

Flare stacks on agricultural biogas plants – safety and operational requirements

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Abstract: The flare stack is a piece of equipment, which is used as a safety element at a biogas plant. In the case of a cogeneration unit or gas boiler failure, the biogas is redirected to the flare stack where it is burned. When the flare stack fails, the biogas releases to the atmosphere and an explosive mixture can form. The paper is focused on the description of the causes, which can cause the failure of the equipment. For this purpose, the individual components are described and, subsequently, the possibilities of their failure are discussed. In the next part of the work, the following scenario is considered: failure of the cogeneration unit and flare stack, the subsequent leakage of the biogas to the atmosphere. The calculation for determining the consequences of the biogas leakage is carried out. The size of the gaseous cloud and the explosion pressure in the case of a vapour cloud explosion are determined. The calculations were carried out by the software ALOHA (version 5.4.7).

Keywords: gas cloud; accidents; modelling software; agriculture

Flare stacks are pieces of equipment utilised for the safe disposal of residual gases in the chemical or petrochemical industry. BADER et al. (2011) state that flare stacks deal with a variety of waste gas composition depending on the type of plant. The material released into a flare system is usually a hydrocarbon, or a mixture of its constituents that can range from hydrogen to heavy hydrocarbons. These gases may contain harmful and potentially toxic vapours that must be burned completely in order to prevent damage to the environment and to a human's health (BADER et al. 2011). Flare stacks are an integral part of different plants in the chemical or petrochemical industry. Examples includes biogas plants in agriculture, waste water management, etc. The flare stack fulfils the function of an

emergency piece of equipment at a biogas plant. In the case of a cogeneration unit (or a gas boiler) issue, the biogas is diverted to a flare and burned. Flare stacks can be divided to three basic categories (BADER et al. 2011): (i) single-point flare (ii) multi-point flare (iii) enclosed flare.

At biogas plants, candlestick flares are usually used. A candlestick flare belongs among the single-point flares. Alternatively, enclosed flares are utilised at biogas plants. However, this equipment is financially more demanding than a single-point flare one (CAINE 2000).

The schema of a single-point flare stack at a biogas plant (including safety features) is given in Fig. 1. This is one of the variants. The technological solutions vary depending on the supplier and the

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customer. The safety requirements are mainly given by the technical standards.

Failure of some of the flare stack components, poor maintenance, operational error or extraordinary operating conditions can cause the release of the biogas to the atmosphere. In the case where there is an ignition source present at the same time – a gas explosion may occur also. The article is focused on the determination and description of accident causes (biogas release from a flare stack) and the determination of the possible consequences.

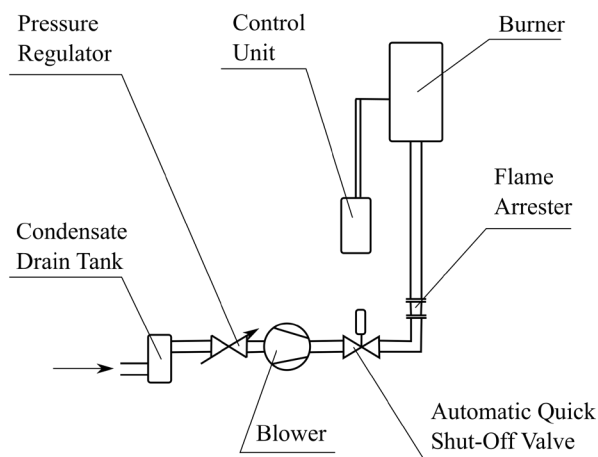


Fig. 1. A possible configuration of a single-point flare stack

MATERIAL AND METHODS

Data collection about accidents was supplied from several sources. These were primarily scientific articles, expert articles, articles from scientific conferences, and databases such as ARIA, eMARS, EMA. In addition, information from newspaper articles was used. Totally two accidents were founded.

The software ALOHA (version 5.4.7), released on September 2016, by the US Environmental Protection Agency (EPA) and the National Oceanic and Atmospheric Administration (NOAA) was used for the mathematical modelling of the consequences of the accidents. Some limitations of this software are the following (EPA and NOAA, 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. Biogas is a mixture of gases and the ALOHA software is not appropriate for the modelling of the mixtures. For this reason, the biogas was replaced by methane.

