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Assessment of Syngas Storage Tank Hazards Taking Account of the Domino Effect

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Abstract: In most countries energy needs are satisfied using fossil fuels. Fossil fuel combustion involves environmental pollution and greenhouse gas emissions. The effect of the depletion of natural resources and the growing awareness of the need to protect the environment are the reasons that clean energy and alternative energy sources have been significant research issues. One of the most important technologies enabling efficient generation of low-emission energy is the gasification process of synthesis gas production. Syngas is primarily composed of hydrogen and carbon monoxide, but depending on the feedstock, it can also contain smaller concentrations, e.g., of carbon dioxide, methane and nitrogen. Because synthesis gas contains flammable and toxic substances, it may pose hazards to humans and the environment at every stage of gas production, storage, transport or final utilization if released uncontrollably. This paper presents the results of analyses related to hazards created by an uncontrollable release of synthesis gas during storage. A failure of a syngas system may cause damage to other, subsequent technological systems and facilities located in the neighborhood and containing dangerous substances. The problem gains special significance if syngas is stored in many tanks, where a failure of one may result in damage to subsequent tanks due to the so-called domino effect. The conditions in which the domino effect may occur are analyzed and the effect occurrence probability is determined depending on the mutual location of the tanks.

Keywords: syngas; storage; hazards; domino effects

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1. Introduction

The development of every economy in response to growing needs of individual communities makes it necessary to produce increasing amounts of energy. These rising energy needs are still primarily satisfied by burning fossil fuels. This is the cause of environmental pollution and greenhouse gas emissions. The requirements aiming to reduce these emissions, the awareness of the hazards resulting therefrom and the need to protect the environment are the reasons why clean energy and alternative energy sources have been significant research issues [1,2]. Energy can be obtained from technologies such as the processes of fuel conversion and gasification, which are considered relatively clean, reliable and energy-efficient [1,2].

The end product of the gasification process is synthesis gas (syngas). It can be an ideal alternative fuel in the field of energy utilization and chemical production. It can also be an important by-product in the petrochemical industry, the production of iron and steel, steam reforming and other production processes [3].

Syngas may be the result of gasification of different feedstocks, such as coal, biomass, wood, waste, hydrocarbons, etc. The commonly used gasification agents are air, oxygen and steam. Synthesis gas is a gas mixture of predominantly carbon monoxide and hydrogen. It can also contain other gases, such as methane, nitrogen or carbon dioxide. The composition depends on the feedstock and the gasifying medium [4,5].

The potential for syngas utilization makes the processes of obtaining synthesis gas from gasification an ongoing topic of research. An analysis of the gasification process of various types of biomass (cellulose, xylans, lignins and starch) to produce syngas rich in carbon monoxide is presented in [6]. The results of experimental testing of gasification of biomass waste (brewery spent grain, wheat straw, hay, pine sawdust) are presented in [7]. The research focuses on determining the effect of the presence of solid catalysts and gasifying agents on syngas composition. The modelling of the process of co-gasification of solid municipal waste and coal using the ASPEN Plus V10 software to optimize operating conditions for the production of hydrogen-rich synthesis gas is presented in [8]. The process of steam co-gasification of fruit waste (banana skins) and lignite is presented in [9]. The research on and the analyses of the gasification process presented in the literature are based not only on the use of substrates such as coal, biomass, etc., but also the post-COVID-19 pandemic medical waste, for example. The use of medical plastic waste as fuel for syngas production is described in [10].

Synthesis gas obtained in various conditions can be used for electricity generation. It is also assumed that it can be used in internal combustion engines, fuel cells, as well as in other fields. For this reason, the analysis of the process of syngas combustion has become an important research topic. Experimental studies on the dynamics of the syngas flame explosion in a narrow channel are presented in [11]. An analysis of the process of syngas combustion in a two-dimensional channel is conducted in [12]. An evaluation of the combustion of a syngas–air mixture in a narrow gap disk reactor is presented in [13]. The use of a mixture of syngas and natural gas in atmospheric burners is analyzed in [14]. The low content of energy in syngas makes it difficult to use this product or its mixtures efficiently. It is shown, however, that mixtures of syngas and natural gas containing up to 15% of syngas by volume can operate in atmospheric natural gas burners without modification. Experimental results of the combustion of natural gas, methane and their mixtures in a bidirectional swirling flow are discussed in [15].

Regardless of the development of the direction of research on the gasification process to obtain synthesis gas and on the possible applications of gas, it must be remembered that in the event of an uncontrolled failure of the syngas system, gas composition and its physicochemical properties can result in dangerous consequences for people and the environment. The hazards of fire and explosion or intoxication during syngas storage, transport and use can lead to injuries and human death and to significant damage to the system itself. Therefore, it is essential to examine the conditions for the safe use, transport and storage of synthesis gas. The threat caused by a syngas leak may be intensified by a domino effect. This phenomenon has also been the subject of many publications.

A hybrid model for dynamically analyzing domino effects in chemical tank farms to address limitations in accounting for the system's state over time and complex parameter interactions is presented in [16]. A dynamic assessment of domino effects in storage tank farms based on a machine learning approach is presented in [17].

In [18], a novel approach is proposed to model the spatial–temporal evolution and perform a risk analysis of fire-induced domino effects based on the synergistic effect and accident evidence. The approach takes account of the fire accident evidence to model the synergistic effect of burning units.

In [19], 165 domino accidents of storage tank areas between 1970 and 2017 are analyzed to establish theoretic models and the event tree. The initial accident probability distribution and four typical accident node escalation models are selected: fire–fire, fire–explosion, explosion–fire, explosion–explosion. The authors of [20] describe the construction of the domino effect scene of an explosion accident in an LPG storage tank area, the analysis of the characteristics of the LPG tank explosion shock wave and the target storage tank failure. In [21], a methodology involving a Domino Evolution Graph (DEG) model and a Minimum Evolution Time (MET) algorithm is proposed to model the spatial–temporal evolution of domino accidents. Synergistic effects and parallel effects of the spatial evolution, as well as superimposed effects of the temporal evolution possibly occurring in complex domino evolution processes, are considered.

