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FACULTY OF MECHANICAL ENGINEERING AND INFORMATION

SIMULATION AND EXPERIMENTAL INVESTIGATION OF EMISSIONS GENERATED IN EXPLOSIVE ENVIRONMENTS

BOOKLET OF PHD THESES

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Miskolc
2025

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1. RESEARCH TASK

1.1. INTRODUCTION

In many industries, we encounter flammable or explosive materials that can pose various hazards to employees, people present at the site, the environment and infrastructure. These hazardous materials can be gases (e.g. hydrogen, acetylene, ammonia), vapours (e.g. benzene, ethanol), and dusts (e.g. metal dusts, organic dusts) or hybrid mixtures of these, where the gas or vapour medium and the dust are present simultaneously.

The scientific study of explosion hazards and their management, as well as the beginnings of their regulation, are linked to mining, primarily coal mining. Throughout the history of mining, there have been numerous accidents involving explosions, which have had serious consequences. These accidents have greatly contributed to society's understanding and management of the risks associated with explosion hazards. The firedamp that often occurs in underground coal mines contains high concentrations of methane gas, which can accumulate in confined spaces where ventilation is limited, thereby preventing the dangerous mixture from being diluted effectively. In addition, fine coal dust mixed with air can also form an explosive mixture. When methane mixes with air and comes into contact with an ignition source, an explosion can occur.
Methane explosions are among the most common and dangerous incidents in mining.

Various laws, regulations, directives and standards (e.g. industry standards, NFPA, API, OSHA) are available for identifying and determining the extent of potentially explosive areas, or more generally, zones (HAC). These help to identify hazardous substances based on their combustion and explosion properties [1], name the various emission sources and regulations in each technology, and define the type and extent of explosive areas based on correlations, ensuring personal safety and compliance with legal requirements.

Research task

In the case of combustible and flammable liquids, gases, vapours, mists or aerosols, which may form explosion-hazardous areas, there are a number of empirical relationships based on experimental data and observations. These relationships and models include, for example, Bernoulli's equation, which describes the flow of liquids and gases through an opening. Another example is choked flow, which can occur when gases and vapours leak under conditions below or above the critical pressure. In the event of a release of hazardous substances, particularly from storage tanks, Henry's law and the Antoine equation are often used to calculate the evaporation rate and the mass flow rate of the release. In addition, liquid leakage, dripping (low-mass-flow leakage) or spillage from individual system components – for example, at flanged joints, pump shaft seals (packings), sampling points or discharge openings – can lead to the formation of puddles or so-called pools. In the latter cases, where the liquid surface area is larger, a number of models are available to describe the evaporation rates. These approaches help to determine emission mass flows and provide precise guidance on which methods can be used for the emission of gases, vapours and liquids, below or above their boiling point. In the case of liquefied gases, single-phase or two-phase flow may occur, depending on the physical and chemical properties of the substance. In addition to physical and chemical properties, emission characteristics also depend on several flow factors. One of the most important parameters is the size of the emission source opening, while other important factors include the emission coefficient and the pressure and temperature of the equipment.

Emission models can be constructed from basic analytical and empirical equations representing the diffusion processes that occur during the release of substances. These include, for example, the Benintendi, Ewan and Moodie, Long, McMillan and Yellow Book models, which can be applied in various aspects and have been partially or completely transposed into standards and guidelines used to define potentially explosive atmospheres. In many cases, there may be uncertainty, as a great deal of information is required to write a given model, but this is not always available.

OBJECTIVES

In my research, I intend to examine the system of explosion conditions, with particular regard to the forms of emission and leakage from equipment containing explosive gases and vapours, their spread using simulation software, as well as the existence of explosion risk and the accuracy of the extent of potentially explosive areas (zones). Given that this is not just an individual problem but a global one, my goal is to conduct simulation and experimental studies of emissions in explosive environments, exclusively in the case of gases and vapours. The regulatory environment is currently diverse, inconsistent and, in some cases, contradictory, which is why I consider it important to conduct a more in-depth study of this area. My goal is also to review the relationships applied in engineering practice in a scientifically sound manner and, if necessary, to formulate recommendations that contribute to increasing safety or avoiding unnecessary oversizing.

In my thesis, I first provide a review of the literature, touching on the conditions for the formation of explosive atmospheres, the explosion-related technical properties associated with their formation, and the legal and standardisation background related to explosion protection. I summarise the types of emissions that occur in explosive environments, which can be single-phase or two-phase, including liquids at ambient temperature, near boiling point or above boiling point, as well as puddle and pool evaporation. The literature review covers propagation models for explosive atmospheres, CFD-based and other simulation environments, and discusses known correlations that can be used to define explosive areas.

Subsequently, in my research, I intend to investigate the evaporation of acetone, as this substance is commonly used in the chemical and beauty industries and may pose an explosion risk. Several correlations are available for determining the rate of evaporation of a liquid onto a surface, and I intend to compare these with the correlations found in the current standard and with average measurement results. The aim is to identify the most accurate correlation possible for the evaporation of acetone and similar liquids, thereby ensuring that the explosion risk is adequately managed.

In the early stages of my research, ANSYS Fluent software was available, and later I also had the opportunity to use the FLACS-CFD environment, so I performed the tests in both simulation environments according to their applicability. During the research related to my thesis, I also used hydrogen as a medium in the propagation tests, as the hydrogen industry has come to the fore in recent years in terms of energy consumption and has become widespread in industrial practice. In addition to hydrogen, I also examined methane emissions, as the extraction, storage, transport and use of natural gas is widespread in Hungary and other countries. Methane is a fully relevant test medium for my topic and, moreover, is expected to remain a non-eliminable substance for many years to come. I review the determination of the explosive zone of mixtures of the two gases together according to the methodology of the MSZ EN IEC 60079-10-1:2021 standard, to which I also propose additions. These additions could form the basis for future revisions of the standard, as there is currently no uniform analytical method for accurately determining explosive areas. One of the goals of my research is to develop an approach that allows for the prediction of explosive zones resulting from the leakage of multi-component gas mixtures.

If the innovations and proposals described in my dissertation for each of the areas studied are implemented, they could contribute to the more efficient development of an expert environment applicable in engineering practice and to the more accurate determination of the extent of potentially explosive areas, thereby reducing the size of areas exposed to explosion risk.

I examined the legislation and domestic and international standards referred to in the research, collecting data up to 3 July 2025. Any changes in legislation and standards that occurred after this date are not included in my thesis.

With regard to other testing procedures and methods related to the topic of the research that may be relevant, such as the explosion risk posed by solid, combustible fibrous materials and dusts, I do not examine the analysis of dust explosion conditions. My thesis does not discuss the formation of mists from combustible liquids, the possibility of aerosol formation, or the processes and behaviour of these mechanisms. It does not cover the examination of the explosion hazard posed by gas-vapour-dust dispersion systems, i.e. hybrid mixtures, when different media are present at the same time. Due to research limitations, I do not examine the evaporation dynamics of multi-component systems and solvent mixtures, the complexity of their relative volatility, and the effect of evaporation-flow interaction on evaporation rate (e.g., local cooling, condensation, surface temperature change). My experimental and simulation studies do not cover the emission of liquefied and two-phase media, which describe their leakage and spread under boundary conditions. I examined the practical applicability of CFD simulations and did not analyse turbulence interactions, turbulent vortex structures, or mixing efficiencies because it covers the examination of general propagation models, and stagnation zones or swirling flows are not part of it. Environmental factors such as solar radiation, humidity, and stable/unstable atmospheric conditions caused by precipitation are not included due to space limitations. My research does not cover the environmental and health effects of the leakage and spread of the explosive substances studied, nor does it detail the requirements that are not fully specified in legal or organisational terms, nor does it discuss their inaccuracies, nor does it cover economic and cost analysis. I suggest further research on the relevant studies mentioned in the chapter on development opportunities at the end of my thesis.

2. SCIENTIFIC BACKGROUND

2.1. COMBUSTION AND EXPLOSION – CONDITIONS FOR THE FORMATION OF AN EXPLOSIVE ENVIRONMENT

An explosion is a sudden reaction involving physical and chemical oxidation or decomposition, accompanied by a change in temperature and/or pressure [2]. It usually occurs between combustible gases, vapours or dusts and the oxygen in the air. For combustion and explosion to occur in the case of gases or vapours, three conditions must be met simultaneously and in one place, as illustrated in Figure 1.

Presence of an oxidising agent: an oxidising agent (e.g. oxygen) is required for an explosion to occur, which participates in the combustion or explosion process. Within this condition, an additional factor is the oxygen concentration limit at which combustion or explosion does not occur. For example, this value is below 10% for ethylene, while for lignite it can be as high as 8%.

Flammable substance: a substance that is flammable or explosive, whose concentration is within the combustion or explosion range and which forms a mixture with an oxidising agent.