ALOHA uses the Gaussian model to predict the gas dispersion. This model is appropriate for neutral gases such as air. The biogas is approximately neutral, and the methane used as a substitute is lighter than the air. For the reason, the modelling results should be taken as approximate ones. The original graphical outputs from ALOHA were replaced by modified figures. The reason is that the software ALOHA does not offer the possibility to edit the graph axes and the original outputs were illegible.

RESULTS AND DISCUSSION

The safety and operational requirements given by the technical standards and rules. Flare stacks are mentioned in several technical standards from the viewpoint of safety. The following technical standards and technical rules can be named: (i) EN 676+A2 :2009, Automatic forced draught burners for gaseous fuels (ii) EN 298 ed. 2:2012, Automatic burner control systems for burners and appliances burning gaseous or liquid fuels (iii) EN 746–2:2011 Industrial thermoprocessing equipment – Part 2: Safety requirements for combustion and fuel handling systems (iv) ISO 25457:2009, Petroleum, petrochemical and natural gas industries – Flare details for general refinery and petrochemical service.

In addition to the above, individual states regulate the rules for the safe operation of flare stacks in their national technical standard and technical rules. In the Czech Republic, for example, these are the following: (i) ČSN 73 0842:2014, Fire protection of buildings – Buildings for agricultural production (ii) ČSN 75 6415:2001, Gas handling of sewage treatment plants (iii) TPG 983 02:2013, Gas handling of biogas plants.

These technical standards and rules generally determine the equipment and safety features of the flare stack [for example EN 746–2:2011, the minimal distance from buildings (for example ČSN 75 6415:2001, ČSN 73 0842:2014 and TPG 983 02:2013) or the operating conditions. The technical standard ISO 25457:2009 is mentioned for completeness. The technical standard ISO 25457:2009 deals with flares, which are installed in plants in the petroleum, petrochemical and natural gas industries. This technical standard determines the parameters of the design. Appendix A of this standard describes the individual parts of flare in detail. Here, safety of equipment is also paid attention to.

However, even if all the requirements of the technical standards and legal regulations are met, an accident may occur. The release of a biogas and the subsequent explosion of the gaseous cloud can be considered as a consequence of an accident.

The description of the selected accidents at a biogas plant. Two flare stack failure accidents were found in the databases. Both accidents were without ignition of the biogas cloud. There was only a leakage. However, it can be assumed that the number of similar accidents will be higher. The reason is that the operators of the biogas plant often have no interest in reporting these accidents to the databases. The descriptions of these accidents are the following:

France, 2016. During the operation of a cogeneration unit a short circuit occurred. The cogeneration unit was shut down. The biogas was redirected to the flare stack. However, the flare stack failed. The mechanical problem with the ignition is mentioned in the report. There are no further specifications available. In accordance with the opinion of the authors, it is possible that there were impurities or sediments which stopped the ignition of the biogas. Standardly, this extraordinary situation is reported automatically to the operator. However, there was also a communication channel failure (Internet connection problems).

France, 2017. Due to the high ambient air temperature, there was a failure of two methane sensors. The automatic system shut down the plant. The pressure in the system increased. For this reason, the biogas was redirected to the flare stack. However, the automatic system unexpectedly shut down the flare stack too. Consequently, the biogas escaped into the atmosphere. In total, 4.2 tonnes of biogas were released into the atmosphere.

Possible causes of the accidents. Accidents in the past are an important source of information. This information can help ensure the safe and reliable operation of the equipment. One method for presenting this information is a fish-bone diagram, where the causes of the accidents are presented. The knowledge about the causes of the accidents (in our case, the release of the biogas) can help prevent future accidents. The fish-bone diagram of the accident causes is given in Fig. 2. The information about the causes of the accidents were acquired from the information of previous accidents and professional articles. In the following text, the individual causes of the accidents will be discussed. For the reason of this paper, the term “Biogas Release”

is considered as an accident. This term means a gas leakage in any quantity.