This publication focuses on evaluating the consequences of fire and explosion of syngas released from a storage tank. The impact of various parameters on the level of potential hazard to humans and the environment is analyzed. Additionally, the influence of the presence of the second tank on the effects of a syngas fire is taken into account. The considered situation of the presence of two tanks in gas production and storage installations is quite common. One of the tanks is charged during syngas production, while syngas can be taken from the other tank and used. In the paper, the quantitatively assessment of the hazards resulting from the presence of two reservoirs next to each other, as well as the assessment of the probability of the domino effect occurring, are discussed. This analysis provides an insight of the magnitude of hazards caused by the storage of syngas and also offers tips on assessing the impact of the distance between tanks on the magnitude of hazards. The results presented may be useful in the process of designing such installations.

2. Syngas Characteristics

Synthesis gas is a multi-component mixture consisting primarily of hydrogen, carbon monoxide, nitrogen and other gases. In most cases, it contains 30 to 60% of carbon monoxide, 25 to 30% of hydrogen, 0 to 5% of methane, 5 to 15% of carbon dioxide, as well as smaller amounts of sulphur compounds, hydrogen sulphide, etc. [22]. The variability of its composition is due to the use of different substrates, the application of different types of gas generators in the gasification process or their operating parameters. The process of designing a gasification plant is therefore based on, among other things, easy access to the raw material used for the potential location and appropriate selection of the gasification technology. The processes utilized to obtain the desired end product is optimized in subsequent stages [23].

Synthesis gas is used in the production of ammonia, methanol, hydrogen and hydrocarbon fuels. The largest share of produced syngas is used to synthesize ammonia for the production of fertilizers ($\sim$55%); the second largest share is the amount of syngas hydrogen used in oil refining processes (22%). Smaller amounts are used to produce methanol (12%). Syngas is also used as a semi-finished product in the production of synthetic oil [24]. It can also be used to generate electricity and heat [25]. Its use as fuel creates broad prospects for the development of energy systems, as they are then less dependent on petroleum-based fuels. The use of syngas is also in line with the interest in obtaining alternative and clean energy. Synthesis gas can be used as fuel for vehicles and fuel cells [24,26].

Synthesis gas is a hazardous substance which, due to the physical and chemical properties of its components, poses fire, explosion and toxic hazards. The course of an emergency event involving syngas depends on system operating parameters, gas composition and/or the occurrence of ignition [27,28]. An emergency event can take the form of a jet fire, a flash fire, as well as a BLEVE phenomenon and an explosion. The occurrence of each of these effects is determined by different conditions, such as system operating parameters, for example. In each case, however, their negative consequences pose substantial hazard to people and the environment. In addition, these consequences can escalate to greater proportions in the event of a domino effect.

3. Hazards Related to an Uncontrolled Release of Syngas from the Storage Tank

3.1. Synthesis Gas Storage

The storage of syngas due to its direct transfer from the gasification plant to use is not a common practice today. The economic benefit and the technical feasibility of the syngas storage process vary depending on, among other things, the physicochemical properties of the gas produced in the gasification process. Syngas composition, energy density, flammability limits, etc., depend on the conditions in which gasification is carried out and on the substrates used in the process. Synthesis gas consists primarily of carbon monoxide and hydrogen and displays relatively low energy density. The density, which usually totals from about a sixth to a third of the density of natural gas, means that larger amounts of syngas are required to generate an equivalent amount of electricity. Therefore, the current analyses of syngas storage processes are based on the possibility of using stored gas to generate electricity during high-demand periods [23]. This can also be a method to improve productivity, reliability and availability of IGCC power plants by increasing syngas availability during scheduled and unscheduled downtimes [23,29]. The analyses also indicate that syngas storage effectively improves the long-term operational coordination of the CCHP system, improves the efficiency of waste heat recovery and increases thermodynamic efficiency [30]. Syngas storage is used not only to improve the conditions of electricity generation; in addition to that, it enables a wider use of synthesis gas and creates opportunities for an additional supply, which can bring economic benefits for both producers and consumers.

The options of syngas storage most often come down to storing compressed gas. This is the most suitable method for large-scale stationary syngas storage. It is also cheaper compared to alternatives such as liquefaction. Compressed gas storage is the simplest solution, which usually requires only a pressure tank and a compressor [23]. Such tanks must be equipped with appropriate safety valves, level, pressure and temperature gauges, etc.

3.2. Hazards Related to an Uncontrolled Release of Synthesis Gas

As already mentioned, the composition of synthesis gas is substantially affected by used substrates and the gasification process itself. The two main components of syngas—hydrogen and carbon monoxide—are the substances that define the hazards related to the processes of the gas storage, transport and use. The hazards include fires, explosions and intoxication [4]. In addition, a fire and an explosion can be the primary events leading to the occurrence of the domino effect. The negative consequences of a fire are the direct impact of the flame and the generated heat flux. In the case of an explosion, the negative effects are the pressure wave and the hazard caused by bits of the ruptured system flying in the air. The heat flux tolerated by humans is 2.5 kW/m^2 at exposure times of less than 5 min. The longer the time, the stronger the pain felt by the victim. Higher heat flux values at the level of 12.5 kW/m^2 can cause the death of 1% of exposed people in one minute; at the exposure time of 10 s, first-degree burns occur. At the heat flux value of 25 kW/m^2, 100% of exposed people die if the exposure time is longer than 1 min, and serious injuries occur at an exposure time of 10 s. The consequences of the explosion impact on humans involve indirect and direct effects. The threshold value of the pressure wave causing rupture of the eardrum of the human ear is 13.8 kPa. In the analysis of the direct effect of a pressure wave on a human, the value of 20 kPa is considered to be the threshold of survival (especially in a confined space). Indirectly, a pressure wave of this value generated from an explosion can knock people down. The pressure wave threshlod of 48.3 kPa is the value for internal injuries caused by the explosion. Indirectly, it results in a 100% probability of human death from injuries caused by bits of the ruptured system flying in the air and acting as missiles. A pressure wave at levels higher than 482.6 kPa arising due to the explosion causes immediate death of humans [4,31].