Ignition source: an external energy source that initiates the reaction. This can be a spark, high temperature, impact or friction – a total of 13 different types are known [3].

Both Hungarian [4] and international literature [3] define the set of conditions as a combustion triangle, as the reaction starts with a flame front, which is followed by pressure waves. Some literature also refers to it as an explosion triangle [5], a term also used in engineering practice, as an explosion is also a combustion process, only an extremely rapid exothermic reaction. Beyond the topic of this thesis, the dust explosion pentagon is also well known [6], which, compared to the combustion triangle, is supplemented by the critical factors of the closed nature of the dust-air mixture and dispersion.

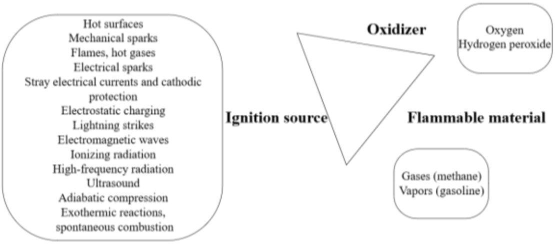

Figure 1: The combustion triangle (author's edit)

The basis of the explosion is therefore essentially combustion, which is a similar phenomenon, but one that acceslerates extremely rapidly and can reach propagation speeds of up to several thousand metres per second [7]. This process can be divided into two main groups according to speed: deflagration and detonation.

The flash point is the lowest temperature at which a liquid evaporates and produces enough vapour to ignite in the presence of an ignition source. This is an important indicator of flammability in fire and explosion protection legislation and standards, and is a parameter frequently used in the handling of hazardous substances.

It is important to clarify that there are two types of flash points, although the term "flash point" is generally used. These are open-air and closed-cup flash points.

Within the so-called explosion range, a mixture of air and combustible material can form an explosive environment, which can cause an explosion when exposed to an ignition source. In the literature, based on the previously derived combustion-explosion theory, this has been referred to more and more frequently in recent decades as the lower and upper flammability limits. However, there are differences between older and newer standards, and some literature uses the terms "combustibility" and "explosive" limits differently. Based on a review of the literature and my own experience, I use the term "explosion limit" because certain equipment, such as gas burners or internal combustion engines – involve the presence of flammable or explosive media, and although the chemical reaction starts as combustion, the controlled, technical design of the equipment prevents the occurrence of explosions known or imagined in industrial environments. However, from an explosion protection point of view, this is precisely why explosion protection is key, which cannot be understood without the concept of explosion.

In the case of LEL, the concentration of combustible material is too low, while in the case of UEL, the concentration of oxidising agent is too high for an explosive environment to develop. Figure 2 clearly illustrates the limits of the explosion range. Exceptions to this are, for example, acetylene, ethylene oxide or hydrazine, which form an explosive environment even in the absence of oxygen and at 100% combustible material concentration. Therefore, the application of certain primary protective measures (inerting) does not provide protection in these cases.

Some studies [8, 9, 10] have found a close correlation between how temperature increases affect LEL and UEL values. Experiments have shown that at higher temperatures, the explosion range of gases widens, so the LEL value decreases while the UEL value increases.

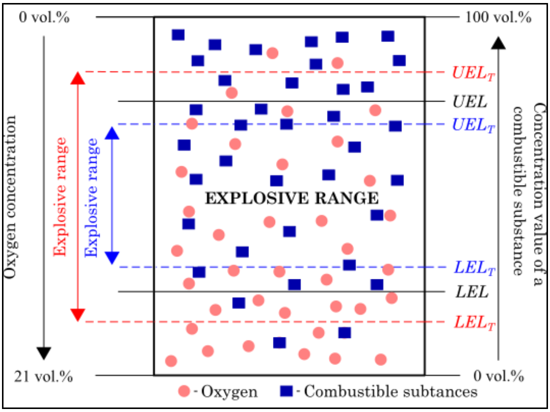

Figure 2: LEL and UEL at ambient and higher temperatures (author's compilation)

The hazards of liquid exposure in the temperature range between the melting point and boiling point depend on a number of factors, including the chemical properties of the liquid, its flammability, and the temperature in the adiabatic state, i.e. the temperature inside the equipment.

Relative density—the ratio of a substance's density to that of a reference substance (air)—is fundamental to determining explosive zones, as it helps to understand how different gases and vapours behave relative to air.

Gases/vapours that are lighter than air (relative density < 1) generally rise and accumulate under the ceiling or in other high places. The literature [11] discusses 13 substances typically found in industrial environments that are lighter than air, 8 of which are explosive: acetylene, ammonia, diborane, ethylene, hydrogen, hydrogen cyanide, methane and carbon monoxide.

2.2. FORMS OF EMISSION OCCURRING IN EXPLOSIVE ENVIRONMENTS

There are several mathematical relationships available for different emission forms, which can be used to determine the emission rate, the total amount emitted and, in the case of finite states, the total duration of the emission. The various mathematical models can be divided into several major emission types, and within these, a distinction must also be made according to phase: there may be a single-phase or two-phase state. Combustible and flammable liquids, gases, vapours, mists or aerosols, which may form explosive areas in a chemical plant, can be defined as emissions or leaks as follows [12-17]:

- single-phase emission of a combustible liquid,
- two-phase emission of combustible liquid,
- evaporation of a pool resulting from a leak of a flammable liquid,
- evaporation from a pool containing flammable liquid,
- leakage of flammable gases,
- leakage of flammable liquefied gases,
- leakage of flammable vapours.

The identification and examination of potentially explosive areas is carried out under normal operating conditions. This refers to the state in which the technological equipment operates within the specified operating parameters. This state also includes the start-up and shutdown phases, as well as periodic maintenance. However, extraordinary events, such as accidents, cannot be considered normal operating conditions.

In the case of a tank or technological equipment, there may be several emission sources. Leaks often occur due to the lack of tightness of tanks or pipes, when small amounts of flammable material escape or a so-called "flash discharge" occurs. Flanged connections, valves and joints can also be significant emission points. Ventilation openings and pressure relief valves, which are used in certain equipment to relieve pressure or for safety reasons, can also cause emissions from time to time. In addition, vapours and gases generated during filling and emptying operations can also be potential emission sources.

As potential emission sources, the interior spaces of such equipment may also contain explosive atmospheres. However, conditions are often more favourable, as in many cases the presence of oxygen is excluded and the concentration of hazardous gas or vapour is above the upper explosion limit [18].

2.3. MODELS FOR THE SPREAD OF EXPLOSIVE ATMOSPHERES

Various analytical models are available for estimating the spread and dispersion of gases and vapours. Although these propagation models are extremely useful, and Ewan and Moodie's model, for example, was published in 1986 and has been known for nearly 40 years, they are often based on such complex relationships that their practical application can be challenging, and standards have therefore not adopted them, or have only adopted them in part. It is true that, based on the literature I examined during my research, these models can provide a mathematically accurate description, but simplification of real-life situations is almost always necessary in order to obtain results that can actually be used.

Ewan and Moodie's model examines the spread of high-pressure combustible gas emissions resulting from pipe damage and from the venting systems of technological equipment [19].

Most of these emissions are turbulent above the critical flow range, as the pressure associated with the equipment is several times higher than normal atmospheric pressure. It is important to note that the radial dispersion term in the model is derived from the CPR 14E Revision history of the 'Yellow Book' model. The aim of the model is to create a larger-scale dispersion model starting from the emission source, which is intended to determine the mixing pattern and flammability limits.

The Long model is a special gas dispersion model [20] developed to model conditions below critical flow, where the Reynolds number is less than 10^4. This means that the flow is still turbulent, but with relatively low turbulence intensity.

The Yellow Book [21] model is designed for conditions above critical flow, where turbulent flow dominates. This model is particularly useful for modelling high-speed and high-Reynolds-number gas emissions, even for determining supersonic jet streams. Its practical application is primarily in chemical plants, where high-pressure combustible gases can be released into the atmosphere.

Renato Benintendi examined a hypothesis [23] that often assumes reduced momentum of impulse characteristic of laminar flow. This approach can be considered conservative, as it assumes that air mixes less with combustible gas, thus allowing for a larger flammable volume. He therefore developed his own model, which examines the effect of density and viscosity differences between air and combustible gas, assuming a laminar system. Benintedini's thinking extended beyond laminar flow to a complete understanding of the laminar-turbulent transition [23] and a comparison with turbulent flow. In the transition range, the laminar hypothesis is often assumed, which is more conservative due to the extension and uncertainty of the laminar-turbulent transition range. Based on his research, he found that the comparison with turbulent flow showed a larger size in the case of laminar flow [22, 24], so it is advisable to use this methodological approach when identifying potentially explosive areas and assessing the risk of flammable gases.

