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A Case Study: Dispersionand Explosion Quantitative Risks Assessment in an Ammonia Plant

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Ammonia, dispersion, modelling, procedure, risk assessment

Abstract
Ammonia is a highly toxic substance, and its dispersion in industrial settings presents significant risks to both personnel and surrounding communities. This study focuses on the risk assessment of ammonia gas dispersion and explosion scenarios in an ammonia plant. The research aims to evaluate the exposure risks associated with ammonia leaks, assess the effectiveness of mitigation measures, and provide safety recommendations. The study uses a semi-integrated 2D modeling approach for consequence modeling, with hazard identification and event tree analysis to calculate leak frequencies and potential final events. The exposure risk evaluation indicates that the entire target area is at risk of exposure to ammonia gas at concentrations above the threshold of 35 ppmv, due to high ammonia content in the process flow and operational pressures. Key findings suggest that the most at-risk areas include control rooms, workshop areas, and assembly points. To mitigate these risks, recommendations include engineering controls, improved toxic gas detection systems, and enhanced safety measures such as regular maintenance of equipment, double-door procedures, and personal protective equipment (PPE). The implications of this research stress the need for ongoing safety assessments and preventive strategies to reduce potential exposure risks in ammonia handling facilities.

INTRODUCTION

Ammonia is known to be a hazardous and toxic substance, can cause eye damage and irritation to the respiratory tract, the ammonia threshold value is 25 ppm (RI, 2018). Ammonia can be detected by humans at concentrations of >5 ppm; The smell is very pervasive at 50 ppm for 10 minutes, humans exposed to Ammonia show mild irritation at 30 ppm (10 minutes), irritation of the eyes, nose, throat, and chest at 50 ppm (10 minutes to 2 hours), to very intense irritation at 80 ppm (30 minutes to 2 hours) (Council, 2007).

Ammonia production has remained stable in recent years. By 2023, global Ammonia production will reach 150 million metric tons. East Asia is the region with the highest Ammonia production, with around 64.6 million metric tons (Department, 2024). Indonesia itself has an ammonia production capacity of 7.09 tons per year (Indonesia, 2024).

Ammonia (NH_3) is a colorless gas composed of nitrogen and hydrogen. This chemical has a nitrogen content of 82.2 percent and is an intermediate required for all downstream nitrogen products. Most of the Ammonia produced is used for agricultural fertilizers as a source of nitrogen for plants. Ammonia is also widely used in cleaning preparations, cooling gas, and plastics manufacturing. The ammonia industry is classified as a significant hazard. The source of fires and explosions in the Ammonia industry is generally a raw material in the form of flammable natural gas, and the process unit uses high temperature and pressure.

The release of 7,000 tons of ammonia, a toxic gas, occurred in 1989, stored in a fertilizer plant tank in Lithuania. This incident has killed 7 people, and 32,000 people have had to be evacuated. The ammonia release event is caused by excessive pressure in the tank (Lithuania, 2007). The cause of the accident could be due to a fault in the technological process during control, or a malfunction of the technological equipment caused by various factors (corrosion, vibration, control error) (Fedorov & Yablonsky, 2024). The active role of the community in developing disaster preparedness villages (community-based disaster preparedness) is needed to deal with emergency situations due to the release of toxic ammonia gas (Novrikasari, 2015). In addition, the preparation of evacuation management based on the results of hazard zone assessments and broader emergency response training efforts can improve the level of community preparedness and disaster management (Novrikasari et al., 2023).

Despite Indonesia's impressive economic growth in recent decades, poverty remains a pervasive issue, particularly in rural areas. The government has allocated substantial resources towards poverty alleviation through increased public spending in key sectors like education, healthcare, and infrastructure. However, the effectiveness of these expenditures in reducing poverty has been questioned. While some regions have seen improvements, poverty persists, especially in rural and underdeveloped areas. This raises the question of whether the increased government expenditure is effectively utilized to target and alleviate poverty, or if there are issues in the allocation and efficiency of such spending.