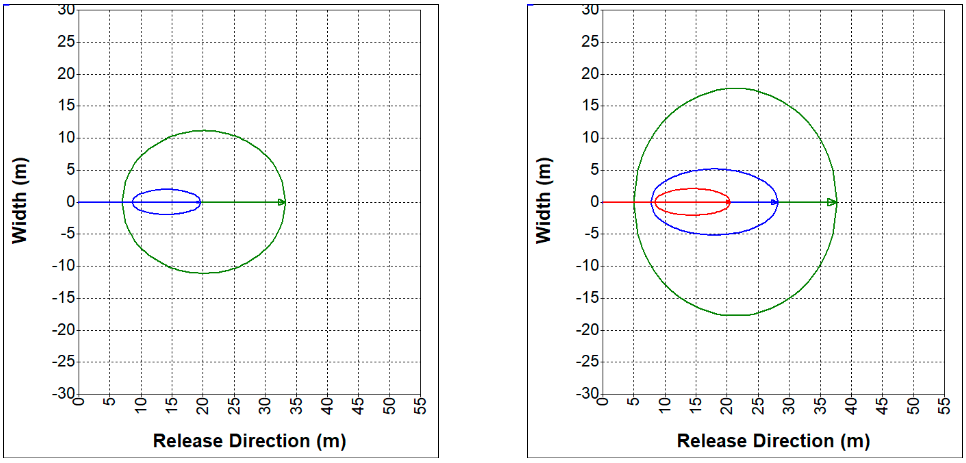
The figures below show example hazard zones arising due to the impact of the heat flux generated from a fire of synthesis gas released from a 10 m^3 tank. In the hazardous event scenario, it is assumed that the damage to the storage tank is a hole with the diameter of 5 cm (a puncture). The presented analyses relate to syngas with the following composition [32]:

- CO—19%, CO_2—12%, H_2—19%, CH_4—2%, N_2—48% (mixture I);
- CO—23%, CO_2—29%, H_2—38%, CH_4—9.5%, N_2—0.5% (mixture II).

The mixtures are obtained from biomass (I) and coal (II) gasification. The potential hazard zones are calculated using the PHAST v6.7. software [33].

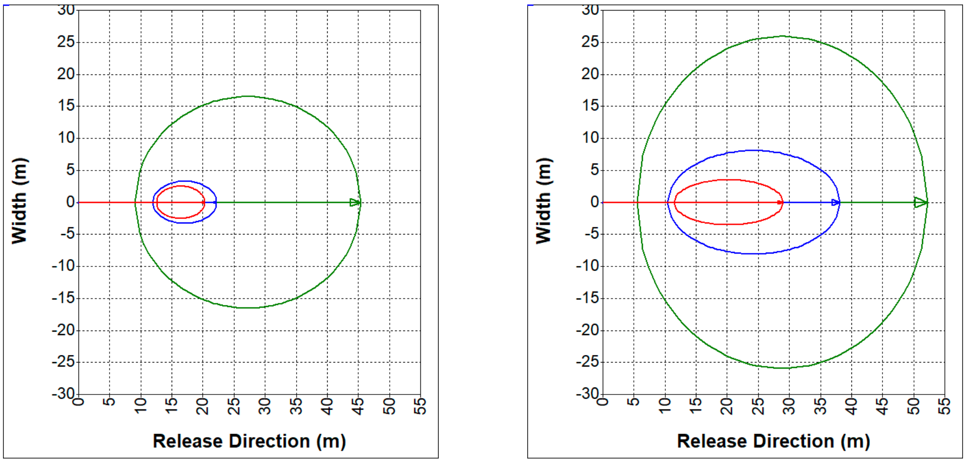
Figures 1 and 2 present fire hazard zones due to thermal radiation exceeding 2.5, 12.5 and 25 kW/m^2—green, blue and red curves, respectively. The pressure in the tank is assumed at 2 MPa and 4 MPa [30]. The wind speed is adopted as 2 m/s and its direction is indicated by the arrows.

The charts presented above indicate that a change in the content of flammable gases in the syngas mixture has a substantial impact on the level of hazard created due to a tank failure. If the hydrogen content is doubled, the hazard zone becomes longer. The doubling of the pressure of the synthesis gas in the tank also causes an increasing level of hazard.



Mixture I Mixture II

Figure 1. Fire hazard zone, p = 2 MPa (radiant heat flux higher than 2.5 kW/m^2—green curve, 12.5 kW/m^2—blue curve and 25 kW/m^2—red curve).