2.4. SIMULATION ENVIRONMENT APPLICABLE TO THE INVESTIGATION OF GAS AND VAPOUR DISPERSION

The atmospheric propagation of explosive gases and vapours is a key factor in all industries and technologies where there is a risk of explosion. The use of appropriate simulation models allows for the accurate identification of potentially explosive areas, taking into account geometric design, operating parameters and weather conditions. Based on this input data, it is possible to optimise safety measures and thus prevent potential industrial accidents.

Since the mid-20th century, a number of simulation software programmes have been developed specifically to model and predict the spread of hazardous substances, or even their combustion and explosion in different environments. These software programmes use various mathematical models to accurately simulate real processes, such as the advection-diffusion equation, Fick's law, the Gaussian, Gaussian Plume, Heavy Gas dispersion, Pasquill-Gifford (P-G), Puff models, and the Taylor dispersion equation. Of particular note are computational fluid dynamics (CFD) simulation software packages, which integrate a number of dispersion models and form the basis for accurate and detailed simulation of flow phenomena. These models include the Navier-Stokes, Reynolds-Averaged Navier-Stokes, Euler-Lagrange equations, Large Eddy, Direct Numerical, and Species Transport models. In my thesis, I examined in detail the applicability of these equations and models, as well as the practical possibilities of various simulation software.

2.5. CFD SIMULATION ENVIRONMENT

Numerical fluid dynamics simulation software (CFD) is based on differential equations, primarily the Navier–Stokes equations, which describe the physical laws of fluid and gas flow. These equations cannot be solved analytically in general form, so simulations use numerical methods. This requires a geometric model, which must be divided into a spatial grid so that the finite volume method (FVM) can be applied.

The solution is sought using iterative algorithms such as Gauss–Seidel, SIMPLE, and PISO. These do not give the final answer immediately, but approach it gradually, which means that the algorithm proceeds in iterative steps until it reaches convergence, i.e. the differences between the two iterations, the residuals, are very small and the result does not change significantly in the next step.

The Fire Dynamics Simulator (FDS) is CFD-based simulation software developed by the National Institute of Standards and Technology (NIST), originally designed to model fire and smoke propagation in enclosed and semi-enclosed spaces. However, as it is open source, it is now increasingly used to study the spread of gases, vapours and liquids [24, 25].

OpenFOAM is open source, CFD-based software that can be widely used to simulate liquids, gases and multiphase flows. Thanks to its flexibility, the software is particularly suitable for modelling the spatial and temporal propagation of explosive substances such as liquefied gases (LNG, LPG), evaporating liquids and flammable gases/vapours.

The investigation of safety risks associated with LNG is crucial, including gas/vapour propagation and the possibility of explosions due to potential emissions. Individual studies [26, 27, 28] present various modelling approaches, ranging from gas/vapour propagation calculation methods using OpenFOAM to density-based solutions simulating detonation-deflagration transition (DDT), with a particular focus on hydrogen-air and LNG vapour explosions.

Fluent and CFX are two prominent simulation software programmes in the ANSYS software portfolio that are widely used in engineering practice, particularly for numerical modelling of gas leaks and the propagation of flammable materials. Both tools are suitable for modelling the extent of explosive hazard areas (zones), and their results can be compared with relevant standards that have been extensively tested in several different studies.

FLACS-CFD is an advanced finite volume method numerical simulation tool developed specifically for modelling the spatial spread and possible ignition of explosive gases and vapours. The software is capable of taking into account geometric obstacles, wind conditions, leakage scenarios and the concentration distribution of flammable substances, thus enabling the accurate determination of hazardous areas. The simulation results can also be used to validate and fine-tune the definition of hazardous areas, supporting safety engineering design in industrial environments.

2.6. OTHER SIMULATION ENVIRONMENTS

Non-CFD-based simulation software is generally based on empirical or simple physical models and can be run quickly, requiring less computing power.

The ALOHA (AREAL LOCATIONS OF HAZARDOUS ATMOSPHERE) software was developed in 1982 by the United States Environmental Protection Agency and the National Oceanic and Atmospheric Administration. Its primary purpose is to model the atmospheric release of hazardous chemicals. It can model BLEVE (Boiling Liquid Expanding Vapor Explosion), VCE (Vapor Cloud Explosion), as well as jet and pool fires and other scenarios [29].

One of the special features of ALOHA is that it contains an extensive chemical database that users can expand according to their needs. Weather data can be entered manually by the user or received directly from a meteorological station. In addition to its user-friendly graphical interface and display, it also includes a mapping add-on called MARPLOT, which allows the visual representation of facilities in the area and the population at risk using custom overlays.

The software offers two types of dispersion models for the substance under investigation: the Gaussian model for gases lighter than air and gases with a molar mass close to that of air, and for gases heavier than air. The mathematical relationships and equations behind the models can be found in the software user manual [30].

During my research, I examined evaporation using the ALOHA software.

2.7. DETERMINATION OF EXPLOSIVE AREAS USING ANALYTICAL RELATIONSHIPS

Over the past 40 years, several analytical relationships have been developed to determine the extent of explosion hazard areas, i.e. explosion hazard zones. These equations can be applied to different emissions and different variables, and their accuracy has been tested in numerous studies using CFD and experimental tests. The approach developed by Tommasini [31], which is also based on his earlier research, is applied in the CEI 31-35 (2012) [32].

Tommasini, Ewan and Moodie examined the correlations using CFX software for methane media with diameters of 0.1-0.25-1.00-1.25-2.50 mm, at a temperature of 30°C and a pressure of 4 bar(g), in accordance with the MSZ EN 60079-10-1:2015, using a minimum of 1.0 metres as a basis. The results were 17.9% higher for Tommasini and 21.1% higher for Ewan and Moodie's model compared to the simulation results [33]. The study recorded these average differences because the test was performed with multiple media, but only these are presented in this literature review. The simulation results were validated according to the results of previous research.

Howard et al. [133 (35)] examined the results of the MSZ EN 60079-10-1:2009 standard, which is still partly based on explosive concentrations, in comparison with the usability of PHOENICS CFD software. This standard already mentions the possibility of evaluation with simulation software. When high-pressure hydrogen flows out through a 0.1-0.2 mm hole, assuming different leakage directions and dilution values, there were multiple differences compared to the CFD results, which the standard also mentions.

Using Souza's equation [162 (36)], the size of the possible zones was examined in the case of leakage of an ammonia medium at a pressure of 10 bar(g), 0.1-0.25-1.00-1.25-2.50 mm, and a temperature of 30°C. The study covered an overpressure of 10 bar(g). Compared to Ewan and Moodie's model, and even Tommasini's equation, the validated CFX results showed an average difference of 13.86%

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3. TEST METHODS

3.1. EXPERIMENTAL AND SIMULATION TESTING OF LIQUID EVAPORATION

I examined the phenomenon of evaporation for a selected liquid, acetone, as a function of several air flow velocities, with the aim of finding the most suitable model for accurately determining the rate of evaporation.

During the research, I analysed the potentially explosive atmosphere for acetone using ALOHA simulation software and compared it with the average results of a series of measurements, where the margin of error was less than 5-7%. I placed a small amount of acetone in a glass jar and first studied the evaporation in the absence of air flow. I then repeated the test at air speeds of 2-4-6 m/s, as different air flow speeds increase the rate of evaporation. I compared the measurement results with several evaporation models and determined which calculation model was closest to the experiments performed.

I used ALOHA software to examine the rate of acetone evaporation, comparing the results with the experimental evaporation values, and also analysed the risk and extent of explosion hazard.

The surface area examined was 0.00096 $^{m^2}$, which is considered a very small surface area. The simulation did not work with the surface area of the glass jar examined, so I increased the liquid surface area by a factor of 10 in the software to compare the experimental and simulation results. Several boundary conditions can be taken into account, such as whether the soil is solid or porous, the temperature of the soil and liquid medium, and various weather factors.

The value calculated by the software at an air flow rate of 2 m/s is 3.59 grams/minute, which corresponds to 5.9833 mg/s when applied to the surface used in the experimental measurement series.

The ALOHA software required a much larger effective surface area to visualise the results. I collected the available weather data for the area under investigation to model a case study.

During the case study simulation, which could occur, for example, in the event of a level control error in a cylindrical steel tank, the initial evaporation rate is 77.2 kilograms/minute from a surface area of 290 m^2, which decreases continuously over time in proportion to the surface area. Based on the boundary conditions examined, I determined the spread of the vapour using the software based on the heavy gas model, as shown in Figure 3. Figure 3 shows the distribution of LEL at a concentration of 20% (ppm) on the horizontal and vertical axes. The software can still display higher concentration distributions in this function, but it cannot interpret the distribution of closer areas as homogeneous, so it cannot be considered reliable.

