

Fire and Explosion Modelling of A Gas Transmission Pipeline In A Populated Residential Area

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Abstract

Several oil and gas distribution pipeline routes pass through a highly populated residential area. Risk assessment based on consequence analysis is being considered to determine the level of danger to improve safety. This paper focuses on modeling the consequences of gas transmission pipeline leakage by reviewing the impact of explosions and fires. The TNT method and fireball modeling determined the overpressure and heat-flux at each radius. Variations of release volume, radius, and pressure were conducted to obtain heat-flux and overpressure values in several event scenarios. Sensitivity analysis using numerical analysis was conducted to determine the most influential parameters. It was found that the radius of the accident point is the main factor affecting the resulting impact, with a contribution of 86.1% for the fire scenario and 64.5% for the explosion scenario. The explosion and fire modeling results show that the safe zone from the accident point is at a radius of more than 500 meters.

Keywords

Fireball, explosion, heat flux, overpressure, consequence

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Submitted : May 28, 2024. Accepted : June 19, 2024. Published : June 29, 2024.

INTRODUCTION

According to the 2023 Statista report, the world's oil and gas demand reached 91 million barrels per day [1] and most of the oil and gas was distributed using pipelines. Pipelines are more effective and efficient than other modes of transportation. Still, considering that the material being transported is flammable hydrocarbons, there are frequent failures in piping systems in the oil and gas industry [2]. Twelve thousand seven hundred eighty-one oil and gas pipeline system failures resulted in 274 deaths in the last 20 years [3]. Therefore, a consequence analysis of fire and explosion impacts is needed to determine the safety zone around high-pressure gas pipelines.

In 2019, an oil pipeline explosion occurred in Mexico, which killed 73 people [4]. That accident occurred because of third-party activities. In February 2023, an explosion of an oil pipeline took place in Riau that killed one person [5]. An oil and gas industry accident also occurred in Jakarta in March 2023 that killed 33 people [6]. This accident was related to a fire and explosion of hydrocarbons. It was initiated by a leak in the hydrocarbon transmission and storage system, followed by the ignition of a fire. Previous research mainly discussed individual impacts. Therefore, this research discusses the unified aspects of fires and explosions and determines the parameters that most influence the resulting impacts. In fire and explosion accidents, a combined impact assessment is assumed to provide a more accurate consequence than an individual one. In fire and explosion accidents, a damage potential (radius) can be increased if the impact of combustion products is considered [7].

Bhisham K. Dhurandher [8] discussed that the starting point of an explosion is the sudden release of hydrocarbon liquid from a pressure vessel into the environment. Then, if it catches fire, the material will immediately burn and form a fireball that releases a substantial amount of energy. Kang Wang [9] has also carried out experiments to determine the impact of fireball explosions using the fireball optimization method by comparing theoretical calculations with field data, and the results are accurate. It is stated that the safe distance from the accident point is 1000 meters. Mohammad Dadashzadeh [10] also introduced an integrated methodology that evaluates the impact of accidents in fire and explosion and found that modeling the impact of accidents is more accurate than individual modeling.

Consequence modeling of pipelines carrying natural gas must be done in two aspects: fire and explosion. Fire modeling is done by determining the fire scenarios and fire types that may form when a pipeline system failure occurs [11]. The fire modeled in this study is a fireball type due to material release and immediate fire ignition for open areas [12]. The impact of a fireball is caused by the resulting heat-flux that propagates and is felt even outside the radius of the fire. The presence of thermal radiation greater than 2.5 kW/m² indicates that the fire can seriously affect human and adjacent assets [13]. Heat-flux of more than 12 kW/m² are considered to cause possible death in humans. While heat-flux in the range of 2 to 12 kW/m² can cause possible injury and heat-flux below 2 kW/m² is categorized as safe. The fatal impact of a fireball can be felt up to a radius of 322 m [14].

Explosion modeling is carried out by the TNT method, which calculates the effect of the explosive force of the released gas by equalizing it with the mass of TNT explosives [11]. The TNT method is employed due to its provision of consistent standards in determining explosion strength, as it equates to the relatively stable explosive power of TNT, and its measurement outcomes can be consistently compared worldwide. This TNT method is straightforward and universally comprehensible, greatly aiding in risk communication to the general public. The fatal impact of an explosion results from overpressure escaping with enormous energy [15]. The explosion's impact can be direct, namely the effect of the overpressure itself, or indirect in the form of an impact due to debris from metal or concrete glued together. Risk of death and damage to buildings may occur if overpressure is more than 7 kPa. In comparison, 2 to 7 kPa overpressure leads to possible injuries and overpressures smaller than 2 kPa are considered safe for people and buildings.