Moreover, taxation policies play a vital role in poverty reduction by redistributing wealth and generating resources for public programs. In Indonesia, however, the tax system remains regressive, mainly with indirect taxes like the value-added tax (VAT) placing a disproportionate burden on low-income households. While there have been efforts to reform tax policies to promote fairness, the tax system still presents challenges for poverty alleviation. The interaction between government expenditure and taxation, and how they jointly affect poverty reduction, remains underexplored. This study investigates how both fiscal policies interact to reduce poverty in Indonesia, considering regional disparities and the effectiveness of existing policies.

This research is urgent due to Indonesia's ongoing challenge of poverty, despite years of government intervention. The gap between rich and poor continues to widen, and while government expenditure has increased, its impact on poverty reduction is unclear. The study's focus on understanding the interplay between government expenditure and taxation policies is crucial for developing more effective fiscal policies. By investigating the relationship between these two factors, the research can provide insights into how Indonesia can optimize its fiscal tools to combat poverty and promote equitable development more effectively.

Previous studies have investigated the role of government expenditures in poverty reduction, particularly in the context of social services. A study by Ayuningtyas and Hermawan (2017) highlighted that public spending on infrastructure and social welfare programs has helped reduce urban poverty. However, this impact has been less pronounced in rural regions, where poverty rates remain high despite increased spending. The study suggested that targeted investments in rural development might yield more significant poverty reduction results.

In terms of taxation, research by Hossain (2014) analyzed the potential of progressive taxation in reducing income inequality and supporting poverty alleviation. While the study found that a progressive tax system could help redistribute wealth, it also pointed out the regressive nature of Indonesia's indirect taxes, which disproportionately affect low-income households. The study called for a reformed tax system to balance the tax burden better and improve the country's poverty alleviation efforts.

Another study by Setiawan (2020) explored the Indonesian government's fiscal policies and their impact on poverty rates. While government expenditures were found to have a positive effect, the study concluded that taxation policies were insufficient in addressing inequality and poverty. Setiawan emphasized the need for a more progressive tax system and more efficient allocation of public funds to ensure that resources effectively target the most vulnerable populations.

Although several studies have focused on the role of government expenditure and taxation in poverty reduction, few have examined the combined effect of these two factors in the Indonesian context. There is a lack of research that explores how government expenditure and tax policies interact and affect poverty levels, especially in rural areas. Moreover, most existing studies have treated these factors in isolation rather than examining their combined impact on poverty. This research aims to fill this gap by analyzing government spending and taxation policies to understand their cumulative effect on poverty reduction in Indonesia.

The novelty of this research lies in its holistic approach to examining government expenditure and taxation policies in Indonesia's context of poverty reduction. By analyzing the combined effects of fiscal policies, this study provides a more comprehensive understanding of how these policies work together to alleviate poverty. The study's focus on regional disparities and how these policies affect different income groups offers new insights into how Indonesia can better target its fiscal interventions to maximize their impact on poverty reduction.

This study investigates the combined effects of government expenditure and taxation policies on poverty levels in Indonesia. The study aims to analyze how these two fiscal policies interact to reduce poverty, focusing on regional disparities and the impact on various income groups. By doing so, the research seeks to provide policy recommendations for improving the effectiveness of government expenditure and tax reforms in addressing poverty in Indonesia.

This research will provide valuable insights for policymakers, economists, and public officials by highlighting the strengths and weaknesses of current fiscal policies in reducing poverty. The findings will offer practical recommendations for improving the efficiency of government spending and reforming the tax system to ensure more equitable poverty alleviation. Additionally, the research will contribute to the ongoing discussion on how fiscal policies can be optimized to promote inclusive economic development and reduce income inequality in Indonesia.

RESEARCH METHODS

The study's implementation began with data collection, including descriptions of the production process, P&ID, PFD, meteorological data, layout drawings, and risk assessments carried out by the company. Next, a failure scenario event tree was created to map and calculate the frequency of possible final events.

