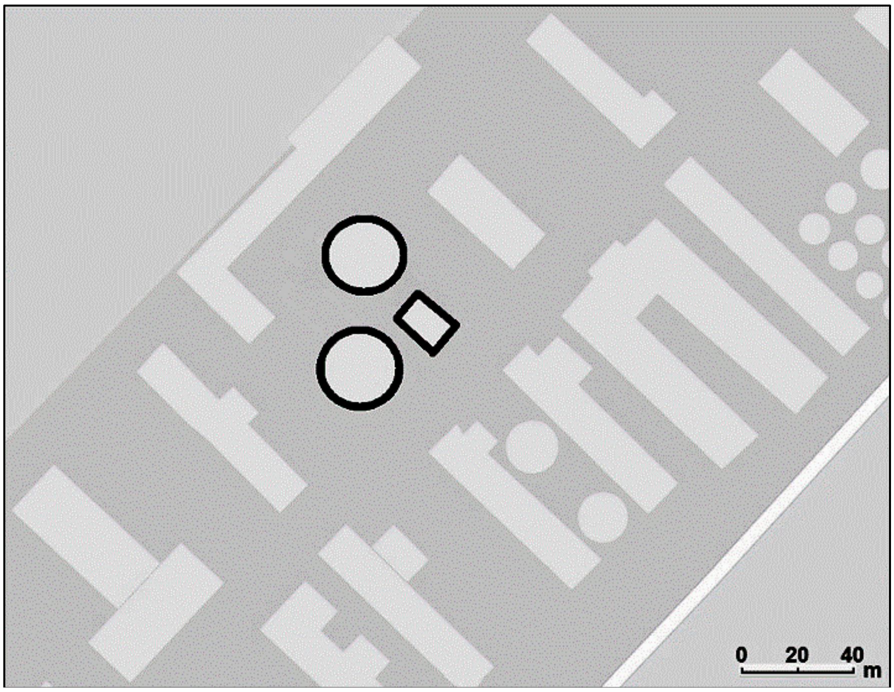

Figure 1. Placement of biogas station within the farm

Obrázek 1. Umístění bioplynové stanice v rámci zemědělského družstva

Modelled scenarios

I. Rupture of gasholders membrane – instantaneous explosion of gas cloud
II. Rupture of gasholders membrane – blast of gas with delay
III. Rupture of gasholders membrane – emptying of the whole volume of gas, without initiation
IV. Rupture of gasholders membrane – initiation of gas and Jet-Fire

Calculation

Calculations in accordance with the equation listed below were carried out for modelling of scenario I. The software ALOHA was used for calculation of other scenarios. The reason is that ALOHA is designed above all for leakage of substances from tanks produced from steel. However, the gasholders in the biogas station are produced from a special textile.

The following experimental equation is valid if the explosion occurs in the air without influencing the pressures by repercussion from the ground or other obstacles (Henrych, 1973):

$$\Delta p = \frac{0.084}{z} + \frac{0.27}{z^2} + \frac{0.7}{z^3} \tag{1}$$

Where:

Δp overpressure at the forefront of shock waves [MPa] z reduced distance

This equation was selected because the gasholder is fixed on the reinforced concrete section of the reactor in the height of about 10 m. Therefore, in the case of explosion, the shockwave does not spread along the ground surface.

A reduced distance is calculated by equation (Henrych, 1973):

$$z = \frac{r}{\sqrt[3]{W_{TNT}}} \quad (2)$$

Where:

R diameter [m]
W_{TNT} TNT equivalent [kg]

Only a part of gaseous system participates in detonation. The volume (which is involved in reaction) depends on many factors, such as atmospheric condition, kind of buildings, type of terrain, etc. Values range from 2% to 70% (Lees, 1996). For example, the value of 3% for open terrain is stated in the method of Exxon (Lees, 1996) or the value 2% is stated in the work of Brasie and Simpson (1968). For this work, the value of 3% has been selected.