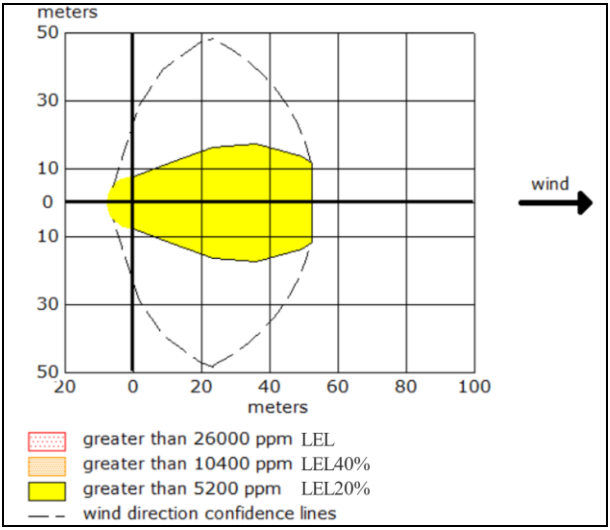

Figure 3: Distribution of the lower explosion limit at a concentration of 20% (author's edit)

In Figure 4, I placed the emission source at a location where, with the specified boundary conditions, the display is still partially limited, only the LEL 20% value is visible, but I was able to determine the distances according to the LEL 40% and LEL concentrations. The extent of LEL 20% is 52 metres, and the extent of LEL 40% is 34 metres. The software can assume a unidirectional air flow at a time, but due to the variable wind direction, I am keeping conservatism in mind, so I have expanded the representation of the hazardous areas to a circle.

Longitude: 20.713633°E
USNG: 34U DU 78706 34629

Time: June 12, 2022 0930 hours ST
Chemical Name: ACETONE
Wind: 2 meters/second from E at 3 meters

THREAT ZONE

🟥 Red	20 meters (not drawn)*	26000 ppm = LEL
🟧 Orange	34 meters (not drawn)*	10400 ppm
🟨 Yellow	52 meters	5200 ppm

*Note: Threat zone was not drawn because effects of near-field patchinessmake dispersion predictions less reliable for short distances.

Model: ALOHA Flammable Area of Vapor Cloud

Figure 4: Depiction of LEL 20%, LEL 40% and LEL concentrations resulting from the evaporation of a large liquid surface area with an air flow of *2* m/s (edited by the author)

I used an analytical balance to examine the rate of evaporation. This device recorded the mass of acetone in the glass jar every 0.2 seconds, providing me with sufficient data on the change in the amount of acetone.

Various models are available for determining the rate of evaporation, which I compared with the evaporation experiments carried out in my research:

$$W_{pár-1} = 3{,}6 \cdot 10^{-8} \cdot \left(\frac{M \cdot P_{gőz}}{T_{körny}}\right) \cdot u^{0{,}78} \cdot {r_{foly}}^{1{,}89}, \tag{3.1.}$$

$$W_{pár-2} = 0{,}3 \cdot u^{0{,}8} \cdot {A_{foly}}^{0{,}9} \cdot T^{-0{,}8} \cdot M \cdot p \cdot \left[\frac{\left(3{,}1+\rho^{-0{,}33}\right)^2}{T^{0{,}5} \cdot \left(\frac{1}{29}+\frac{1}{M}\right)^2}\right]^{-0{,}67}, \tag{3.2.}$$

$$W_{pár-3} = 1{,}4 \cdot \frac{0{,}284 \cdot M^{2/3} \cdot p}{R \cdot T} \cdot A_{foly}, \tag{3.3.}$$

$$W_{pár-4} = \frac{0{,}284\cdot u^{0{,}78}\cdot M^{2/3}\cdot A_{foly}\cdot p}{R\cdot T}, \tag{3.4.}$$

$$W_{pár-5} = \frac{M\cdot 0{,}00438\cdot u^{0{,}78}\cdot\left(\frac{18}{M}\right)^{1/3}\cdot A_{foly}\cdot p}{R\cdot T}, \tag{3.5.}$$

$$W_{pár-6} = \frac{18{,}3\cdot 10^{-3}\cdot u^{0{,}78}\cdot M^{2/3}\cdot A_{foly}\cdot p}{R\cdot T}, \tag{3.6.}$$

The evaporation results obtained using the models are shown in Table 1, together with the air flow values. In the test without air flow, I assumed a negligible value of 0.2 m/s due to Brownian motion [36].

	u=0.2 m/s	**u=2 m/s**	**u=4 m/s**	**u=6 m/s**
Model 3.1	W_{pair-1} =1.714 mg/s	W_{pair-1} =10.332 mg/s	W_{pair-1} =17.741 mg/s	W_{pair-1} =24.341 mg/s
Model 3.2	W_{pair-2} =11.838 mg/s	W_{pair-2} =74.696 mg/s	W_{pair-2} =130.053 mg/s	W_{pair-2}=179.884 mg/s
Model 3.3	W_{pair-3} =4.254 mg/s	W_{pair-3} =4.254 mg/s	W_{pair-3} =4.254 mg/s	W_{pair-3} =4.254 mg/s
Model 3.4	W_{pair-4} =0.904 mg/s	W_{pair-4} =5.449 mg/s	W_{pair-4} =9.356 mg/s	W_{pair-4} =12.837 mg/s
Model 3.5	W_{pair-5} =0.037 mg/s	W_{pair-5} =0.221 mg/s	W_{pair-5} =0.381 mg/s	W_{pair-5} =0.523 mg/s
Model 3.6	W_{pair-6} =0.058 mg/s	W_{pair6}=0.351 mg/s	$W_{vapour6}$ =0.602 mg/s	$W_{vapour-6}$ =0.827 mg/s

Table 1: Comparison of the results of the evaporation models used in the experiment (compiled by the author)

I compared the results of the experiment and the models and found that, in the case of acetone medium, model (3.4) is closest to my measured results for the evaporation studied. The percentage deviation is low, except for the 2 m/s air flow, where I observed a 12% deviation.

The simulation result falls between 6.171 mg/s and 5.449 mg/s when referenced to the surface used in the experiment performed at 2 m/s, thus confirming that the correlations used by the software are consistent with the values measured during the experiment. The results of the experiments, simulations and models are shown in Figure 5 on two separate graphs, as the results of the test performed with model (3.2) differ significantly from the results of the other models.

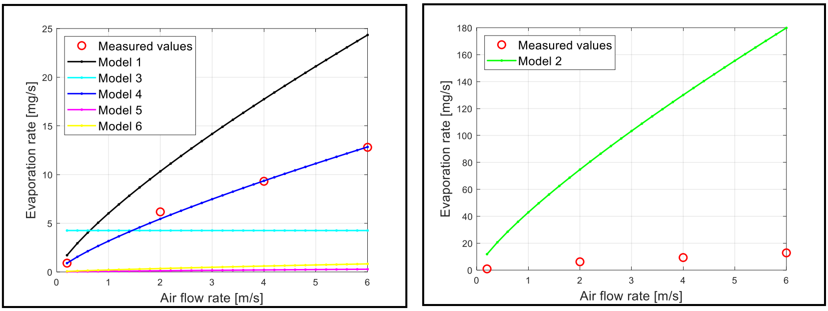

Figure 5: Comparison of the results of the measurements, simulations and models (author's edit)

Based on the results obtained from the measurements and models, it can be seen that there is a calculation that can determine the rate of evaporation and give results consistent with the experimental results. I observed how different airflow velocities affect the rate of evaporation, which allows more hazardous substances to enter the atmosphere directly.

3.2. MODELLING IN THE ANSYS FLUENT SIMULATION ENVIRONMENT

Using ANSYS Fluent software, I investigated the spread of hydrogen, propane and methane gas media in my research under conditions with and without air flow and under different air flow conditions. The purpose of the simulation models I built was to examine the effects of different airflows during a given emission and to analyse the characteristics of the emission and the spread of the gas cloud as a function of different pressures and different outflow directions.

The investigation of the spread of hydrogen, one of the best-known explosive gases, was motivated by the fact that renewable energy sources have gained enormous ground at the beginning of the 21st century and the use of hydrogen-powered vehicles, for example, is becoming increasingly widespread as a replacement for fossil fuels. In the simulation, I examined the spread under two different air flow conditions at air flow values of 2 and 11 m/s.

Figure 6 shows the distribution of air flow in the examined area when the air flow speed is 2 m/s. At low air flow, after colliding with obstacles (compressor, tank and filling column), it practically disappears, remaining negligible, which can even result in the leaking gas becoming locally concentrated, as the air movement does not provide sufficient dilution. In addition, changes in the direction and speed of the air flow also have a significant effect on the spread of gases, especially if the leak is not uniform and may collide with environmental obstacles.