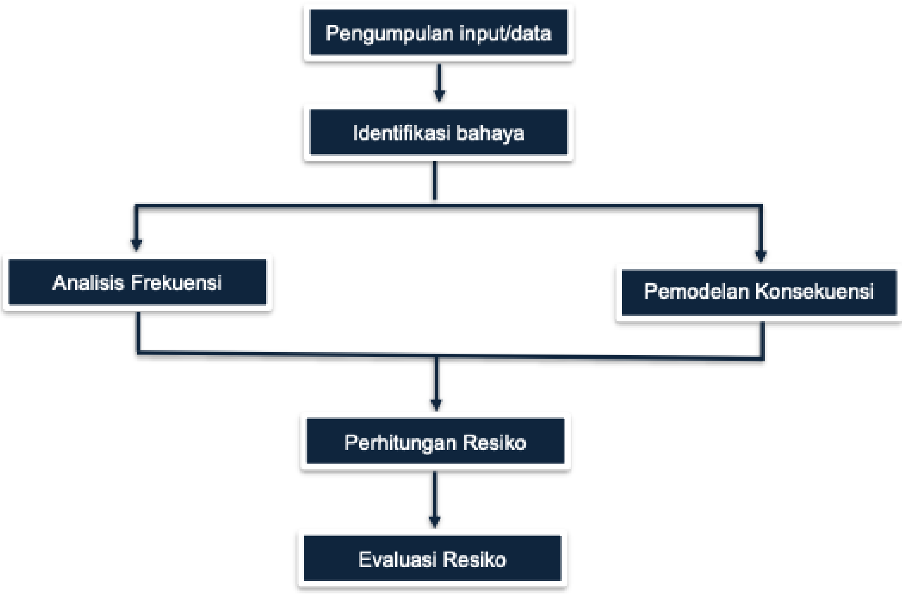

Figure 1 Research Flow of Dispersion and Explosion Studies

Then, modeling each failure scenario's leaks and possible final events was carried out in a simulator based on a two-dimensional (2D) semi-integral method. At this stage, the rate and duration of the leak, as well as the range of dispersion, fire, and explosion exposures are estimated It is important to note that simulators with a 2D approach do not take into account the effects of geometry (e.g., soil contours, obstructions within the plant) on the leak and its dispersal impact. Thus, the resulting exposure range assumes that the scattering impact occurs on an open surface without a hitch. However, an embankment in the tank area has been considered, i.e., liquid will be retained in the embankment as long as the volume of spilled liquid does not exceed the height of the embankment. Contours per threshold value, which denote the range of leak consequences for each final event, are then plotted on the facility imaging map.

RESULTS AND DISCUSSION

The X plant used as the research object was the petrochemical industry in Karawang Regency, Cikampek District. The industry has two factories, 1A and 1B, with an ammonia production capacity of 570,000 MT/year, and has two storage tanks with a capacity of 5,000 and 10,000 m3, respectively. The industry uses raw natural gas, air, and water to produce ammonia. In the Refining Unit, natural gas is separated from impurities such as sulfur and mercury to be further reacted with water vapor and air in the Steam Reform Unit. The process produces a synthesis gas, which is then further processed through *the High Temperature Shift Converter* and *Low Temperature Shift Converter* in the Shift Conversion Unit. The output is then fed into the CO2 Separation Unit. The CO2 gas is then sent to the Urea Plant, while the synthesis gas is further processed in the Methanation Unit, where the remaining carbon dioxide is reacted with hydrogen into methane gas. The synthesis gas produced by the Metanator is forwarded to the Reactor to be reacted into Ammonia. Warm liquid ammonia products (30°C) are delivered to the Urea Plant as raw material for urea production. Cold liquid Ammonia products (-33°C) are flowed into the 2101-F/FA Ammonia Storage Tank. In addition to Ammonia, hydrogen gas with 99% purity and CO gas are produced as by-products.

Figure 2 Petrochemical Plant Facilities

Identification of Ammonia Chemicals

At room temperature, ammonia is a colorless gas that is flammable and has a pungent odor. This substance is known by the name Ammonia (NH3) and has several synonyms, such as ammonia gas, Anhydrous Ammonia, Liquid Ammonia, and Nitrosil (NIOSH, 2024). In Europe, ammonia is a regulated pollutant, and the potential impact of agricultural emissions on nearby sensitive habitats is usually assessed using atmospheric dispersion models (Theobald et al., 2015).