Software

The software ALOHA 5.4.5 by EPA and NOAA was used in scenarios II, III and IV. An advantage of this software is its simplicity and easy operation. Limitations of this software are the following (U.S. Environmental Protection Agency and National Oceanic and Atmospheric Agency, 2007):

- very low wind speeds;
- very stable atmospheric conditions;
- wind shifts;
- particulates or chemical mixing;
- or concentration patchiness, particularly near the release source;
- or terrain steering effects

Based on this, wind speeds of minimum 5 km per hour and unstable atmospheric conditions were included. Biogas is a mixture of gases and ALOHA is not suitable for modelling of mixtures. For this reason, conservatively, the variant of pure methane leakage was received for the purpose of work.

Input data

a) Quality of biogas - Biogas is a mixture of CO_2 and flammable gas CH_4, which is produced by bacterial conversion of organic matter under anaerobic (oxygen-free) conditions (Raven and Gregersen, 2007). Gases CO_2 and CH_4 are majority gases; however biogas also contains various different kinds of gases. Minor gases include e.g. hydrogen, carbon monoxide, water vapour, hydrogen sulphide, ammonia, nitrous oxide and hydrogen chloride (Straka, 2006).

Methane and hydrogen sulphide are the most important gases from the view point of safety. Therefore, this work is focused on deflagration and dispersion of methane. Generally, the concentration of methane in biogas is variable and can reach value up to 75% (Vitázek and Havelka, 2011) in dependence on used material and technology. The concentration of methane in biogas is standardly around 60 – 65% at agricultural biogas plants. Explosion limits for biogas with concentration of 60% of methane and 40% carbon dioxide is 6% as lower explosion limit (LEL) and 12% as upper explosion limit (UEL) (SLFG, Safety rules for biogas system, 2008). A conservative approach is applied in modelling, i. e. the pure methane is considered.

b) The amount of gases - The gasholder is of conical shape; diameter of cone is 30 m and height is 8 m. The volume of such solid structure is 1885 m^3. The value of 200 kPa is considered as overpressure in the gasholder. The volume is 1987 m^3 (1426 kg) at normal pressure. ALOHA does not permit to select a cone type of cylinder for calculation. Therefore a vertical cylinder was selected as a substitution.

c) Weather - Weather data were taken from the meteorological station. A prevailing direction of wind is from northwest. Values of meteorological conditions were set at average values and are listed in Table 1.

Table 1. Meteorological conditions

Tabulka 1. Meteorologické podmínky

Condition	Value
Direction of wind	NW
Cloud cover	7
Air temperature	10 °C
Humidity	70%
Wind speed	5 $m*s^{-1}$
Stability class	D

Results and discussion

Scenario I

Scenario I considers the situation when the membrane of gasholder ruptures and the whole volume of biogas explodes. Nevertheless, it can be assumed that this scenario is rather unlikely. The rupture of gasholders can be caused by lightning, which initiated a flammable mixture at the same time. This type of accident occurred in the Czech Republic in 2011 (Trávníček and Kotek, 2015).

Consequences of explosion of the entire volume of substances cannot be determined by software ALOHA because it does not offer any similar scenario to be used for calculation. Therefore, the equations 1 and 2 were used.

The values of overpressures depending on the distances are shown in Figure 2. This graph is divided into four zones where each of them represents a degree of damage classification. This classification is given in Table 2.