Flare stack components. The flare stack is a piece of equipment which is composed from various components. The number of emergency situ-

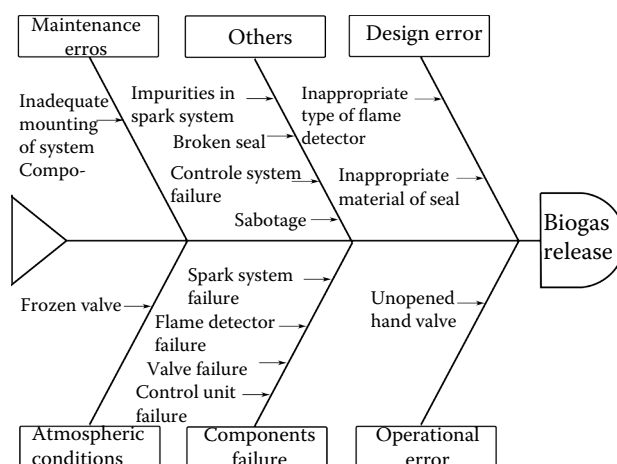


Fig. 2. The fish-bone diagram of the biogas release

ations when a flare stack operates can only occur several times a year. This increases the demand on the maintenance of the individual flare stacks components. These components must be ensured of their trouble-free operation in the case of extraordinary events. There are many variants of the features. These features can work on various physical principles. This fact can also limit their operation during an extraordinary event. Unsuitable operating conditions of these components or the inappropriate choice of components (design error) may cause their failure and, consequently, a malfunction of the entire system. These elements include, for example: a flame detector, a spark system, a flame arrester, pipes, a blower, etc.

(i) Flame Detectors. Flame detectors operate on various principles. The basic principles of the flame detection are the following (BURIŠIN 2008; BELLOVICH et al. 2007): a bimetal fuse, a thermoelectric fuse, ionisation fuses, IR sensors, an acoustic fuse, UV sensors, a combination of the foregoing principles UV/IR.

BELLOVICH et al. (2007) provides a comparison of the selected flame detectors (the thermocouple, flame ionisation, IR sensor and acoustic fuse) to the atmospheric conditions. For example, the flame ionisation system is resistant to rain, fog, snow, steam, direct or reflected sunlight. The thermocouple detector is not resistant to rain or steam (water vapour). The rain cools down the thermocouple.

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For this reason, it is important to ensure the installation with protection against rain. The flame ionisation system (the PBS Power Equipment, s.r.o.) or UV probe (BMF HAASE Energietechnik GmbH) belongs among the most frequently used sensors in the biogas plant's flare stacks.

The limiting factor can be the burning temperature also. This is especially true for the flame detection system, which is based on the thermocouple or ionisation. Here, high temperatures can damage the system. The flame temperature during the combustion of the biogas is about 850°C. All the mentioned systems can be used for flares at biogas plants from the temperature point of view.

Accidents are an important source of information about the principles of flame sensor failures. Detectors can fail in the main ways, as is apparent from accidents which were caused by the failure of the flame detectors. Whether during the ignition sequence or in a flame-out situation, a false positive signal can result in allowing the unburned gas into the fire equipment, which could then suddenly ignite and cause an explosion. There are several possible causes of a run-away condition (BAKER et al., 2011): (i) Improper wiring in the flame detector; typically occurs if the lead wires are reversed or shorted (ii) Inadequate quench gas in the Geiger–Müller tube. This may occur because the initial amount of the quench gas was insufficient as manufactured or because the quench gas has leaked out due to an improper seal or crack in the tube.

It is important to stick to the manufacturer's instructions in order for the flame detector to properly function. The sensor life is also limited, depending on the type and manufacturer. A life of around 40,000 h is stated for the UV sensors (BAKER et al. 2011). SAINT (2012) states that UV sensors can be a suitable choice for outdoor use. However, a combined UV sensor with an IR sensor provides higher resistance against potential false alarms caused by high-energy flashes from reflective surfaces. The sources (which can cause a false signal) have a dual character – natural and anthropogenic. For example, lightning belongs to a natural source. Sources such as an artificial light source, welding, the radiation from heating units and the like belongs to the anthropogenic sources.