Ammonia is highly soluble in water and freezes at –77.7°C and boils at –33.3°C. Ammonia gas is highly flammable, with an ignition limit of about 15.4–33.6 percent of the volume of ammonia gas in the air (Yarandi et al., 2021). Ammonia gas decomposes at temperatures above 400°C to produce hydrogen. Information about the physical properties of ammonia can be seen in the following table:

Table 1 Ammonia Characteristics (OSHA)

Nama	**Amonia**
CAS Number	7664-41-7
Formula	NH_3
Synonyms	anhydrous ammonia, aqueous ammonia
Molecular weight	17 gr
NFPA Health Rating	3
PEL-TWA (OSHA PEL, ACGIH, Permenaker 5/2018)	25ppm (17 mg/m^3)

Date Meteorologists

The effect of pressure on the dispersion of ammonia shows that the concentration of ammonia near the source increases with the increase in pressure, whereas the dispersion of ammonia away from the source is mainly affected by the wind field (Tan et al., 2020). Wind direction and wind speed data around industrial facilities obtained from the records of wind direction, wind density, and atmospheric stability levels are classified into several classes of relationships between the Pasquill-Gifford atmospheric stability class and wind speed. The following meteorological data have been collected:

Table 2 Meteorological data used in the study

Parameter	Value
Ambient average pressure	100.6 kPa
Ambient average temperature	28.2 ^{oC}
Average relative humidity	73,9%
Ground surface roughness	0,5
Dominant wind direction	Northeast
Average wind speed	2 m/s
Atmospheric stability	Highly Stable

Sumber: (Harrell & Barbacci, 2018), (Pupuk Kujang, 2024)

Identify Potential Hazards Using *Fault Tree Analysis* (FTA)
The frequency calculation for each possible final event of each leak scenario is evaluated using the event tree as exemplified in the following figure:

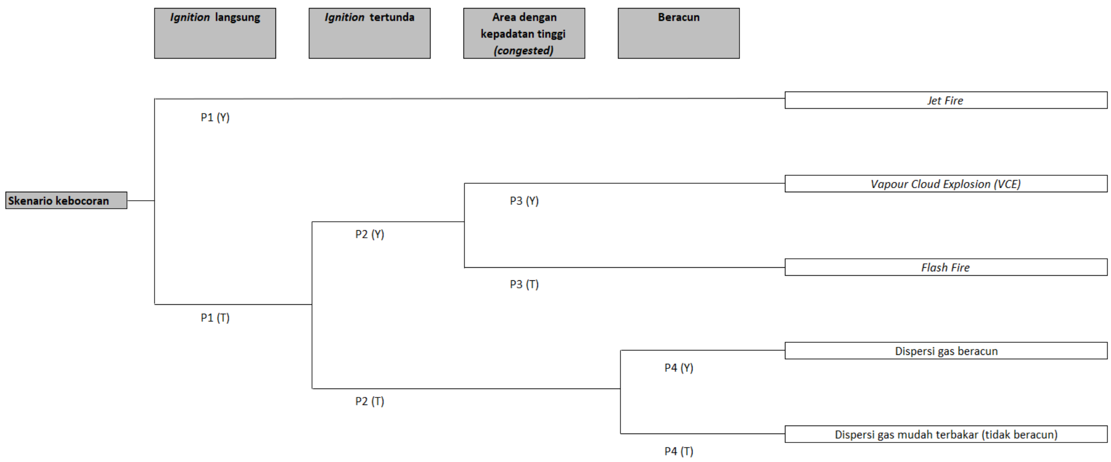

Figure 3 Occurrence tree for gas leak scenario

Here is a quick explanation of the possible end events of a leak scenario:

1. Jet fire is a fire that results from igniting jet gas or splashes of atomized liquid that come out of high-pressure equipment directly. The impact that endangers individuals is the intensity of radiation emitted from the jet fire. The occurrence of jet fires is directional (only in a certain direction).
2. A pool fire is a liquid fire caused by flammable steam formed on a spill pond. The impact that endangers individuals is the intensity of radiation emitted from the pool

fire.