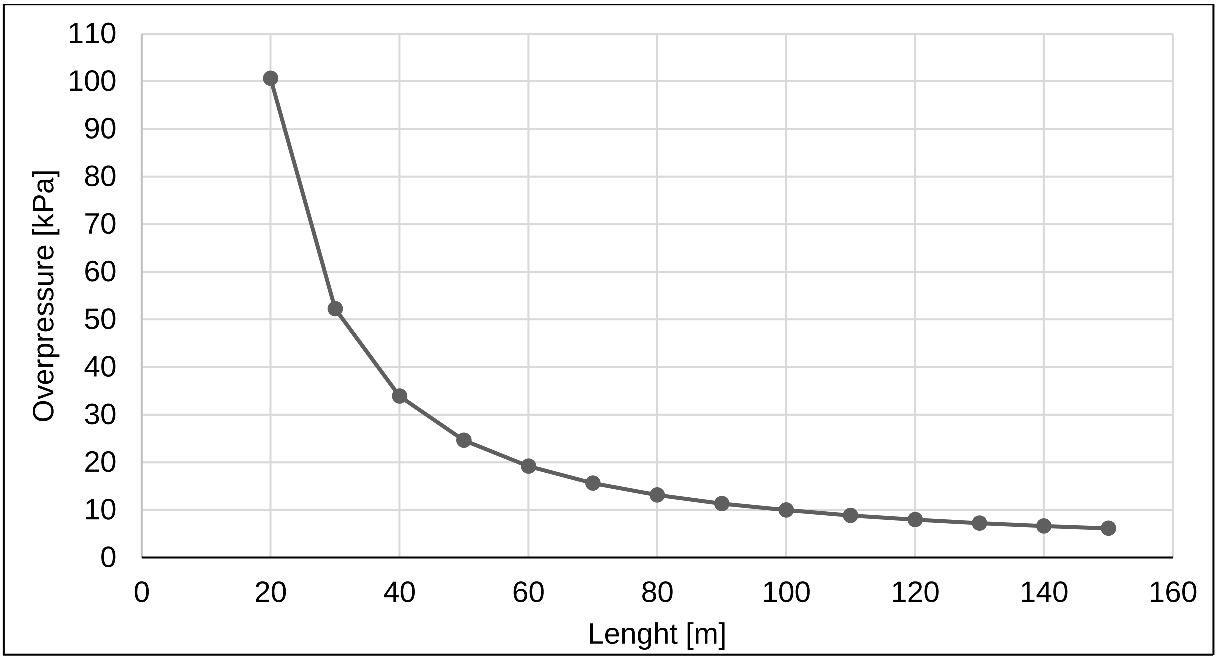

Figure 2. Dependence of overpressure on the distance from the source

Obrázek 2. Závislost přetlaku na vzdálenosti od zdroje

Table 2. Damage classification (Stephens, 1970)

Tabulka 2. Klasifikace poškození objektu

Zone	Damage level	Overpressure [kPa]	Overpressure [psi]
A	Total destruction	> 69	> 10
B	Severe damage	> 20.7	> 3
C	Moderate damage	> 9	> 1.3
D	Light damage	> 3.45	> 0.5

A total destruction occurs up to the distance of approximately 23 m from the middle point of gasholder. Severe damage will be up to the distance of about 60 m. The effects of the respective damage are shown in Table 3. Assuming nearest buildings are located at the distance of about 50 m (technical buildings are only 20 m far from the gasholders), damage would be extensive.

Table 3. Effects of respective damage by blast wave (Clancey, 1972)

Tabulka 3. Účinky tlakové vlny

Effect	Overpressure (kPa)
Breakage of windows, small, under strain	0.7
Minor damage to house structure	4.8
Partial demolition of houses	6.9
Partial collapse of walls and roofs of houses	13.8
Loaded train wagons overturned	48.3
Probable total destruction of buildings	69

However, the effect of damage would be actually less intensive for several reasons. The first reason is that the amount of methane in biogas is approximately 60% (the concentration depends on the type of technology and material, which is processed); the second reason is that the gasholders are located on the steel concrete reactor in similar height as the surrounding buildings. The shockwave should not to have such an effect as in the case when it spreads along the surface. The next reason is that mixing of explosive substances is limited by the manner in which the gasholder will rupture and how strong the initiation will be. The process of methanogenesis is primarily anaerobic. When the membrane rupture is initiated by (for example) lightning, only a limited volume of biogas will be mixed with air. Moreover, a part of shockwave energy will be expended to damage of membrane. Last but not least the TNT model is applicable above all for detonation with overpressure 100 kPa and more and for a great distances (Makovička and Janovský, 2008). From this it follows that the calculated values are approximate and the estimated consequences are very conservative. Nevertheless, with regard to the foregoing, can be said that the placement of buildings in vicinity (as in the model case) is not suitable. This situation increases the risk of injuries of employees or livestock by wreck of gasholder, roof or smashed windows.