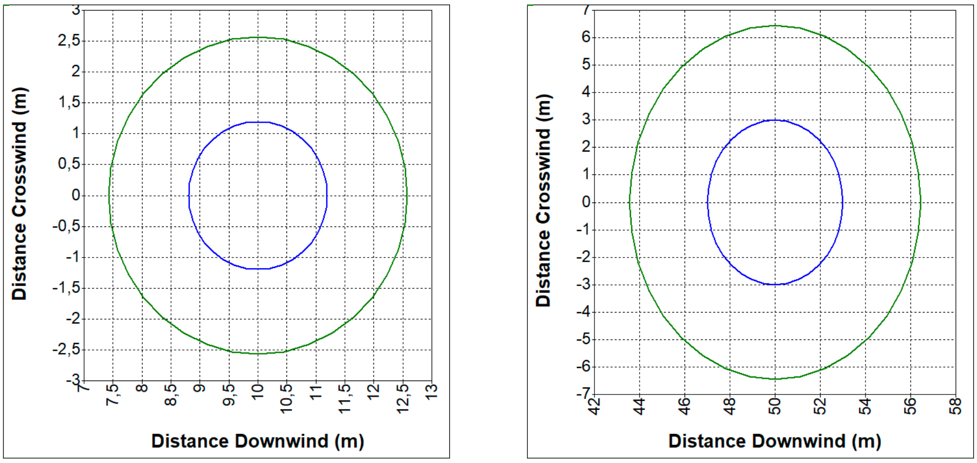
Mixture I Mixture II

Figure 2. Fire hazard zone, p = 4 MPa (radiant heat flux higher than 2.5 kW/m^2—green curve, 12.5 kW/m^2—blue curve and 25 kW/m^2—red curve).

The failure of the tank, in the case of delayed ignition, may also pose an explosion hazard. Figures 3 and 4 present hazard zones related to an explosion of released synthesis gas. The assumed parameters of syngas and the storage tank are the same as in the analysis of the fire hazard. The hazard zone corresponds to the explosion-generated pressure wave with values higher than 13.8 kPa and 48.3 kPa (green and blue curves, respectively). The two values mentioned above are the threshold for the rupture of the eardrum and internal injuries, respectively.

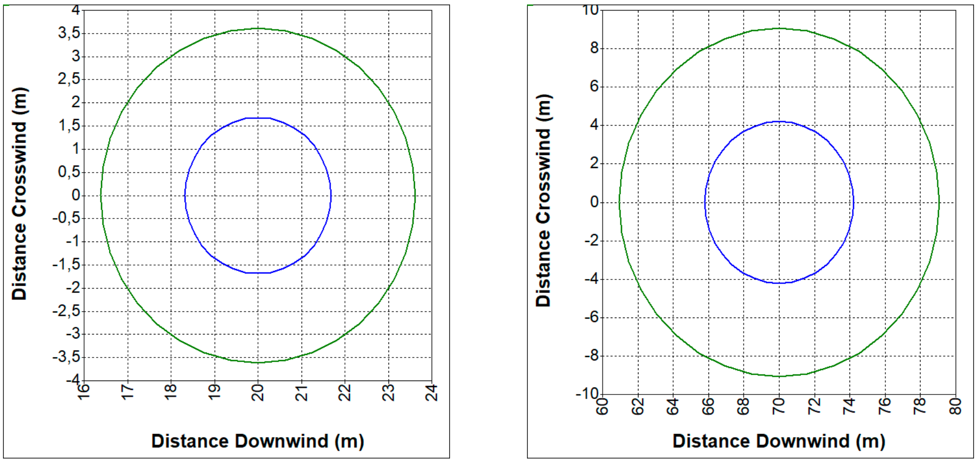
The calculated results indicate that the zone related to overpressure higher than 482.6 kPa causing immediate human death does not occur in any scenario.

Analyzing the charts presented above, it should be noted that this is the worst possible scenario of hazards posed by the effects of an explosion. The charts are presented at a certain distance from the failure (damage) site, which is due to the moving of the cloud of the flammable gas and its delayed ignition. The presented situation concerns the biggest area of the occurrence of the explosion effects. At the place of the delayed ignition, the synthesis gas concentration, despite the cloud moving and being dispersed by wind, is still above the lower flammability limit, which is one of the prerequisites for the explosion to occur. At smaller distances, the analyzed explosion effects also occur, but the range of their impact is smaller.



Mixture I Mixture II

Figure 3. Explosion hazard zone, *p* = 2 MPa (overpressure higher than 13.8 kPa—green curve, 48.3 kPa—blue curve).

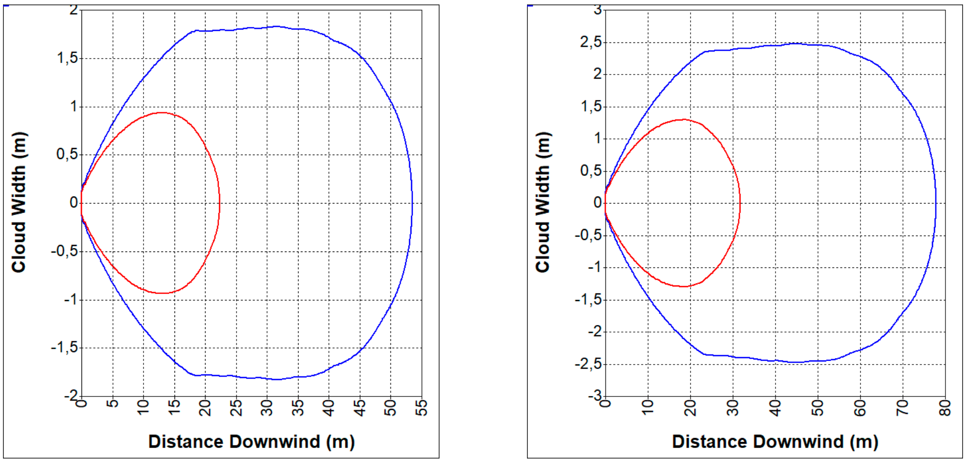


Mixture I Mixture II

Figure 4. Explosion hazard zone, *p* = 4 MPa (overpressure higher than 13.8 kPa—green curve, 48.3 kPa—blue curve).