3. Flash fire is ignited by the dispersion of flammable gases in areas without density or confinement. Since the flash fire phenomenon is very fast, the exposure range is represented by the dispersion distribution of gases with a concentration of 100% LFL.
4. A *vapour cloud explosion* (VCE) is an event ignited by the dispersion of flammable gases in an area with a degree of density or confinement. Impacts that harm individuals are in the form of excess pressure and debris resulting from explosions. However, please note that this study only measured the consequences of the impact of the explosion in the form of overpressure.
5. Dispersion is the distribution of unignited gases due to the release of gases or flashes (*flashed gas*) into the atmosphere, which are influenced by the release characteristics and environmental conditions. The impact that harms the individual is expressed in the form of concentration.

Potential hazards have been identified by considering the substance's characteristics, operating conditions, and the limitations of the production process. Ammonia Plant X has three main hazardous materials: 88% methane, natural gas, and Ammonia (liquid and gas). The evaluation target in the area around the exposure to ammonia stockpiles of plant X can be seen in Figure 4, where there are factory control centers 1A and 1B, workshop areas, and employee housing areas of plant X.

Figure 4. Evaluation Targets

Based on the consequence calculation, an Ammonia leak at the X plant facility will result in a dispersion of Ammonia gas with the lowest exposure concentration that does not cause death (25 ppmv with an exposure duration of 8 hours, 35 ppmv with an exposure duration of 15 minutes) at a distance of more than 10 km, from the source of the leak. The farthest distance is generated by the Ammonia Storage Tank area, as the volume of liquid ammonia stored is around 14,000 m. The dispersion of ammonia gas, which has the potential to cause individual death, is found within a radius of 2.3 km from Plant X (Table 3).

Table 3 Maximum exposure radius of each event at a given threshold

Exposure Type	Maximum Exposure Radius (m)
Jet Fire Radiation 4 kW/m^2	174
Jet Fire Radiation 12,5 kW/m^2	161
Pool Fire Radiation 4 kW/m^2	102
Pool Fire Radiation 12,5 kW/m^2	73
Pool Fire Radiation 35 kW/m^2	47
Flash Fire 100% LFL	81
Toxic Gas Dispersion (Ammonia) 25 ppmv	25.897
Toxic Gas Dispersion (Ammonia) 35 ppmv	21.447

Figure 5 shows the presence of an elliptical contour indicating the range of consequences by considering the wind direction; this indicates that the area not covered by it is considered not to be affected by the consequences of the leak scenario. A perfectly circular contour shows the effect zone, which is any area that can potentially be exposed to the consequences of the leak scenario. These contours are displayed to provide a comprehensive picture of the range of consequences without considering the direction of the wind.

Figure 5 Contour of the death rate due to exposure to toxic gases (ammonia) with medium leakage size and wind speed of 2 m/s

Discussion

Air pollution is a global issue that contributes to more than four million premature deaths each year, in the process of managing ammonia gas, regulating air circulation is the main thing, both to support normal operations and to deal with emergency release situations (Salamonowicz et al., 2022). In this study, Plant X, located in Cikampek, faces potential risks of technological disasters, including explosions, fires, and ammonia gas leaks. Ammonia is a colorless, corrosive, and highly toxic hazardous substance, with the potential to interfere with health, such as causing bronchitis and even death. A study of the consequences of accidents involving chemicals that can pose hazards such as fire, explosion, and the spread of toxic substances that have the potential to support activities such as risk assessment, planning, intervention, and evacuation (Besiktas et al., 2024).

The dominant wind direction at Plant X is northeast with an average speed of 2m/s, an average ambient temperature of 28.2°C, and a relative humidity of 73.9%. Atmospheric conditions play a role in changing the characteristics of chemicals that spread in the air (Cheliotis et al., 2021). The speed and direction of the wind determine the pattern and rate of its spread. Winds at low speeds slow down the dispersion rate or even allow chemicals to accumulate in a location. In addition, humidity and temperature factors also affect the buoyancy of the chemical (Rizzo et al., 2020). Wind fields can significantly increase the turbulent flow field, accelerate ammonia dilution, and reinforce horizontal movement trends (Tan et al., 2020).