Scenario II

The next scenario presupposes that biogas begins to leak through the hole created by mechanical damage or lightening. However, biogas is initiated with delay (Koopman, Ermak, 2007). This scenario can occur in the case when the gasholder has only one layer. Nevertheless, a frequent solution of gasholders is a double-layer system. In this case, damage to the first layer means a drop in air pressure between the layers; leakage of biogas is highly unlikely. This model example assumes a one-layer gasholder system. The opening size is set to 80 cm (for the case of mechanical damage). The results are shown in Figures 3 and 4.

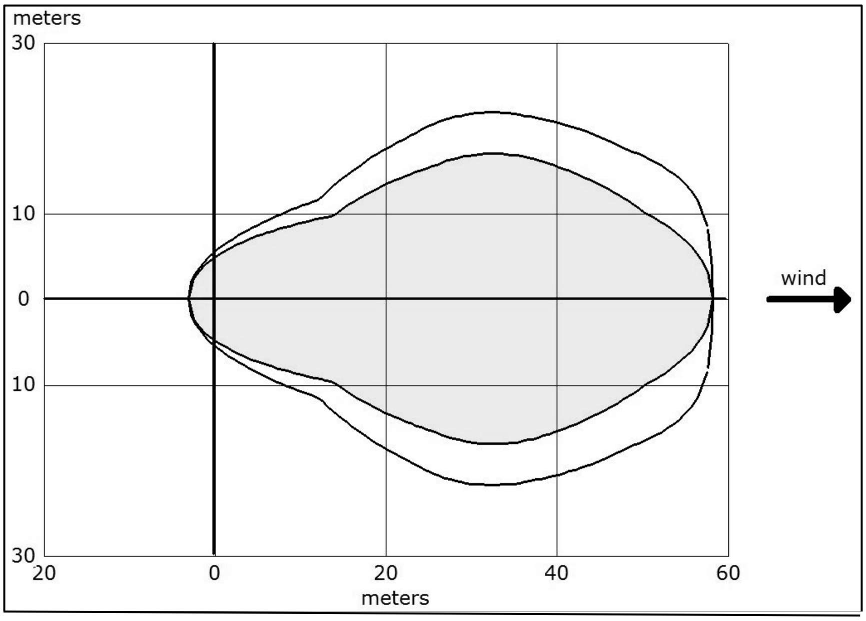

Figure 3. Threat zone of blast

Obrázek 3. Plocha ohrožená výbuchem

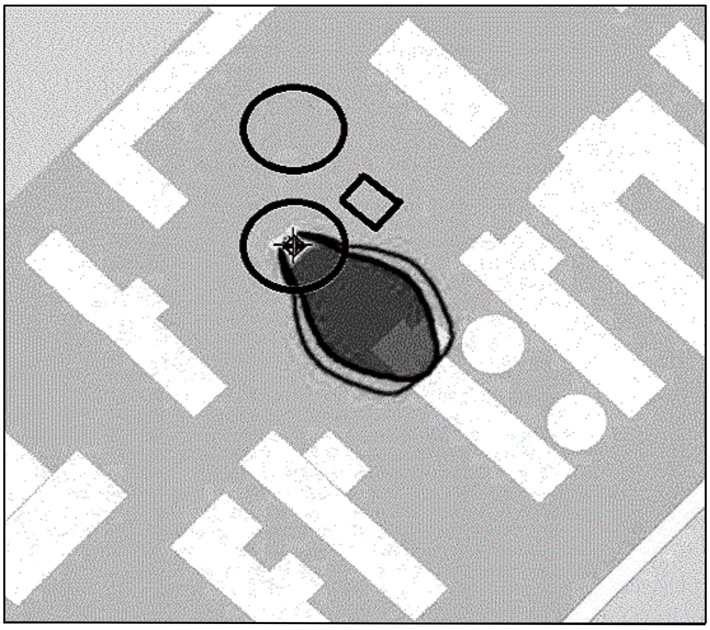

Figure 4. Threat zone on the plan of farm area

Obrázek 4. Plocha ohrožená výbuchem umístěná na mapovém podkladu

The threat zone shown in the figures does not represent a blast area from a single explosion, but rather a composite of potential blast areas for all different ignition time scenarios. A drawn zone in the figures shows where the overpressure of potential shockwaves is higher than 6.89 kPa (1.0 psi) and lower than 24.1 kPa (3.5 psi). In this zone, damage to parts of agricultural buildings can occur along with injuries of persons (or animals) in the nearby area.

If the hole in the gasholder occurs due to defects in material, it can be assumed that the size of this hole would be negligible. In this case, leakage of biogas would disperse to the atmosphere and the explosive mixture would probably not have arisen.

Unfortunately the membrane gasholders are not a frequent solution in chemical industries and thus the data about probabilities of rupture of gasholders membrane are not available.

Scenario III

This scenario is similar to the previous scenario; the only difference is that initiation does not occur (Nicholls, 1979). A gaseous cloud creates with potential possibility of initiation. The size of this cloud is shown in Figures 5 and 6. The cloud is divided into three areas; the first one (the smallest) is the zone with concentration of gas greater than 50 000 ppm while the concentration of gas in the second zone is greater than 30 000 and lower than 50 000 ppm, and the largest zone represents the zone with concentration of gas greater than 5 000 ppm and lower than 30 000 ppm.