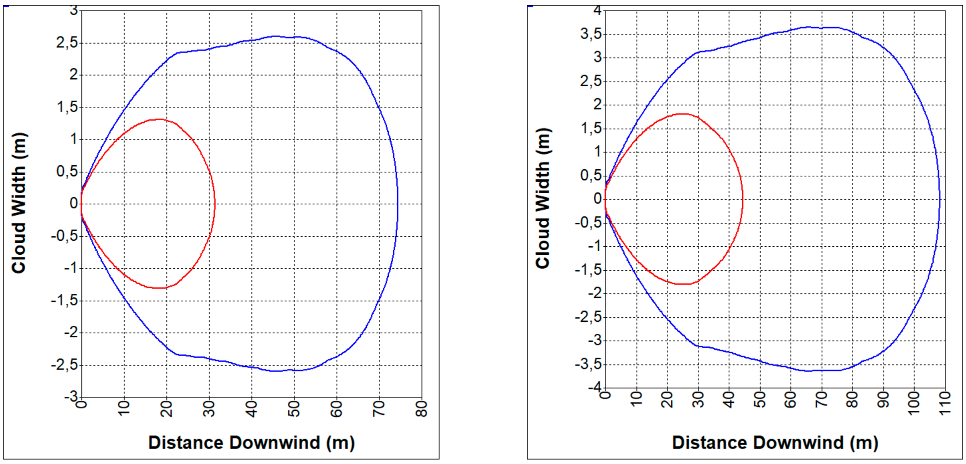
If the syngas cloud does not ignite, another hazard to humans can be gas toxicity. The toxicity is caused carbon monoxide, with is a syngas component. Lower concentrations of synthesis gas at the level of 100–200 ppm can cause headaches or dizziness, nausea and fatigue depending on the exposure time. The value of 800 ppm causes collapse and loss of consciousness after 1 h of exposure, and death occurs within 2–3 h. If the value is twice that high, death occurs within 1–2 h. Carbon monoxide concentrations higher than 3200 ppm result in nausea and dizziness after 5–10 min of exposure. At longer exposure times, collapse and loss of consciousness (30 min) and death (1 h) occur. Concentrations at the level of 6400 ppm cause death within 30 min. At the level of 12,800 ppm, people lose consciousness and die within 1–3 min.

Figures 5 and 6 below show example hazard zones arising due to the toxic impact of syngas released from a 10 m^3 tank. The charts illustrate the occurrence of different levels of hazardous concentration, i.e., 6400 ppm and 12,800 ppm (blue and red curves, respectively).



Mixture I Mixture II

Figure 5. Hazard zone related to the concentration due to the syngas release, p = 2 MPa (concentration higher than 6400 ppm—blue curve, 12,800 ppm—red curve).



Mixture I Mixture II

Figure 6. Hazard zone related to the concentration due to the syngas release, p = 4 MPa (concentration higher than 6400 ppm—blue curve, 12,800 ppm—red curve).

4. The Domino Effect

4.1. The Domino Effect Characteristic

The development of the chemical, petrochemical or power industry leads to an increase in the number of production plants using hazardous substances with flammable, explosive and toxic properties. This also involves an increase in the number and scale of storage tanks in which these substances are stored. The limited space of the location of the storage tanks and systems at the plants can contribute to the occurrence of dangerous phenomena in the form of fires, explosions, as well as the domino effect. The leak and fire of oil that occurred in China in 2015 is an example of such accident. The fire, due to which three storage tanks ruptured and burned, triggered a domino effect. The tanks also re-ignited many times during the rescue operation. A domino effect also occurred in 2019 in the USA, where a petrol storage tank fire spread to other neighbouring tanks located at the ITC Petrochemical oil storage facility in Houston, Texas. Some of the tanks ignited due to the impact of high levels of the thermal radiation flux [34,35].

According to the definition, the domino effect is a series of consecutive events in which the effects of an earlier event are enhanced by successive secondary events, eventually leading to end events. It is also an event defined as the release of a hazardous substance into the environment, which can disrupt other systems in such a way that events escalate and further releases spread. The domino effect is characterized by three basic properties. The first involves the occurrence of the primary emergency event (fire or explosion). The second concerns the spreading of the primary accident onto other systems, tanks, etc., due to the impact of the so-called "escalation vector", e.g., in the form of thermal radiation or a pressure wave. The last property is the enhancement of the consequences. Due to the "escalation" effect, the consequences are more severe than in the case of the occurrence of the primary event only [34–36].

The analyses of past incidents indicate that the most common place where domino-type accidents occur is storage area. Accidents are most often caused by fires, explosions and leaks of toxic substances. However, toxic substances do not cause damage to other systems/tanks directly and are therefore not included in the domino effect analysis. As indicated by the results of an analysis of 225 domino effect incidents, 52.4% of them were triggered by a fire and the remaining 47.6% by explosion. The sequence of events initiated by a fire most often resulted in explosions (62 cases) and other fires (40 cases). The initial event in the form of an explosion led to fires (62 cases) or fires that caused subsequent explosions (21 cases) [34]. It should also be noted that the magnitude of the consequences of a domino effect accident is also influenced by the physicochemical properties of the substances involved in it. For example, the highest number of domino effect accidents involved LPG (72), petrol (33) and crude oil (29) [36].

4.2. Range of Zones Causing Another Tank Destruction

In the event of an uncontrolled release of syngas from a tank that causes a fire or an explosion, another hazard may be created—the potential occurrence of the domino effect phenomenon. The thermal radiation generated by the syngas fire, as well as the pressure wave and the ruptured tank fragments flying in the air due to the explosion, may escalate into more accidents and failures. The primary event effects depend on the mutual position of the systems and tanks at the storage site (cf. Figure 7). A catastrophic complete rupture of the primary system tank creates a hazard propagating in all directions. In the case of partial damage (a puncture), the hazard level depends on the puncture location. For a jet fire, due to the jet direction, the released gas poses a hazard to systems located on the tank side with the puncture [37,38].