(ii) Flame Arresters. In accordance with the technical standard ISO 16852 :2010, flame arresters are devices, which are connected to the opening on the vessel or into the connecting pipe system of

the vessels. The fixed function of these devices is to allow the flow, but prevent the flame transmission. The choice of the type of the flame arrester depends on many factors such as the type of substance which it is (transported or processed), the physical condition, the location in a system, etc. On the basis of these properties, the material of the arrester, the maximum experimental safety gap (eventually, the choice of the liquid flame arrester), the maximum allowable processing pressure or temperature are chosen. In the case of flares at biogas plants, flame arresters are most frequently installed into a pipe (i.e., an Inline Deflagration Flame Arrester). The example of a flame arrester at a biogas plant is an arrester with a maximum experimental gap < 0.9 mm, a maximum permissible pressure of 1.2 bar and a maximum permissible gas temperature of 60°C. For example, 1.4301 steel is a material, which is used for the production of this type of arrester. It is a chromium-nickel stainless steel, with the share of the chromium ranging from 17.5 to 19.5 w.t. (%) and with the share of the nickel ranging from 8.0 to 10.5 w.t. (%). It is the steel which is most often used in the food industry. It is also used in the chemical industry, for example, for the production of an apparatus for producing nitric acid, fertilisers and the like. Flame arresters with a thermocouple are utilised for larger pipe diameters (DN 80). The material used is 1.4310 chromium nickel steel. The share of the chromium is from 6.0 to 19.0 w.t. (%) and the share of the nickel is from 6.0 to 9.5 w.t. (%). 1.4310 steel has a higher tensile strength, which may reach values up to 2,000 N·mm⁻² when compared to 1.4301 steel.

The main flame arrester element type can be a so-called crimped ribbon construction. The authors EDWARDS and NORRIS (1999) state that the resulting construction is inherently strong allowing it to be used for more demanding detonation arresters, although deflagration types also exist. The construction is also highly reproducible with the accurate cell size control. The straight parallel cells are a useful additional feature, which, in combination with a relatively high free area percentage, leads to pressure drops that are quite low in comparison to most other element types which have a labyrinth cell structure. The crimped ribbon is considerably more expensive compared to other arrester element construction types. The crimped ribbon construction can have a free area as high as 60–75% (EDWARDS, NORRIS 1999).

The Maximum Experimental Safe Gap (MESG) belongs to one of the most important parameters, which helps to ensure the correct functioning of the flame arrester. The value of the MESG also depends on the type of the device (methodology), in which the value was measured. In this regard, an interesting work was made by Britton (BRITTON 2000), which shows the MESG differences for the individual substances and the different methodologies.

The author BRITTON (2000) states that the differences in the MESG between some substances can be significant (for example, acetylene or ammonia). Somewhere, the differences are slight (methane) or no difference (benzene). For this reason, the MESG is not a reliable measure of the effectiveness of the flame arresters. This is also stated in the technical standard ISO 16852:2010. It should also be noted that the MESG is a function of pressure. This parameter also has not been verified for a wide range of gas mixtures. When there is doubt, it is always necessary to seek expert advice.

In accordance with the technical standard ISO 16852:2010, it is also suitable to pay attention to sudden changes in cross-section of the pipes and the ambient temperature. Bends in the valves, changing the diameter of the pipe, elbows (etc.) can increase the reverse turbulence which increases the pressure in the system and reduces the efficiency of the flame arrester. For this reason, flame arresters should be placed where changes in the cross section do not occur. Flame arresters should not be placed in the vicinity of powerful sources of heat also. The failure of the flame arrester can be caused by an increased temperature when it is not designed for this temperature.

The contents of the solid particles in a gas are also an important aspect. Solid particles can clog the internal flame arrester element. This increases the pressure loss in the system and the efficiency of the flame arrester. It is, thus, necessary to periodically check the flame arrester.

(iii) Spark System. Flame ignition is possible in several ways. The fundamental ways that can be included are: a high voltage ignition electrode, a heater coil, and an auxiliary burner.

A high voltage ignition electrode is the most commonly used device for the ignition of a biogas in flares. The failure of the electrode can cause a leak of the biogas to the surroundings and an explosive atmosphere can arise. The safety function is set with the use of the control unit. So, in the case of an emergency at the biogas plant and the

subsequent biogas flow into the flare, the electrode causes the discharge several times in an interval. In case that the gas flow is not ignited, thus the flame arrester is not sent a positive signal, the supply of the biogas into burner is closed.