The scenarios of this study are leaks in the form of *jet fire*, *pool fire*, *flash fire*, *vapour cloud explosion* (VCE), and dispersed ammonia gas. Ammonia is highly toxic, and with new applications and increasing global demand, stricter standards are needed to ensure its safe handling. After a cooled ammonia spill, cold ammonia gas will react with moist air, resulting in a fog, in an environment with a high concentration of ammonia, this fog will contain a mixture of liquid ammonia droplets and water due to the very strong hygroscopic properties of ammonia (Skarsvåg et al., 2024). The dispersion of ammonia in a closed area differs from that of an open environment in that the resistance amplifies the turbulence intensity of the nearby stream field. The importance of joint efforts is not only in reducing the formation of ammonia vapor clouds, but also in overcoming the accumulation of ammonia liquids (Hamzah et al., 2024).

Vertical ammonia releases produce the most severe consequences and should always be avoided. Reducing the duration of discharge and the rate of transfer flow can reduce the severity (Ng et al., 2023) and the use of a water curtain system to reduce ammonia vapour is an effective action in absorbing ammonia dispersion (Cheng et al., 2014). The spread of toxic gas or vapor clouds due to ammonia tank leaks can extend to a radius of 2.2 km in the dry season and 2.3 km in the rainy season, meanwhile, the effect of a pool fire results in exposure to thermal radiation that covers a danger zone radius of 57 meters in the dry season and 58 meters in the rainy season. (Herlambang et al., 2023).

Figure 5 shows that the entire target area is at risk of exposure to Ammonia gas dispersion at a threshold of 35 ppmv. This is due to the high Ammonia content in the process flow, and most processing units operate at high pressures. These results reaffirm the importance of efforts to prevent Ammonia gas leaks at the X Plant facility. *Control Room 1A/1B*, Workshop Area, and Craftshop are areas that have the potential to be exposed even at the lowest thresholds that cannot be tolerated in all consequences of the incident, namely heat radiation (4 kW/m2, burn injuries after 30 seconds of exposure), 100% LFL gas dispersion, ammonia dispersion (35 ppmv, respiratory tract irritation after 15 minutes of exposure), and explosions (0.35 barg causes 30% of deaths and 0.035 barg causes broken building glass). On the other hand, exposure to heat radiation due to pond fires does not pose a significant risk to all evaluation target areas. *Control Room* 1A/1B and Workshop Area are vulnerable to exposure even at the lowest thresholds that cannot be tolerated in all consequences of 100% LFL gas dispersion and ammonia dispersion (35 ppmv, respiratory irritation after 15 minutes of exposure). This is due to the location of the two areas close to the factory where the leak scenario begins.

Based on the study's results, several recommendations can be considered to reduce the risk of exposure to personnel/buildings in the area in and/or around the X Plant facility to a tolerable level, such as engineering control, administrative control, and strict control of the use of personal protective equipment. In addition to recommendations that reduce the risk of exposure, the following general recommendations can also be considered as a supporting effort to implement Process Safety Management (*Process Safety Management*).

CONCLUSION

Gas dispersion studies of the Ammonia Storage Tank 2101-F/FA area have included hazard identification, calculation of leak frequency and final events, consequence modeling based on a semi-integral 2D approach, and exposure risk evaluation at predetermined targets. Based on the exposure risk evaluation, the entire target area is at risk of exposure to ammonia gas dispersion at a threshold of 35 ppmv. This is due to the high ammonia content in the process flow and the fact that most processing units are being operated. These findings highlight the critical need for enhanced safety measures and contingency planning to minimize potential exposure risks.

Future research should explore the effectiveness of various mitigation strategies, such as improving ventilation systems or implementing ammonia leak detection systems, to reduce exposure risks. Additionally, further studies should focus on evaluating the long-term effects of ammonia exposure on both personnel and the environment and assessing the potential risks of multiple leak scenarios co-occurring. Investigating advanced modeling techniques, such as computational fluid dynamics (CFD), could offer more precise and detailed predictions of gas dispersion patterns, providing more robust risk management strategies for the area.

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