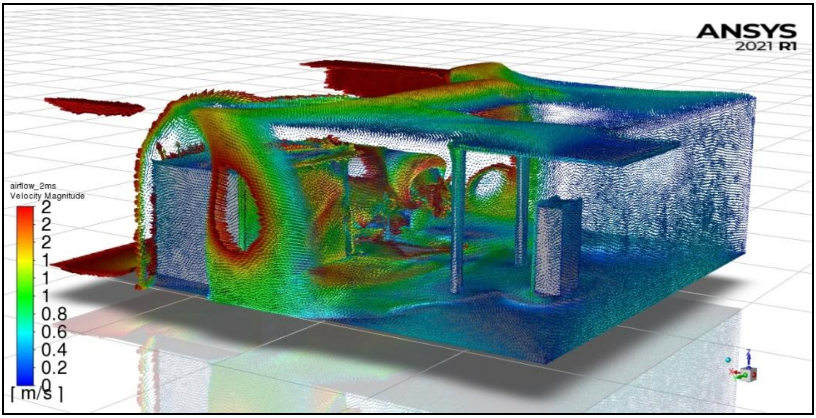

Figure 6: Distribution of air flow at a speed of 2 m/s in the environment under investigation (author's edit)

In both simulations, when the airflows were different, I examined the models with LEL 20% hydrogen (0.8 vol.%) and a much lower concentration (0.05 vol.%). During the test, low air flow has no effect on hydrogen leakage, as it will continue to spread in the normal direction due to its outflow velocity. The direction of the hydrogen gas cloud radius does not change even at a concentration of 0.05% by volume and an air flow of 2 m/s, as shown in Figure 7. It follows that under the air flow conditions studied, the spread of hydrogen is primarily determined by the outflow characteristics and not by the ambient air movement.

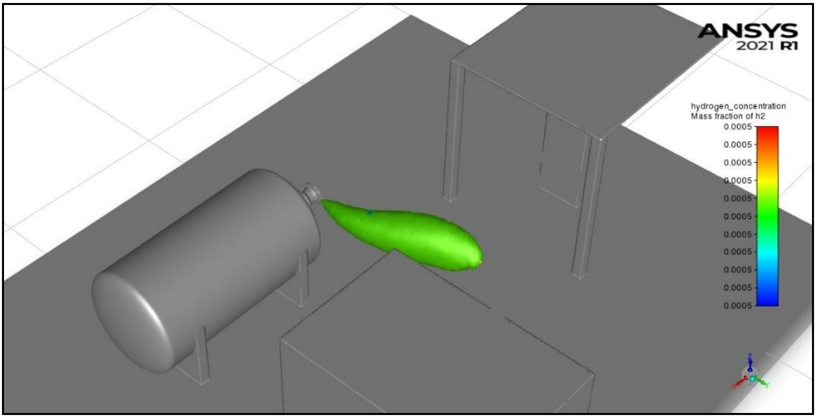

Figure 7: Distribution of air flow at a speed of 2 m/s in the environment under investigation (author's edit)

Compared to the 2 m/s air flow, an air flow more than five times that value creates turbulent conditions around the obstacles in the area. These air flow distributions are shown in Figure 8. The figure shows that there are air flows that remain in line with the axis of the fuel pump column and the tank next to the obstacles.

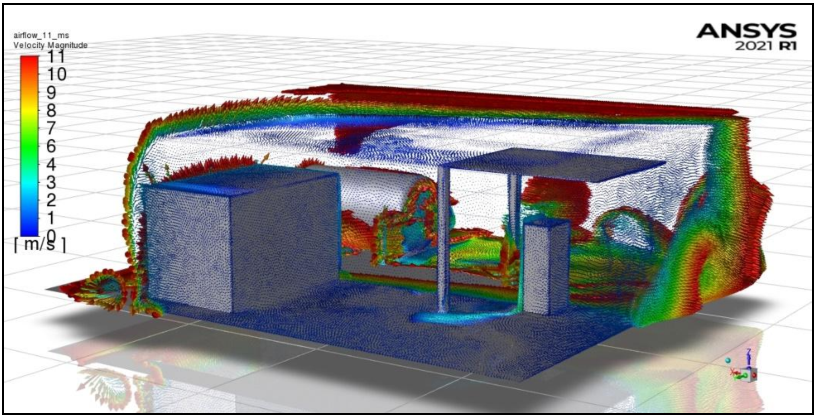

Figure 8: Distribution of air flow at a speed of 11 m/s in the environment under investigation (author's edit)

Looking at Figure 9, it is clear that even at lower concentrations, this air flow was sufficient to influence the spread of emissions.

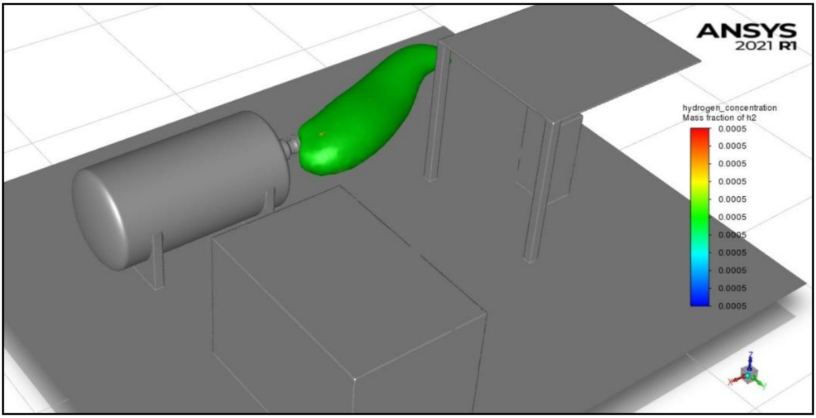

Figure 9: Spread of 0.05 vol.% hydrogen at an air flow velocity of 11 m/s (author's edit)

Significant differences can be observed in the simulations performed with the two different air flows. The low air flow is unable to influence the spread of hydrogen gas from emissions above the critical flow, in contrast to the much higher air flow. In both cases, the presence of the gas cloud can already be considered dangerous in the immediate vicinity of the emission. These dispersion conditions were determined under normal operating conditions in accordance with the literature and standards.

I examined the spread of propane, a gas heavier than air, in the case of different outflow directions and different air flows. In my dissertation, I describe in detail that air flow plays a significant role in the spread of gases, but the direction of the outflow is also important in the event of a leak, for which I created simulation models.

The three emission sources of identical size, with a diameter of 5 mm, are marked with numbers 1, 2 and 3 in Figure 10, and larger views of them can be seen in Figure 11.

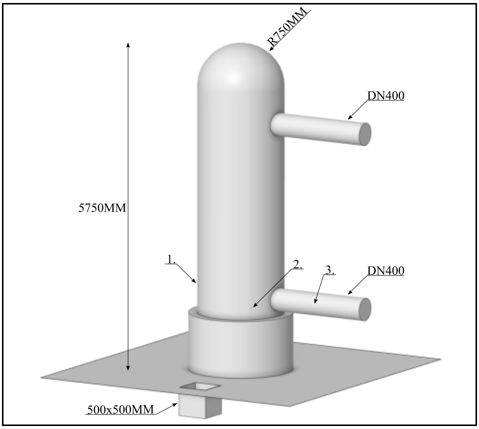

Figure 10: Geometric model of the propane-propylene column (author's edit)

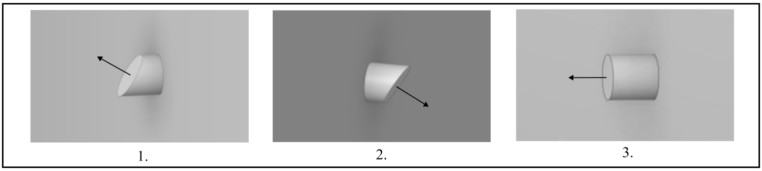

Figure 11: 1. Upward flow, 2. Downward flow, 3. Normal flow (author's edit)

The lowest air flow rate tested (2 m/s) had an effect on the spread of the gas medium with a lower explosion limit concentration (1.7 vol.%) compared to the initial time point, despite the high outflow velocity (Figure 12). The direction and concentration of gas spread not only depend on the outflow and air flow intensity, but are also significantly influenced by the physical properties of the gas, in particular its density, which determines how the gas can interact with environmental obstacles in the expected direction of spread, thereby influencing the formation of areas with hazardous concentrations.

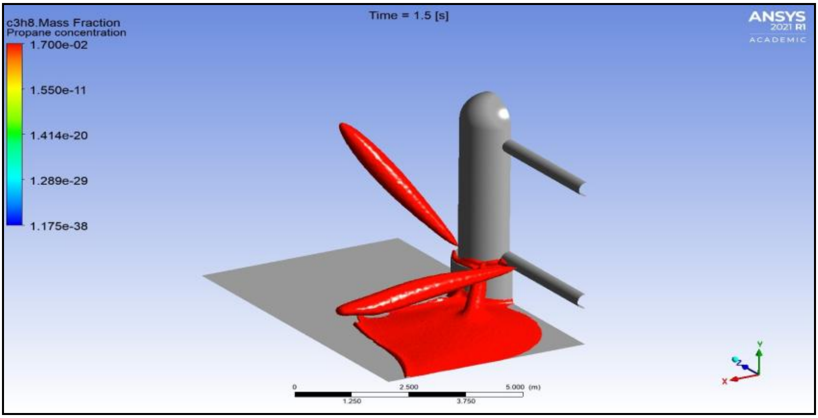

Figure 12: Spread of 1.7 vol.% propane at an air flow rate of 2 m/s in 0.1 seconds (author's edit)

At an air flow rate of 10 m/s, the effect is already visible at 0.5 seconds in the simulation.