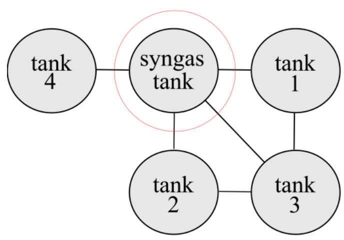


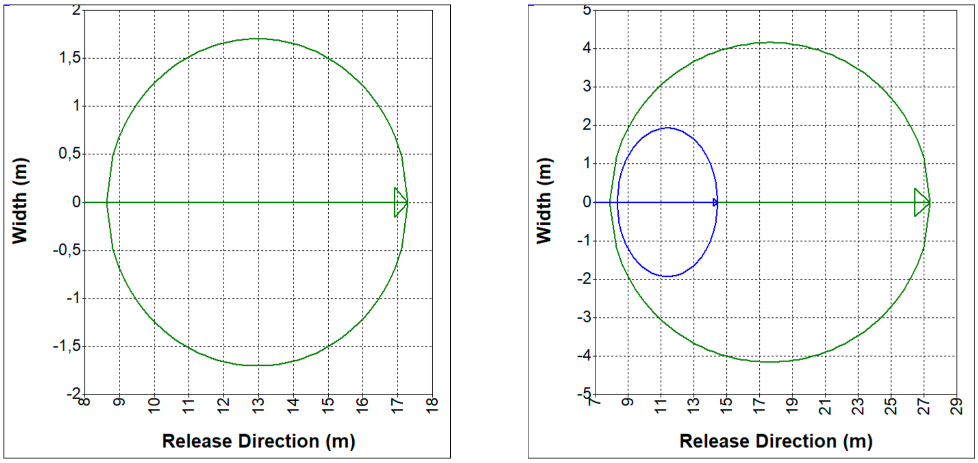
Figure 7. Example layout of tanks.

Considering that the occurrence of the domino effect depends on some factors, the literature offers different threshold values of the physical consequences of the primary system failure that may cause the domino effect. Generally, in the case of fires lasting for a short time, such as the flash fire or the fireball, the impact of the generated heat flux may be too short to cause damage to other systems. Nevertheless, the domino effect is still possible in such a situation. Jet fires and pool fires last much longer and therefore these fire types cause the domino effect the most often.

According to [34,38,39], for jet fires and pool fires, the threshold values causing damage to atmospheric and pressure tanks are 15 and 50 kW/m^2, respectively, at the exposure time of a few minutes. The threshold values of pressure waves causing damage depending on the system/tank types are 17–22 kPa.

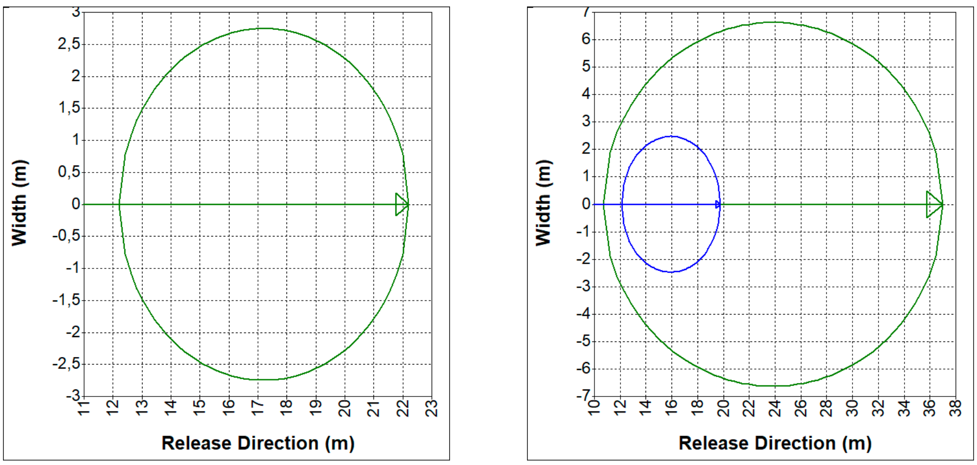
If a fire of syngas occurs due to a 5 cm puncture in the tank wall, the hazard zones related to the impact of thermal radiation with the threshold values of 15 and 50 kW/m^2

(green and blue curves) reach the maximum range of 27 and 14 m for p = 2MPa (Figure 8) and 37 and 20 metres for p = 4MPa (Figure 9), respectively, for Mixture II with a higher content of hydrogen. For Mixture I, there is no zone with heat flux values higher than 50 kW/m^2, and the zone corresponding to the heat flux at the level of 15 kW/m^2 reaches the value of about 22 metres (p = 4 MPa) and 17 metres (p = 2 MPa). This means that if there are more storage tanks of syngas or other dangerous substances within these zones, the consequences of the primary tank failure may escalate, leading to the occurrence of the domino effect.



Mixture I Mixture II

Figure 8. Fire hazard zone, p = 2 MPa (radiant heat flux higher than 15 kW/m^2—green curve, 50 kW/m^2—blue curve).

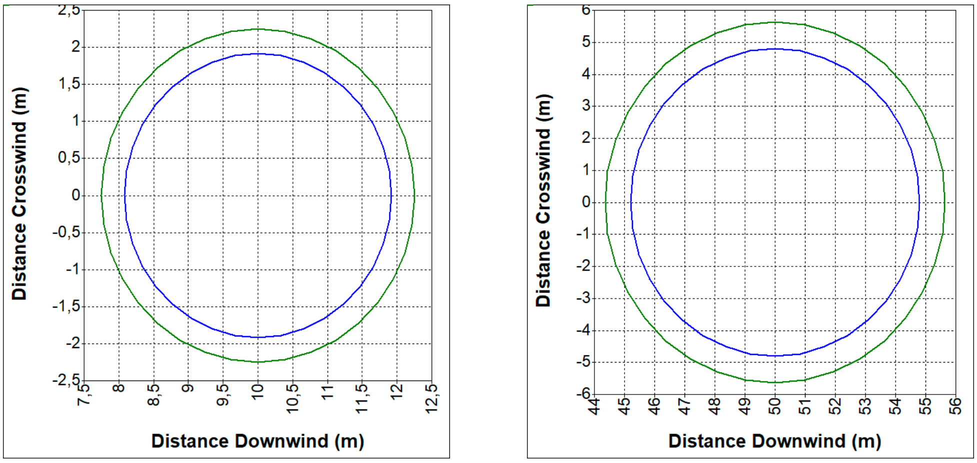


Mixture I Mixture II

Figure 9. Fire hazard zone, p = 4 MPa (radiant heat flux higher than 15 kW/m^2—green curve, 50 kW/m^2—blue curve).