This paper aims to model the consequence of fire and explosion of a gas transmission pipeline in a highly populated area. This study does not explicitly consider the third explosion impact in damage analysis. It only focuses on the direct impacts of fire and explosion events in the form of heat flux and overpressure.

METHODS

The analysis of the consequences of gas pipeline system failure encompasses two aspects: fire and explosion. Both aspects are discussed separately using different methods, yet they yield the same output, which is the determination of hazard and safe zone categories from the accident point. The sequence of each stage can be seen in Figure 1.

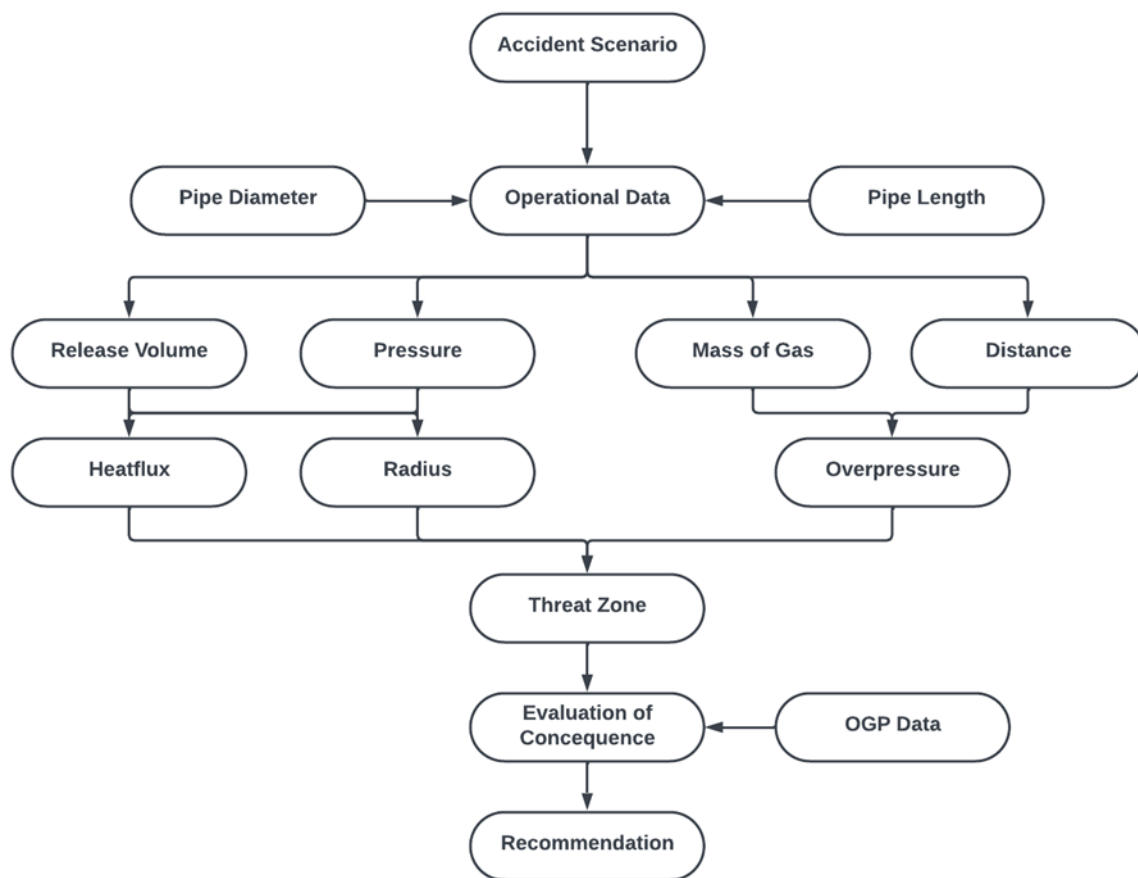


Figure 1. Conceptual Model

Figure 1 shows the conceptual model from the initial stages to the research's end. The research starts by determining the accident scenario and collecting pipeline operation data from the company and the Ministry of Energy and Mineral Resources. Consequence modeling is divided into two sectors: fire and explosion. In the consequences of fire, release volume and operating pressure variations are carried out [8]. Variations in the gas mass are carried out in the consequences of explosion [16]. This research was conducted on a 24-inch diameter gas pipeline exposed across the highway with a total length of 30 meters.