Figure 13 shows that the gas clouds are distorted even at 0.5 seconds, and the normal outflow direction is also clearly "pushed up", but this causes the lower explosion limit to appear at a shorter distance.

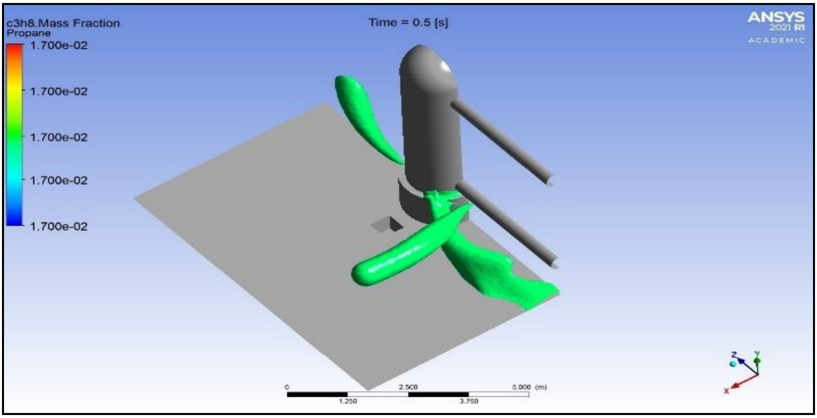

Figure 13: Spread of 1.7 vol.% propane at an air flow velocity of 10 m/s at 0.5 seconds (author's edit)

In the case of dispersions examined at an air flow of 20 m/s, the direction of dispersion of the gas clouds changes almost immediately, as shown in Figure 14.

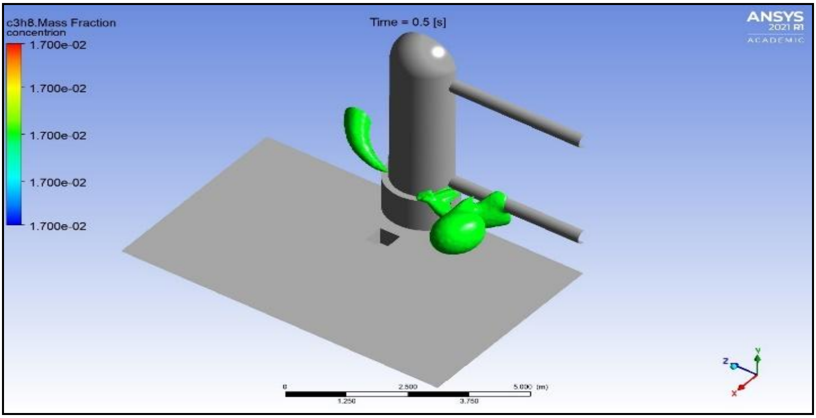

Figure 14: Spread of 1.7 vol.% propane at an air flow velocity of 20 m/s after 0.5 seconds (author's edit)

In the case of higher air flow, the assumed direction of propagation of the medium was significantly altered. Values of 10 and 20 m/s occur less frequently in industrial environments, but cannot be completely ruled out. I found that high air flow can reduce the volume of gas at explosive concentrations, but the instantaneous direction and speed of the medium and the exact location of the leak source are difficult to determine in reality.

In the case of low and high pressure leaks, an important starting point is the adiabatic expansion polytropic index of the gas or vapour medium, from which the critical pressure of the medium can be determined. If the pressure of the medium is below this value, the subcritical flow range applies. Otherwise, conditions above the critical flow and other related analytical models will apply.

Gas cloud propagation below and above critical flow has different characteristics, which affects the extent of potentially explosive areas. Below critical flow, without turbulent flow conditions, a short jet forms at low velocity, which appears more concentrated around the emission source. Above critical flow, a high-velocity jet with turbulent flow characteristics is formed, which can extend further away from the emission source.

I simulated the propagation of the two types of emissions using ANSYS Fluent on a device filled with methane, on which I defined a gap. In the first case, starting from low pressure, the rate of gas emission decreases over time as the pressure in the tank also decreases from 180,000 Pa to approximately 107,000 Pa during the test run. The temporal progression of the gas emission rate between the start and end of the test period is shown in Figure 15.

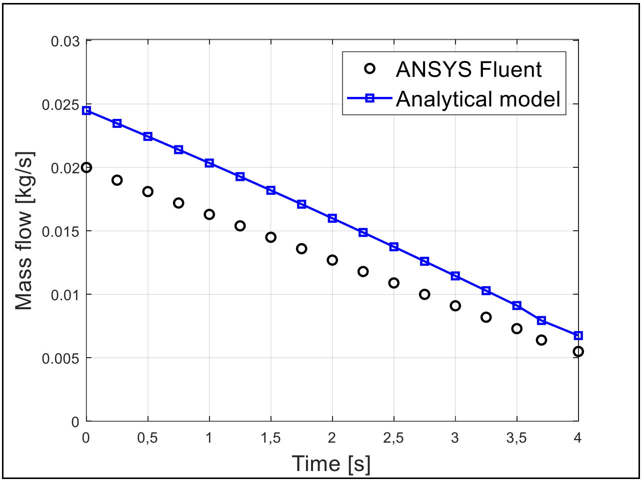

Figure 15: Change in methane emissions below the critical flow rate as a function of time (author's edit)

The 20% LEL value of methane is 0.88 vol.%. Initially, a longer jet was observed, then, as time passed, due to the decreasing pressure, a slowdown occurred and the gas spread out, and due to the expansion, it was able to penetrate into the area below ground level. At LEL 40% - 1.76 vol.%, the gas clouds are slightly thinner in both cases. The length and extent of LEL-4.4 vol.% increases over time.

The boundary conditions of the variables during the critical flow test are almost identical to those below critical flow, except that the internal pressure of the medium is higher, precisely 600,000 Pa. The simulation period studied was 10.5 seconds, which required 18 days of running time. The temporal evolution of the gas emission rate between the beginning and end of the examined period is shown in Figure 16. The gas emission rate decreases over time as the pressure in the tank also decreases.

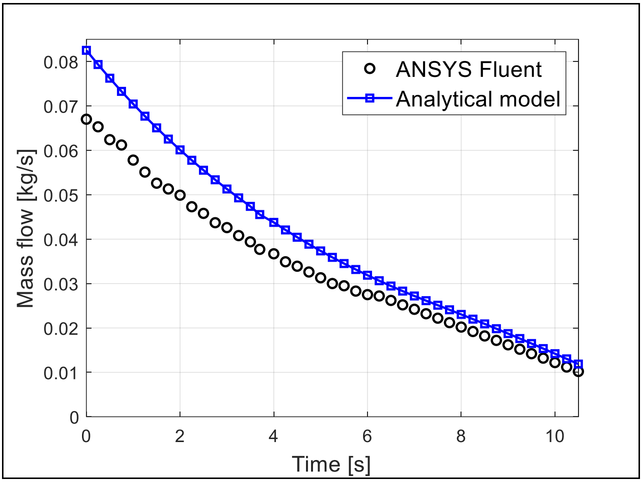

Figure 16: Change in methane emissions above the critical flow rate as a function of time (author's edit)

The simulation models I have created result in a smaller zone, but their determination is much more time-consuming than the analytical relationships, which result in higher emission values and a larger explosion hazard area, thus deviating towards safety.

My investigations show that, contrary to expectations, gases lighter than air were able to penetrate below ground level in both subcritical and supercritical flow conditions. This phenomenon is of particular safety significance, as it refutes the simplified assumption that such gases spread exclusively upwards.

Ignoring this can lead to an underestimation of hazardous areas, but at the same time, the use of simulation models is even more important, as hidden hazards – such as those caused by spaces below ground level – can be identified in a real industrial model.

3.3. MODELLING IN THE FLACS-CFD SIMULATION ENVIRONMENT

The most well-known numerical simulation software (CFD) is based on the finite volume method, of which I examined the applicability of FLACS-CFD software during my research. As this software is suitable for determining the spread and explosion hazard zones during the leakage of multicomponent gases, the aim of my investigation was to extend the relationships according to standard calculations to gas mixtures and to compare them with the results of simulation models. Having examined several possible methodologies, I found that there is no specific analytical procedure available for determining explosive areas, so my goal is also to predict explosive zones caused by multicomponent gases.