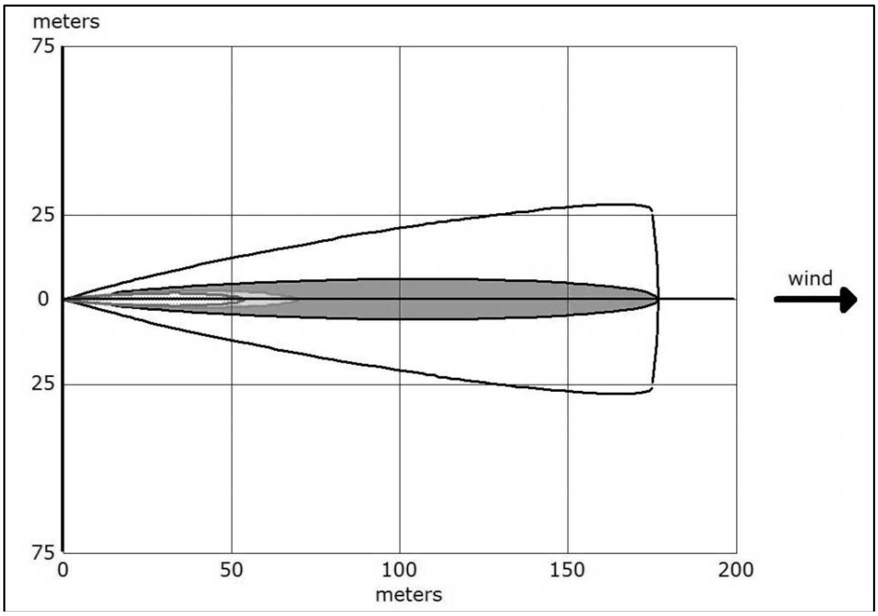

Figure 5. Threat zone of flammable area

Obrázek 5. Plocha ohrožená výbušnou atmosférou

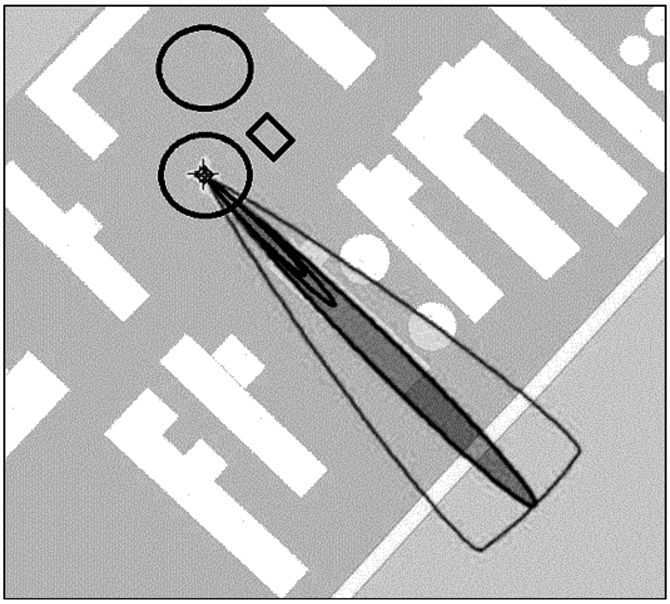

Figure 6. Threat zone of flammable area on the plan of farm

Obrázek 6. Plocha ohrožená výbušnou atmosférou umístěna na mapovém podkladu

The lower explosion limit of biogas with concentration 60% of methane is 60 000 ppm. In the case of substitution of this value to a mathematical model, no zone was drawn.

Scenario IV

The last scenario represents the situation with no explosion; however biogas is burnt as jet-fire (Lowesmith, 2007). The opening size is considered the same as in scenario II, i.e. 80 cm. Threat zones are given by Figures 7 and 8. The area is divided into three zones. In the first zone (the smallest), the thermal radiation is higher than 10 $kW*m^{-2}$. In the second zone it is higher than 5 $kW*m^{-2}$ but lower than 10 $kW*m^{-2}$ and in the last zone the thermal radiation is higher than 2 $kW*m^{-2}$ but lower than 5 $kW*m^{-2}$. In accordance with EPA, if the value of thermal radiation is higher than 10 $kW*m^{-2}$, there is a risk of lethality within 60 s. If the value is higher than 5 $kW*m^{-2}$, there is a risk of second degree burns within 60 s and at 2 $kW*m^{-2}$ there is a risk of pain within 60 s.