(iv) Other components. Components such as a blower, valves and seals, etc. are parts of the flare stack. When the blower fails, the gauge pressure of the gas will not be sufficient enough and the flame will not be stable. The volumetric flow rate decreases and the pressure in the gas holders increases. If this situation lasted a long time, the biogas could leak through the liquid fuse placed on the gas holder.

In the case of a valve failure – the valve does not open – a similar situation as in the previous case occurs. The pressure in the gas holder increases and the biogas flows through the liquid fuse into the atmosphere. Small leaks can occur due to a leakage in the valve or thanks to any damaged seals.

Operational Error. Some biogas plant technologies are not equipped with an automatic valve. In the case of extraordinary event, the alarm warns the operator. Subsequently, the operator opens the valve manually. A situation may occur when the valve will not be opened by the operator. Afterwards, the pressure in the gas holder increases and the biogas flows through the liquid fuse into the atmosphere.

Atmospheric Condition. Generally, extreme atmospheric conditions can cause the failure of the equipment. It may be, for example, the freezing of the valve or the failure of the electronic elements due to high temperatures. The choice of adequate elements for the flare stack is fundamental for the trouble-free operation.

Others causes. Other possible causes can be impurities in the spark system, a control system failure or sabotage. Impurities in the spark system can cause the failure of the ignition of the gas mixture. Exceptionally, the operating conditions can cause an error of the automatic control system. This is obvious, for example, from the accident in France in 2017 (see the section “The description of the selected accidents at a biogas plant”).

Modelling the consequences of the biogas release from the flare stack. For the purpose of modelling the consequences, the following scenario was chosen: the cogeneration unit fails and it subsequently shuts down, the automatic control unit redirects the biogas to a flare stack, however, the flare stack fails too, then the biogas is released into the atmosphere. The software ALOHA was

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used for modelling the consequences of this scenario. The significant limitations of this software are the absence of mathematical models for modelling the gas mixture release. Methane was used as a substitute for the biogas. This gas is a major gas in the biogas. Nevertheless, the biogas has different physical and chemical properties. It is, above all, the density of a gas. The density of the biogas (60% of CH_4 and 40% of CO_2) is similar as the density of air. It can be assumed that the biogas will behave neutral to the air. However, the density of methane is lower and it is lighter than air. The results of the models are indicative.

The procedures described by Novák et al. (2007) can be used for the calculation of the basic state variables of the gas mixture. Or, it can also be assumed (under defined circumstances) that the biogas behaves as an ideal gas – the time consumption for the calculation is much lower. This approach was used, for example, in the work by VITÁZEK et al. (2016).

The following boundary conditions were selected: the temperature (t) of the gas = 40°C , absolute pressure (p) of the gas = 105 kPa, the velocity (v) of the wind = $1 \text{ m}\cdot\text{s}^{-1}$ (at 10 m above ground), the temperature of the ambient air (t_a) = 10°C , the class of the atmospheric stability (F–by Pasquill), the volumetric gas flow rate (V) = $500 \text{ m}^3\cdot\text{h}^{-1}$ (this corresponds to a power source of about 1000 kW_{el}). An overgrown/built up terrain is assumed in the calculation. It follows from the above conditions that a conservative approach has been chosen for the calculation.

In the first step, the greatness of the gaseous clouds with various gas concentrations were calculated. Three levels of concentrations were selected: 50,000 ppm (100% of lower explosive limit – LEL), 30,000 ppm (60% of LEL), 5,000 ppm (10% of LEL). The LEL values are for methane. The calculated concentrations are the gas concentrations at the ground level. The results are given in Table 1. Modified graphical outputs are given in Figs 3–5.

The results for the different point source heights are presented in Table 1. The height (h) = 0 m is possible to consider as a conservative approach. This is obvious from Table 1. The LEL was achieved only in this case. The length of the gaseous cloud is 63 m. In next cases, the value of the LEL was not achieved. When the source is in the higher point, the explosive mixture at ground level does not arise. However, the situation at another height level can be different. However, it can be assumed that the gas will be diluted more quickly at higher levels.