Numerical fluid dynamics simulation can be used to optimise the placement of gas detectors, as this method allows for the accurate modelling and analysis of gas or vapour flow in different environments. This can be particularly useful when the goal is to ensure that gas detectors detect the presence of potentially hazardous substances with the greatest possible efficiency.

In this study, I placed 12 gas detectors – monitor points – in the geometric model of an ammonia compressor located in a cooling system room. I examined three different leaks in the simulation, with a mass flow rate of 0.5 kg/s, a leak duration of 10 seconds, and a simulation run time of 20 seconds, but with different outflow directions. In the simulation, I examined the detection properties of the possible gas detectors as a function of time and concentration to determine how effective they are.

The room, i.e. the technological and simulation environment examined, is shown in Figure 17. The compressor containing the ammonia refrigerant (R717) is located in the centre of the room.

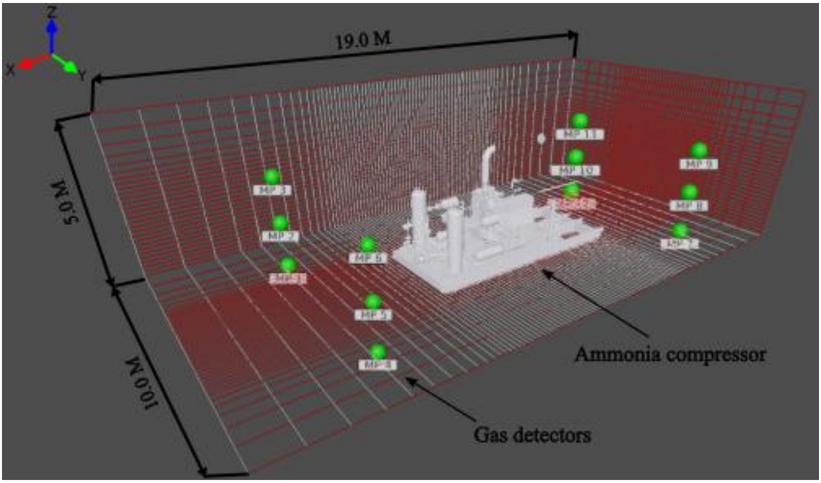

Figure 17: Geometric model of the technological and simulation environment under investigation (author's edit)

I determined the signal level of the gas detectors based on section 9.3.3 of standard MSZ EN 378-3:2016+A1:2021, which is 0.05 vol.% for the pre-alarm and 3.0 vol.% for the main alarm. According to the relevant MSZ EN 378 series of standards, when the pre-alarm level is reached, an acoustic and visual signal must be given and artificial emergency ventilation must be activated at the same time. When the main alarm level is reached, an acoustic and visual signal must be given, equipment containing ammonia must be automatically shut down, and equipment in the room that could be considered an ignition source from an electrical point of view must be de-energised. with the exception of explosion-proof products (e.g. gas detectors, alarm units, emergency lighting, emergency ventilation and emergency lighting) installed in accordance with IIA T1 (e.g. Zone 2).

Based on the results of the three simulations, I concluded (leakage test unrestricted +x propagation direction, leakage test restricted +z propagation direction, leak detection unrestricted in the +z direction) that when the leak spreads unimpeded, the installed gas detectors record the concentrations according to a well-defined trend relative to their position. However, when the leak point encountered an obstacle in its local environment, it split into several gas clouds in multiple directions, causing the detectors to detect concentrations that were not uniform and did not follow the same trends, regardless of their position.

I have verified that the spread of gas and vapour media can be well represented by simulating the leak.

During the design process, the detectors to be installed, their response and their optimal layout can be determined, which provides information and safety support to industrial operators.

In terms of coverage, 3-5 gas detectors in the room under investigation would allow any leaks to be detected quickly. Due to the relative density of gas, it is recommended that these detectors be placed upwards, towards the ceiling. The importance of placing particular emphasis on optimisation testing with gas detectors is clearly confirmed by cases that have occurred in industrial environments. There have been accidents where air flow in the vicinity of a gas detector affected its efficiency, leading to the formation of areas where the explosive gas reached the lower explosion limit and, due to the handling of inappropriate ignition sources, the conditions for combustion and explosion were present, resulting in an explosion. Based on my test results, it is therefore crucial to use not only the minimum of one gas detector specified by the MSZ EN 378-3:2016+A1:2021 standard, but also at least two gas detectors as specified in Chapter 9.4.2 of TvMI 13.5:2025.02.01. 9.4.2. – but also to install multiple gas detectors for double operational safety and redundancy – it is also essential to install multiple gas concentration detectors for safety reasons, as my simulation results lead me to conclude that numerous leakage conditions may occur in which the factors affecting emissions mentioned in my thesis, such as environmental obstacles, air movement, etc., influence the spread and detection in the initial stage of leakage is essential from a safety point of view. In my opinion, this approach should be set out in more detail in the MSZ EN 60079-29 series of standards, and the findings and requirements set out in the aforementioned series of standards should be strictly adhered to by organisations involved in occupational safety, fire safety and explosion protection.

In the case of explosive areas containing gas mixtures, there is currently no specific standard or methodology available for determining explosive areas. Compared to pure substances, multi-component mixtures have different chemical, physical, combustion and explosion properties. My thesis presents the definitions of these variables and how they can be implemented in the initial equations used to determine the explosive area of a mixture, which are as follows:

- molar mass,
- adiabatic expansion polytropic index (required to determine the specific heat at constant pressure),
- specific heat,
- critical pressure,
- gas or vapour density,
- lower explosion limit.

By extending the relationships mentioned above and those specified in MSZ IEC 60079-10-1:2021 [37], it is possible to determine the extent of potentially explosive areas in the case of gas mixtures, for which I present the results of calculations and simulations performed on a hydrogen-methane mixture in the following subchapter.

For the hydrogen-methane mixture, the values of the variables as a function of different concentrations are shown in Table 2.

Hydrogen [vol.%]	Methane [vol.%]	Critical pressure [Pa]	Polytropic index of adiabatic expansion [-]	Molar mass [kg/kmol]	Gas density [kg/m^3]	LEL [vol.%]	Species heat [J/(kmol·K)]
0	100	185 904	1,30	16,04	0,63	4,40	2224,36
10	90	185 985	1,31	14,64	0,58	4,36	2429,38
20	80	186 083	1,31	13,24	0,52	4,31	2676,01
30	70	186 205	1,31	11,83	0,47	4,27	2978,36
40	60	186 359	1,31	10,43	0,41	4,23	3357,75
50	50	186 563	1,31	9,03	0,36	4,19	3847,90
60	40	186 843	1,32	7,63	0,30	4,15	4505,61
70	30	187 253	1,33	6,23	0,25	4,11	5434,51
80	20	187 909	1,34	4,82	0,19	4,07	6845,91
90	10	189 128	1,36	3,42	0,14	4,04	9247,59
100	0	192 188	1,41	2,02	0,08	4,00	14245,28

Table 2: Variable values for hydrogen-methane mixtures at different concentrations (compiled by the author)

I conducted the tests under three different conditions: small gap, low pressure (5 bar(g), temperature 25°C and assumed gap size at a flanged connection, for example, 1.375·10-6 m^2), small gap, high pressure (160 bar(g), temperature 25°C and assumed gap size at a flanged connection, for example 1.375·10-6 m($^{2)}$)and large gap, low pressure (5 bar(g), temperature 25°C and assumed gap size at a flanged connection, for example 6221.139·10-3 m^2).

Figures 18, 19 and 20 show the results for the conditions examined as a function of concentration and zone extent.

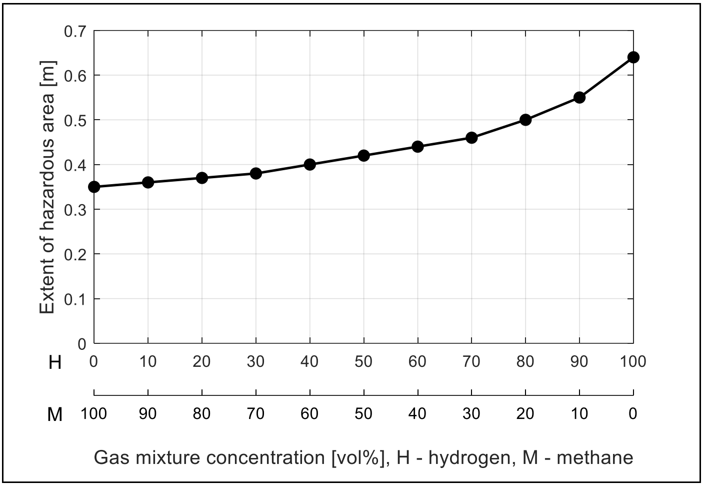

Figure 18: Extent of the explosive area as a function of concentration distribution (small gap, low pressure) (author's edit)