This data is necessary to assume variations in the release volume of the pipeline during leakage incidents. Meanwhile, the operating pressure ranges from 250 to 500 Psi depending on delivery requirements, thus variations are conducted within the range of 250 to 500 Psi to obtain more modeling and consequently, more accurate results. After obtaining the heat-flux and overpressure values, the hazard level assessment refers to the IOGP (International Association of Oil and Gas Producers) data [17] closes by providing recommendations based on the level of risk obtained. Furthermore, the process of calculating heat flux and overpressure is as follows:

Fireball

A fireball is a spherical fire with a large diameter that occurs quickly [11]. Heat-flux calculation is done through the following procedures:

1. Dimensions and Duration

$$M = f V \rho_{mat} \quad (1)$$

$$D_{max} = c_2 M^{1/3} \quad (2)$$

$$t_{max} = c_3 M^{1/3} \quad (3)$$

Where M is gass mass (kg), V is the release volume of the flammable gas, f is friction factor, c_2 ($5,8 \text{ mk}g^{-1/3}$), c_3 ($0,45 \text{ sk}g^{-1/3}$)

2. Burning Rate

$$m' = \frac{M}{(0.888\pi D_{max}^2) t_{max}} \quad (4)$$

3. Maximum Surface Emitting Power

$$SEP_{max} = F_s m' \Delta H_c \quad (5)$$

$$F_s = c_6 P_{sv}^{0.32} \quad (6)$$

Where F_s is the fraction of radiation, ΔH_c is the heat of combustion of gas and P_{sv} is partial vapor pressure, c_6 ($0,00325 P_a^{-0.32}$)

4. Actual Surface Emitting Power

$$SEP_{act} = SEP_{max} \quad (7)$$

5. View Factor

$$F_{view} = \left(\frac{R}{X}\right)^2 \quad (8)$$

$$X = \sqrt{H^2 + a^2} \quad (9)$$

Where R is the radius of the fireball, H is the height of fire from the ground, a is the distance from the fire to the receptor. X is the distance from the fire core to the receptor.

6. Heat Flux

$$q' = SEP_{act} F_{view} \tau_a \quad (10)$$

$$\tau_a = c_7 [P_w (X - R)]^{-0.09} \quad (11)$$

$$P_w = RHP_w^0 \quad (12)$$

Where τ_a is atmospheric transmissivity, P_w is pressure water vapor, RH is humidity ratio. c_7 ($2,02 P_a^{0.09} m^{0.09}$).

TNT Method

Explosion modeling using the TNT method is done through the following procedure:

1. Equivalent TNT Mass

$$M_{TNT} = \frac{f_E \Delta H_c M_G}{\Delta H_{TNT}} \quad (13)$$

Where f_E is the fraction of energy, ΔH_c is the heat of combustion of flammable gas, ΔH_{TNT} is the heat of combustion of TNT, M_G is gas mass (kg).

2. Scaled Distance

$$Z = \frac{x}{M_{TNT}^{1/3}} \quad (14)$$

Where x is the distance from the center of the explosion.

3. Overpressure

$$P_s = \frac{[80.800(1 + \frac{Z}{4.5})]}{\sqrt{1 + [\frac{Z}{0.048}]^2} \sqrt{1 + [\frac{Z}{0.32}]^2} \sqrt{1 + [\frac{Z}{1.35}]^2}} \quad (15)$$

RESULT AND DISCUSSION

This paper selects a highly populated area in Limo Subdistrict, Depok City, West Java as the case study. In this location, a gas pipeline is built above a main road and close to a highway. Thus, it is crucial to determine the threat zones in these locations in case of fire and explosion from this pipeline. Modeling the consequences of fire and explosion around gas pipelines results in heat-flux and overpressure in several scenarios of variation in release volume and operating pressure at each modeled radius.