The value of the gauge pressure will be higher than 6.9 kPa (1.0 psi), but at the same time lower than 20.7 kPa (3.0 psi). The size of the affected area is dependent on the time, when the initiation occurs.

Table 1: The results of the modelling

Concentration (ppm)	H of the source (m)	L of the gaseous cloud (m)
50,000	0	63
	1	–
	2	–
30,000	0	81
	1	63
	2	–
5,000	0	204
	1	198
	2	177

ppm – parts per million

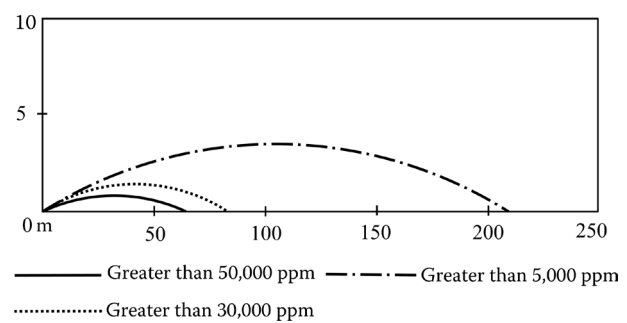


Fig. 3. The flammable threat zone for a height source of 0 m

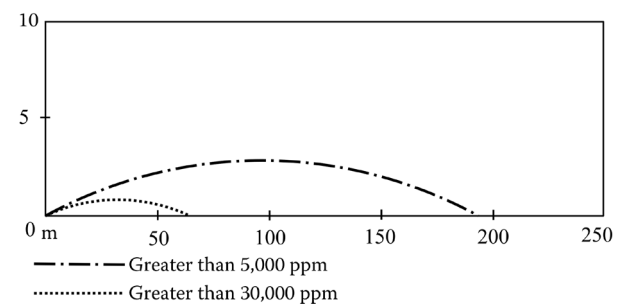


Fig. 4. The flammable threat zone for a height source of 1 m

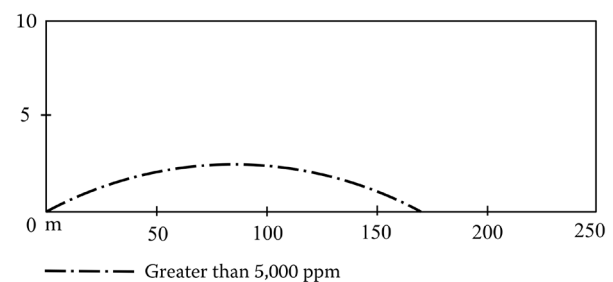


Fig. 5. The flammable threat zone for a height source of 2 m

In accordance with the methodology of CPR 18E (Commissie voor de Preventie van Rampen) (UIJT DE HAAG, P.A.M., ALE, 1999; RIVM, 2009), the fatal injuries of people are not assumed in this case.

CONCLUSION

The trouble-free operation of the flare stack depends on the properly selected components, which will work even in the case of extraordinary operating conditions, and on the proper maintenance. In the case of an extraordinary situation (for example, a cogeneration unit failure) and a flare stack's failure, the biogas flows to the atmosphere. There are two ways for the leakage to occur. The first way is a leakage through the burner and the second is through the liquid fuse placed on the biogas holder. The modelled scenario assumes that the biogas is released through the burner of a flare stack. From the results of the model, it is possible to presume that in the case of a leakage of the biogas, the formation of the explosive mixture at ground level is not probable. However, this formation is possible at higher levels. The hot surfaces on the roof of the cogeneration unit building can pose a certain hazard. From this perspective, it is, therefore, inappropriate to place the cogeneration unit building at a short distance from a flare stack. In the case that it is not possible, the sufficient height of the flare stack must be ensured, in order for the gaseous cloud to be dispersed away from the possible sources of ignition. It is appropriate to consult the specific values of the distance or the height of the flare stack with a specialist. Nevertheless, the limits of the legal regulations and technical standards must always be met.

The resulting explosion pressure achieves relatively low values. The movement of people in a biogas plant is low in the object (it is usually only one operator). It is possible to regard the resulting risk of the considered scenario as acceptable.

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