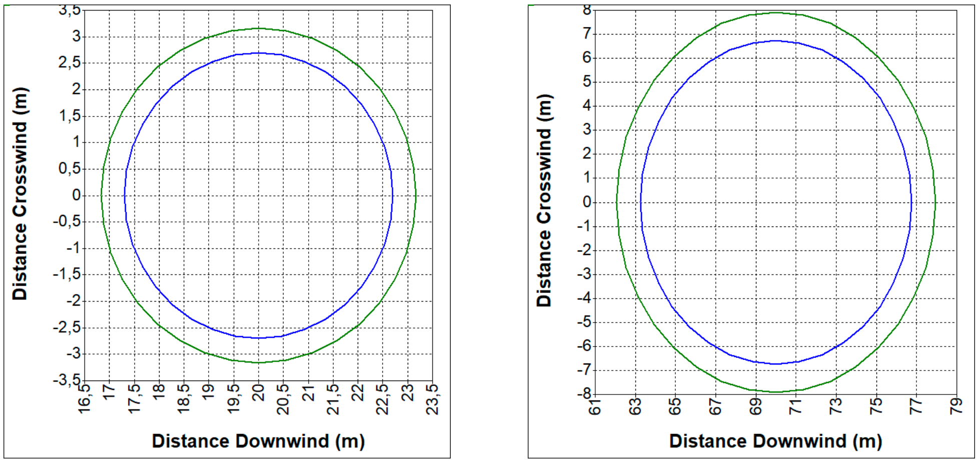
If a syngas storage tank is ruptured, the dangerous event is also an explosion. In the event of the tank explosion, the domino effect cannot be excluded and the hazard zones related to the impact of the pressure wave responsible for the destruction of subsequent tanks are presented in Figures 10 and 11. For Mixture II, the zone with high pressure wave values covers the area with a radius of about 5 m for the smaller pressure and about 7 m for the bigger pressure.

As already mentioned, the hazard zone is presented for the worst-case scenario and is related to the delayed ignition effect and the moving of the cloud of released syngas.



Mixture I Mixture II

Figure 10. Explosion hazard zone, p = 2 MPa (overpressure higher than 17 kPa—green curve, 22 kPa—blue curve).



Mixture I Mixture II

Figure 11. Explosion hazard zone, p = 4 MPa (overpressure higher than 17 kPa—green curve, 22 kPa—blue curve).

4.3. Probability of Domino Effect Occurrence

The above-described zones of the impact of increased thermal radiation or the pressure wave arising due to a syngas storage tank failure indicate that if another tank is placed within them, it is possible that it will also become damaged. This will enhance the negative effects of the primary tank failure. Calculations are performed below of the probability of such an event, i.e., of the occurrence of the domino effect for two tanks located next to each other (cf. Figure 12). A failure of one of them occurrs, the released gas ignites and a jet fire follows.

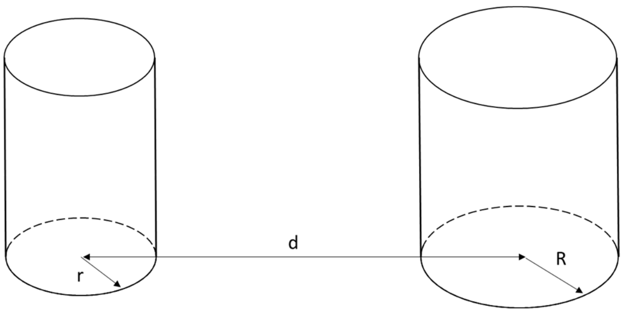


Figure 12. Mutual position of tanks with different diameters.

The probability of the domino effect occurrence is calculated using the computational algorithm described, among others, in [40]. According to this work, the probability depends on the dimensions of the two tanks, as well as on the location of the hole in Tank A, conventionally referred to as the "source" tank, and the direction of the released gas jet, the impact of which might affect Tank B. The probability of the domino effect occurrence is therefore expressed as

$$P_d = P_1 \cdot P_2 \tag{1}$$

where

P_1—the probability that the hole created due to the failure of Tank A is located on the perimeter facing Tank B,
P_2—the probability that the jet released from the hole in Tank A flows in the direction suitable for the jet to reach Tank B.

The method of finding probabilities P_1 and P_2 is based on the geometric relations between two projections of sections of two tanks with different diameters (cf. Figure 13).

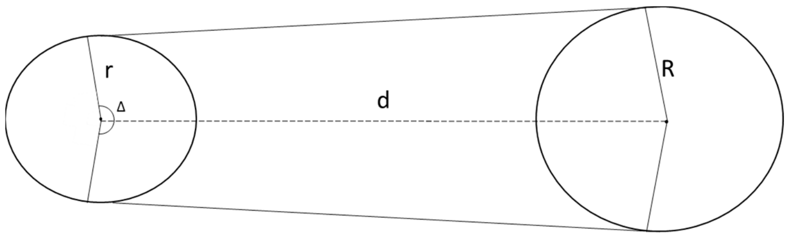


Figure 13. Projection of sections of the two tanks under analysis.