The initial stage in modeling the heat flux from the fireball is to determine the dimensions and duration of the fireball. [Table 1](#) shows the calculation results for the dimensions and duration.

Table 1 Maximum Diameter and Exposure Time of Fireball

Release Volume (L)	Mass of Gas (kg)	Max Diameter (m)	Max Exposure Time (s)	Height (m)
5.000	2.113	74,42	5,77	74,42
10.000	4.226	93,77	7,27	93,77
20.000	8.452	118,14	9,16	118,14
30.000	12.678	135,24	10,49	135,24

[Table 1](#) shows that the mass of gas released, maximum diameter, maximum time, and maximum height obtained differ depending on the volume of gas released. The more gas volume is released, the higher the gas mass, which results in the maximum diameter, maximum time, and height of the fireball also getting more significant. So, it can be concluded that the gas mass, maximum diameter, maximum time, and height of the fireball core from the ground are proportional to the volume of gas released from the pipeline. The difference in the maximum diameter value of the fireball in each scenario will affect the heat-flux level.

Results

Fire modeling is carried out to obtain heat-flux values; hazard level assessment refers to IOGP data. Hazard categories are determined by giving colors in several radii: red indicates a danger radius with the impact of death, yellow indicates the impact of injury, and green is a safe zone. The hazard categories are presented in [Table 2](#), while [Figure 2](#) shows the relationship between heat-flux and radius.

Table 2 Hazard Categories

Color Categories	Heat Flux	Overpressure	Hazard Categories
	$>12 \text{ kW/m}^2$	$> 7 \text{ kPa}$	Lethality
	$2 - 12.5 \text{ kW/m}^2$	$2 - 7 \text{ kPa}$	Injury
	$< 2 \text{ kW/m}^2$	$< 2 \text{ kPa}$	Safe