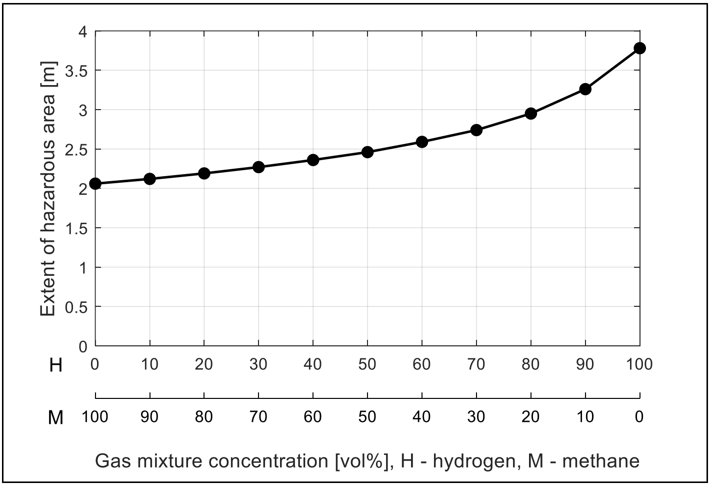

Figure 19: Extent of the explosive area as a function of concentration distribution (small gap, high pressure) (author's edit)

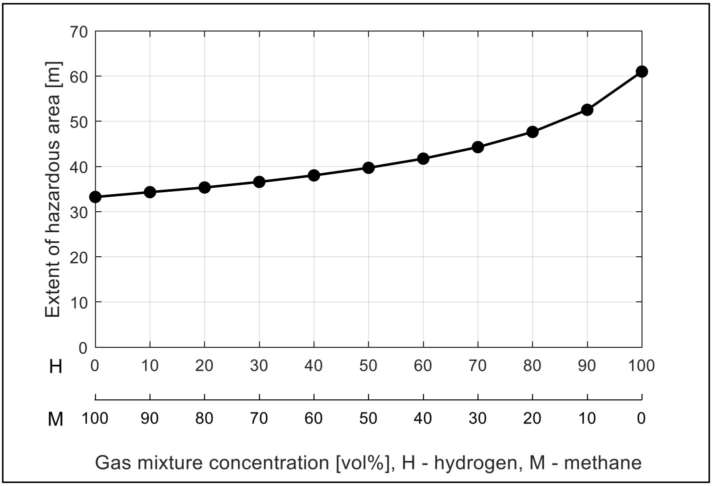

Figure 20: Extent of the explosive area as a function of concentration distribution (large gap, low pressure) (author's edit)

Using FLACS-CFD simulation, I created a model to examine three leaks, which simulate the spread of gas cloud mixtures with different concentrations at large gap sizes and low pressures. In my study, I modelled the state of the explosive gas cloud for three different gas mixtures and compared the results with those calculated by the new extended analytical models. In each simulation, I obtained lower values according to the extended relationships.

4. NEW SCIENTIFIC RESULTS

T1. I found that the literature and standard correlations for the free-surface evaporation of acetone give significantly different results. Through simulation and experimental studies, I have verified that the methodology of the US Environmental Protection Agency (EPA) provides the best agreement with the studies, therefore, contrary to the current regulations, it is recommended to apply the following correlation of the referenced standard in engineering practice. [P1, P4]

$$W_{pár} = \frac{0{,}284 \cdot u^{0{,}78} \cdot M^{2/3} \cdot A_{foly} \cdot p}{R \cdot T}$$

T2. I examined the extent of explosive areas formed by hydrogen and propane emissions in an ANSYS simulation environment for airflows of different speeds and directions. I found that the air velocity has a significant effect on the shape and extent of the zone formed, but the current standard environment ignores this effect. [P3, P8]

T3. In the case of methane escaping through a gap identified in a standard environment, I verified that different emission characteristics have an effect on the formation and spread of the gas cloud. With regard to outflow below and above critical pressure conditions, I have verified that explosive concentrations can form even in environments below sea level in media with a relative density lower than that of air. The standard provisions do not provide an adequate assessment methodology in all circumstances and thus under-regulate the requirements, so they need to be reviewed. [P6, P7]

T4. Using FLACS-CFD simulation, which is based on finite volume numerical fluid dynamics simulation equations, I examined risk management measures for a possible ammonia leak using a gas concentration sensor. I have confirmed that, in enclosed spaces with obstacles, perfect protection cannot be ensured with a gas concentration detector placed in the immediate vicinity of the leak point, as my simulation tests clearly show. I have concluded that optimising the placement of detectors is of paramount importance from a safety perspective and that the placement of at least one gas detector in accordance with the applicable standard cannot ensure safe operating conditions. Therefore, in order to increase safety, I have made recommendations regarding the quantity and quality of gas detectors, because it is important to intervene as quickly as possible when applying the necessary technical and organisational measures. [P12]

T5. After examining the methodology for determining potentially explosive areas for gas mixtures, I concluded that there is no specific procedure for determining the extent of explosive zones for gas mixtures. Supplementing the relationships for pure substances in the MSZ EN IEC 60079-10-1:2021 standard, I have developed a new calculation method that can be used to determine the size of the potentially explosive area of gas mixtures more accurately. [P15]

5. DEVELOPMENT OPPORTUNITIES

I would like to continue the work I have started in my research on explosion protection – the emission, leakage and spread of explosive substances. I would like to examine the models used in the acetone evaporation experiment in relation to several substances that occur in significant quantities in chemical and other industrial environments, with particular regard to the volatility of liquid mixtures. I would like to validate the most suitable model to date by reviewing it and possibly introducing new variables and measurements.

I would like to examine the effect of air flow according to additional media and geometric and environmental conditions, as this topic is not covered in sufficient detail by the regulatory environment. Furthermore, my goal is to prepare CFD simulations in which I examine the behaviour of explosive gases and vapours in the interior of ventilation systems. The aim of the research is to determine the extent of the risk under given conditions and the airflow conditions under which the risk of explosion can be considered negligible. In addition, my goal is to determine the maximum emission value at which there is no risk of explosion. I would like to validate this with the results of simulation experiments. I would also like to use CFD simulations to examine the risk of explosion hazard areas that can develop in enclosed spaces, with particular regard to the air exchange rate and its increased or decreased values. During the investigation, I would like to focus on whether the installation of one or more extraction points ensures more favourable operating conditions and, if so, how the safety of a room can be optimised and the operation of the system made more efficient. We have already started to develop models for the latter.

Among the factors influencing weather conditions, I would like to examine the limits of the propagation effects caused by humidity and precipitation, considering how much they influence the propagation of gases lighter than air in terms of relative density, and how gases and vapours affect propagation during emissions below and above critical flow. and vapours during emissions below and above critical flow.

Development opportunities

I would like to apply the methodology of explosive gas mixtures to several media, examining the state of dispersion and phase separation between the components. I would like to examine the emission coefficient value for gaps with different geometries, and I would also like to experimentally examine the lower explosion limit properties of the aforementioned gas mixtures in the laboratory of the Institute of Chemical Engineering. This will create the most accurate methodology possible for determining explosion-hazardous areas in such cases.

The results of research achieved to date and in the future can be applied to all industrial areas and technologies where there is a risk of explosion caused by gases and vapours, in particular to domestic and international legislation and standards relating to explosion protection. Decree 54/2014. (XII. 5.) BM of the National Fire Protection Regulations on explosion protection and the Fire Protection Technical Guidelines on explosion protection do not fully cover the requirements and need to be amended. Furthermore, old Hungarian standards could be replaced with international standards that are in line with current explosion protection science, either partially or fully harmonised, on a professional basis, thereby improving the regulatory system. Educational development is also necessary.

6. LIST OF PUBLICATIONS RELATED TO THE TOPIC OF THE RESEARCH FIELD

P1. Levente Tugyi, Dr. Zoltán Siménfalvi, Dr. Gábor L. Szepesi, "Experimental and theoretical investigation of acetone evaporation", *MULTIDISCIPLINARY SCIENCES: COMMUNICATION OF THE UNIVERSITY OF MISKOLC 11:* 5 pp. 132-144., 13 p. (2021), DOI: https://doi.org/10.35925/j.multi.2021.5.13

P2. Levente Tugyi, Dr. Zoltán Siménfalvi, Dr. Gábor Szepesi L., "Investigation of liquid exposure in potentially explosive atmospheres", *XXIV. Spring Wind Conference* 2021 Proceedings II., 28-30 May 2021, University of Miskolc, pp. 233-238

P3. Levente Tugyi, Zoltán Siménfalvi, Gábor L Szepesi, "The Application of CFD Software for Modelling the Dispersion of Hydrogen Gas at Renewable Energy Fueling Stations", *LECTURE NOTES IN MECHANICAL ENGINEERING Vehicle and Automotive Engineering* 4 pp. 483-490., 8 p. (2022), DOI: 10.1007/978-3-031-15211-5_40

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