The probability can be expressed using the following relation [40]:

$$P_1 = \frac{\Delta}{2\pi} \tag{2}$$

$$P_2 = s \cdot P_{2L1} + (1 - s) \cdot P_{2L2} \tag{3}$$

$$P_{2L2} = \frac{2arcsin\left(\frac{R}{\sqrt{d^2 + r^2 - 2rd \cdot cos\delta_{L2}}}\right)}{\pi} \tag{4}$$

$$\delta_{L2} = \frac{L_2}{2r} \tag{5}$$

$$L_2 = r \cdot \arccos\left(\frac{R + r}{d}\right) \tag{6}$$

$$L_1 = r \cdot \left(\frac{\Delta}{2} - \delta_t\right) \tag{7}$$

$$\delta_t = \frac{L_2}{r} \tag{8}$$

$$s = \frac{L_1}{L1 + L_2} \tag{9}$$

The above algorithm is used to calculate the probability of the occurrence of the domino effect between two tanks with the volume of 10 m^3 or 20 m^3 with the same height of 2.5 m, taking different variants of diameters into consideration. Three such variants are considered:

- Variant 1: Tank A radius: 1.125 m, Tank B radius: 1.125 m,
- Variant 2: Tank A radius: 1.60 m, Tank B radius: 1.60 m,
- Variant 3: Tank A radius: 1.125 m, Tank B radius: 1.60 m.

The results of the calculations of probability P_d depending on distance d between the tanks for the three variants mentioned above are presented in Figure 14.

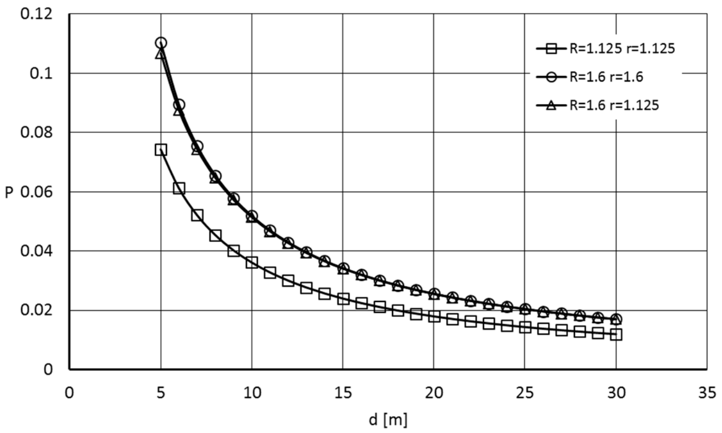


Figure 14. Distance-dependent probability of the domino effect for the three variants of Tank A and Tank B.

For example, for Variant 1 and the distance of 5 m between the tanks, probability P_d totals 0.0749. For the same distance in Variant 2, the probability is 0.110. If the distance between the tanks rises to 15 m, the probability values drop to 0.0240 and 0.0342, respectively.

The above-calculated values of domino effect occurrence probability P_d after a prior failure of one tank make it possible to estimate the unconditioned probability of the occurrence of the phenomenon. Denoting the source tank failure probability as $P(A)$ and the other tank failure probability as $P(B)$, the total probability of Tank B failure becomes

$$P_t(B) = P(B/A) + P(B) \tag{10}$$

where $P(B/A)$ is the conditioned probability of Tank B failure on the condition that Tank A is damaged first. The probability can be calculated as

$$P(B/A) = P(A) \cdot P_d \tag{11}$$

If the considered domino effect is due to a jet fire of Tank A, the probability calculations as per (10) should additionally take account of the probability of ignition of the gas jet released from Tank A—P_i. The following is then obtained:

$$P_t(B) = P(A) \cdot P_d \cdot P_i + P(B) \tag{12}$$

For the above-analysed tanks with the bigger volume located 5 m from each other, assuming $P(A)$ and $P(B)$ as 10^{-5} [1/year] [41] and ignition probability P_i as 0.5, the total probability value obtained from Formula (12) is $P_t = 1.055 \times 10^{-5}$ [1/year].

5. Summary and Conclusions

The paper focuses on the hazards related to syngas storage.

A release of syngas from a tank may be followed by immediate ignition or delayed ignition; in addition, the gas may disperse in the atmosphere without causing fire or explosion hazards. In the event of immediate ignition, the potential hazard is a jet fire. Delayed ignition creates an explosion hazard. The level of hazard to humans and the environment depends on, among other things, the composition of the syngas, the geometry and the operating parameters of the tank (the pressure of the gas).

The heat flux generated by the jet fire of syngas stored in a tank with the volume of 10 m^3 under the pressure of 4 MPa poses a hazard to human life and health in the area ranging up to 30 m from the failure site. The human hazard zones arising due to the pressure wave generated during a syngas explosion which is the threshold value for internal injuries reach the range of about 7 m.

The analysis of hazards related to synthesis gas storage should also take account of the possibility of domino effect occurrence. In the event of partial damage to the syngas storage tank (a puncture) and fire, the safe zone where the domino effect can be avoided beginning at a distance higher than 35 metres from the primary "source" tank. Up to this downwind-defined limit, no other systems should be placed containing dangerous substances whose destruction might cause further loss. In the event of syngas storage tank failure and an explosion, the safe zone begins at the distance of about 78 m from the first tank and its range depends on the syngas composition. This value is associated, among other things, with the delayed ignition effect and the moving of the released syngas cloud. If the distance between the two tanks is shorter than specified above, the domino effect may occur. The probability of domino effect occurrence depends on the size of the tanks and the distance between them. The case of placing two tanks with capacities of 10 m^3 and 20 m^3 at a distance of 5 m from each other indicates that the increase in the probability of damage to the second tank caused by damage to the first tank and the occurrence of the domino effect is 0.055×10^{-5} [1/year].

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