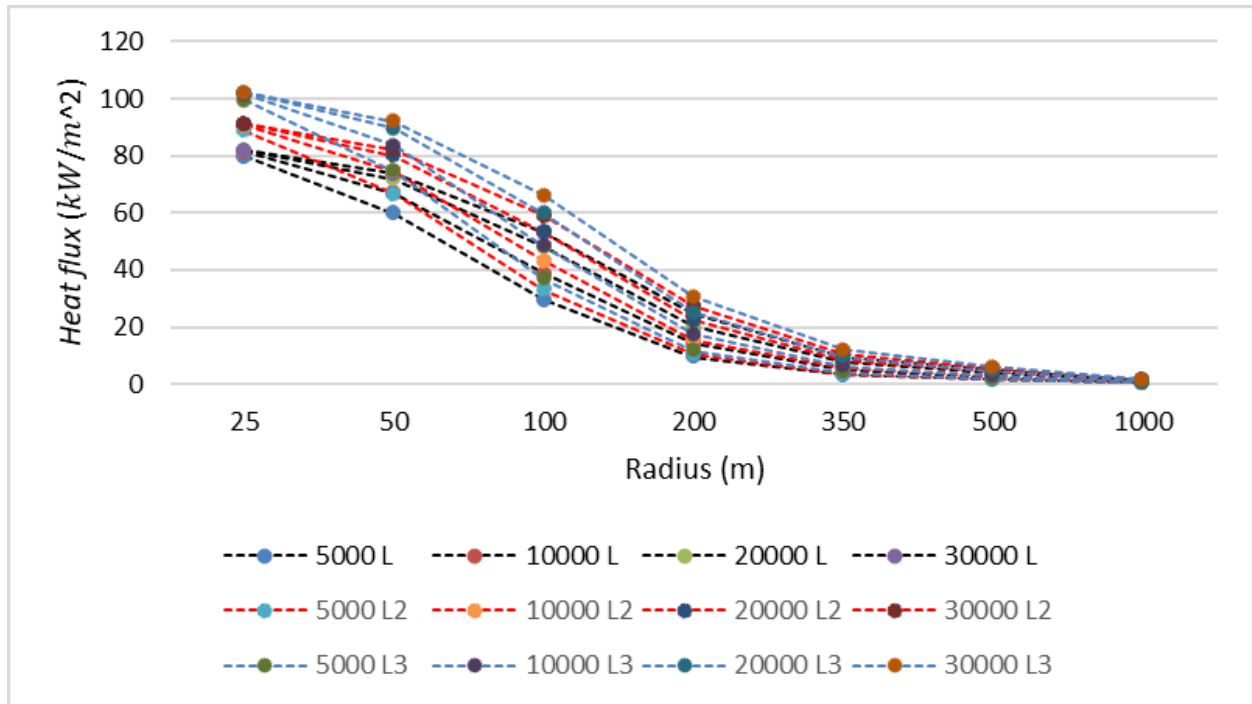


Figure 1 Heat-flux based on variation of volume release at modeled radius

Figure 2 shows the change of heat-flux value in several radii due to the variation of the release volume and operating pressure. The color difference of the dots on the curve shows the variation of release volume: L indicates an operating pressure of 250 Psi, L2 indicates an operating pressure of 350 Psi, and L3 indicates an operating pressure of 500 Psi. The operating pressure and the amount of release volume are proportional to the value of heat-flux generated, while the radius of the accident point is inversely proportional to the value of heat-flux. Threat zone and safe zone categories as consequences of fireball can be seen in Figure 3.

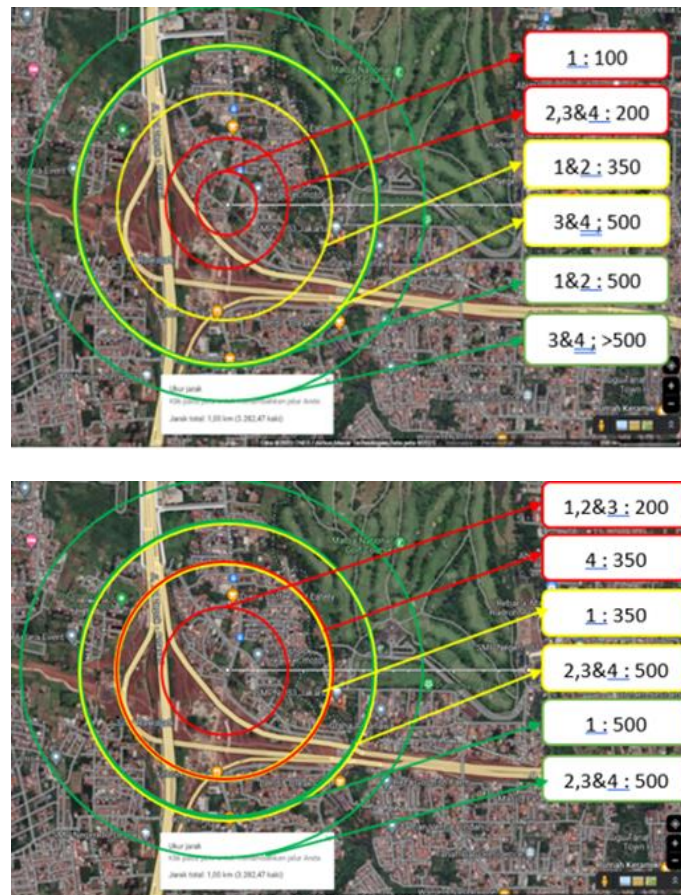


Figure 2 Threat zone of heat-flux

Figure 3 shows the hazard level categories in multiple radii for 250 and 500 psi operating pressures. Scenarios 1,2,3 and 4 indicate the difference in total release volume. At an operating pressure of 250 psi, the fatality zone is up to a radius of 200 meters, which has the potential to damage 150 houses and cause human death. While at an operating pressure of 500 Psi, the fatality zone is up to a radius of 350 meters, potentially damaging ± 1000 houses. A safe zone is at a radius of more than 500 meters from the point of the accident. Meanwhile, the graph depicting the consequences of explosion based on variations in release volume can be seen in Figure 4.