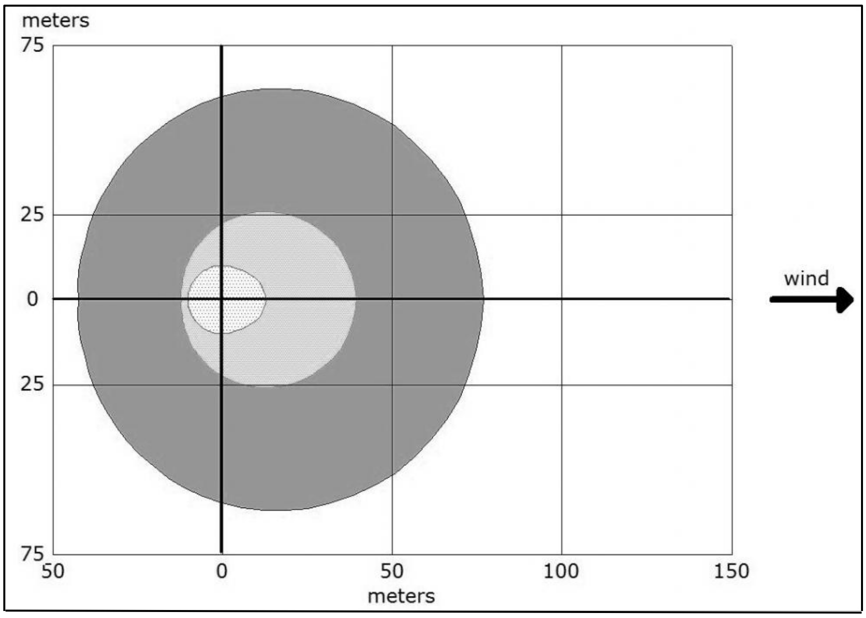

Figure 7. Threat zone of thermal radiation

Obrázek 7. Plocha ohrožena tepelným tokem

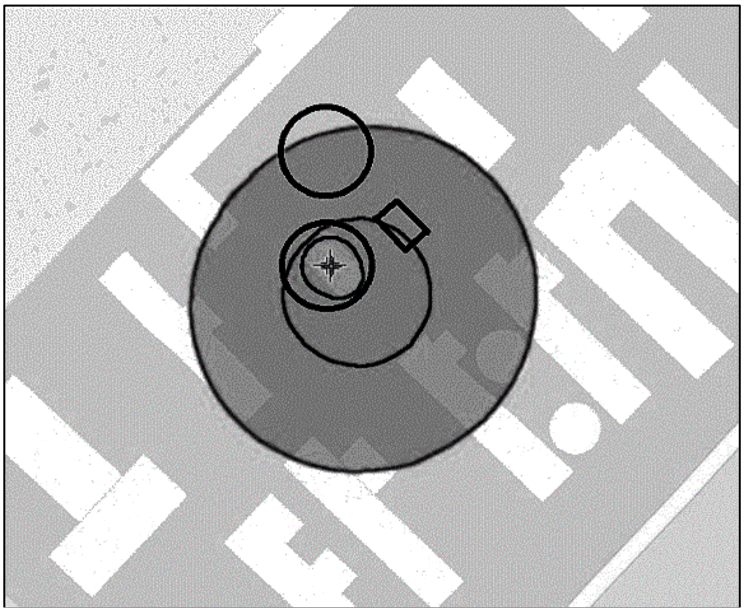

Figure 8. Threat zone of thermal radiation on the plan of farm

Obrázek 8. Plocha ohrožena tepelným tokem umístěna na mapovém podkladu

In the case when the diameter of opening size was considered to be 5 cm, the diameter of the area with thermal radiation > 10 kW*m^{-2} would be approximately 20 m. The diameter of gasholder is 30 m. This implies that if the hole is created somewhere at the perimeter of gasholder, fatal injuries can occur at the distance of up to 10 m from the gasholder.

Conclusion

The article was devoted to modelling of biogas leakage from the gasholder and to the consequences that would occur due to initiation of explosive mixtures. A conservative approach was chosen for the case when biogas was replaced by methane in ALOHA software and for calculations. In terms of safety, the advantage of biogas is that it is generated mostly in anaerobic environment at low pressure (nevertheless, some technologies utilize an air for reduction of H_2S in biogas, but concentration is such to an explosion atmosphere do not arise). In this regard it can be expected that the consequences of potential initiation of explosive or flammable mixture are not as intensive as in the case of gasholders on other hydrocarbons. It seems that the results of this work can confirm this assumption. However, the risks should not be underestimated. The results represented by the figures show that in the surrounding area of the gasholder, fatal injuries or property damage can occur. From this viewpoint, the placement of gasholder in close vicinity (as in the model case) of buildings is not recommended. This increases a risk of injuries of people or animals who can reside in the surrounding buildings. The results of calculations in work can be summarized as follows:

- Consequences of the first scenario would be the most extensive in accordance with assumption. However, the leakage of whole volume of biogas and its explosion is unlikely. The deflagration of part of biogas volume is more likely.

- The second scenario assume a leakage of biogas and its deflagration with delay. The value of overpressure ranges from 1.0 psi to 3.5 psi. In the case the front part of building near gasholder would be probably damaged.
- If a whole volume of biogas leakage without initiation (third scenario), the area with concentration of gas between 3%$_{vol}$ – 5%$_{vol}$ is approximately 70 m long and 10 m wide. It is an area, where high risk of ignition exists.
- In the case of fourth scenario (jet-flame) fatal injuries occurs within a diameter of 10 m. It means only in the immediate vicinity of the biogas reactor.

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