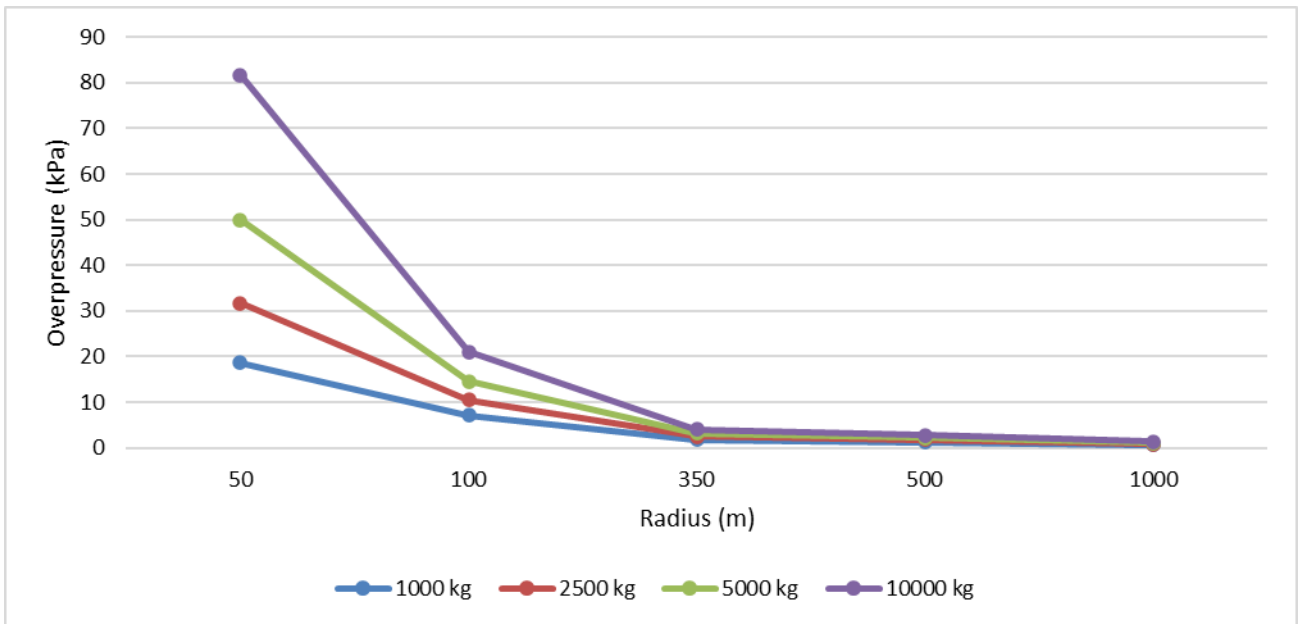


Figure 3 Overpressure based on variation of mass release at several modeled radius

Figure 4 shows the value of overpressure in several radii due to variations in the mass of the release gas. The overpressure value is proportional to the mass of the released gas but inversely proportional to the radius of the explosion point. The overpressure value drops significantly from a radius of 50 meters to 100 meters. Threat zone and safe zone categories as consequences of explosion can be seen in Figure 5. This Figure shows the categories of danger levels due to overpressure. Modeling the explosion hazard level is divided into four scenarios based on the amount of gas release mass. The red zone for all scenarios is at a radius of 100 m with overpressure values of more than 7 kPa. A radius of 100 m for explosions in all scenarios causes death. However, for the impact on structures, scenarios 1 and 2 can only destroy buildings at a radius of 50 m. A safe zone is at a radius of more than 500 meters from the point of explosion. Summary of the results of heatflux calculation at each scenario can be seen in Table 3.



Figure 5 Threat zona of overpressure

Table 1. Summary of heat-flux in each scenario

Pressure 250 Psi							
Volume (L)	Heat-flux (kW/m ²)						
	a=25m	a=50m	a=100m	a=200m	a=350m	a=500m	a=1.000m
5.000	79,66	59,78	29,53	9,46	3,18	1,54	0,36
10.000	81,33	66,80	38,66	14,03	4,94	2,42	0,58
20.000	81,84	71,77	47,88	20,15	7,56	3,77	0,92
30.000	81,75	73,77	52,90	24,44	9,61	4,87	1,20
Pressure 350 Psi							
Volume (L)	Heat-flux (kW/m ²)						
	a=25m	a=50m	a=100m	a=200m	a=350m	a=500m	a=1.000m
5.000	88,71	66,57	32,89	10,53	3,55	1,72	0,40
10.000	90,57	74,40	43,05	15,63	5,50	2,69	0,64
20.000	91,14	79,93	53,32	22,44	8,42	4,20	1,02
30.000	91,05	82,16	58,91	27,22	10,70	5,42	1,33
Pressure 500 Psi							
Volume (L)	Heat-flux (kW/m ²)						
	a=25m	a=50m	a=100m	a=200m	a=350m	a=500m	a=1.000m
5.000	99,44	74,62	36,87	11,81	3,98	1,92	0,45
10.000	101,53	83,39	48,26	17,52	6,17	3,02	0,72
20.000	102,16	89,59	59,77	25,16	9,44	4,71	1,14
30.000	102,05	92,09	66,04	30,51	12,00	6,08	1,50

Table 3 presents the results of the complete heat-flux calculation for all scenarios. Color categories that indicate the level of danger based on the reference of the International Association of Oil and Gas Producers data. Red indicates fatality areas, yellow for areas with possible injuries, and green is safe. The summary of overpressure is shown in Table 4.

Table 3 Summary of Overpressure at each scenario

Gas Mass (kg)	Ps (kPa)				
	x = 50 m	x = 100 m	x = 350 m	x = 500 m	x = 1.000 m
1.000	18,66	7,15	1,85	1,28	0,64
2.500	31,72	10,55	2,53	1,75	0,87
5.000	49,92	14,63	3,22	2,22	1,10
10.000	81,73	21,08	4,12	2,82	1,39

Table 4 presents the results of the complete overpressure calculation for all scenarios. Color categories that indicate the level of danger based on the reference of the International Association of Oil and Gas Producers (IOGP) data. Red indicates fatality areas, yellow indicates areas with possible injuries, and green is a safe area. Sensitivity analysis is carried out to determine the most influential parameters that affect the result. The sensitivity data view that affects heatflux can be seen in Figure 6, while the sensitivity data view that affects overpressure is shown in Figure 7.

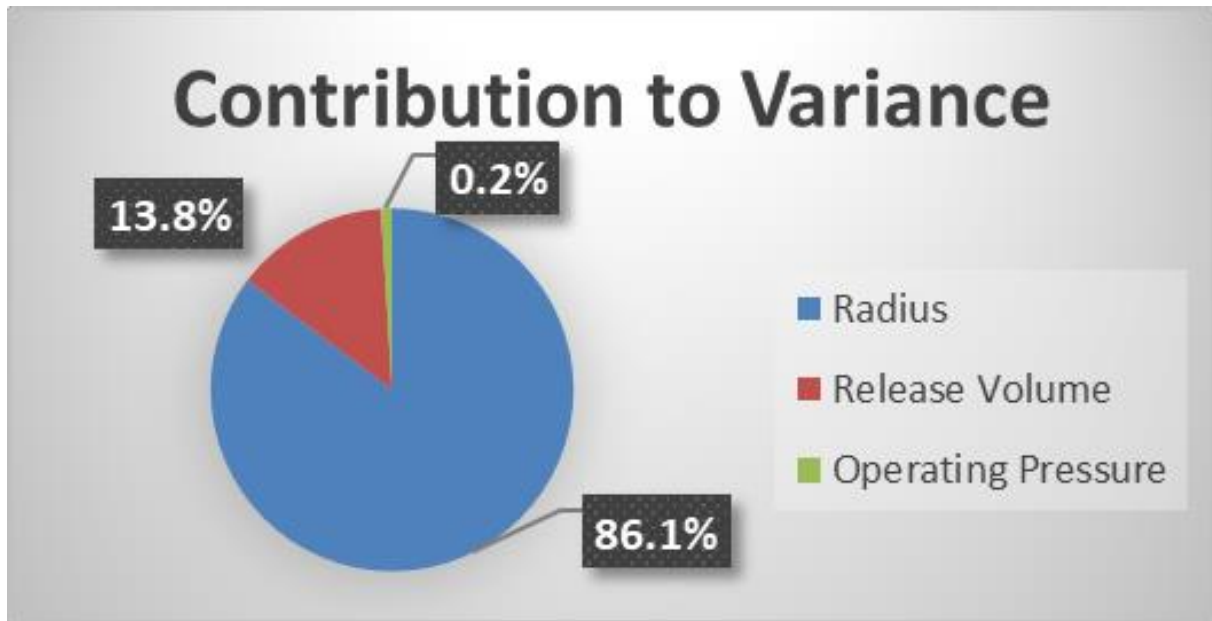


Figure 4 Sensitivity Data View of Heat-flux

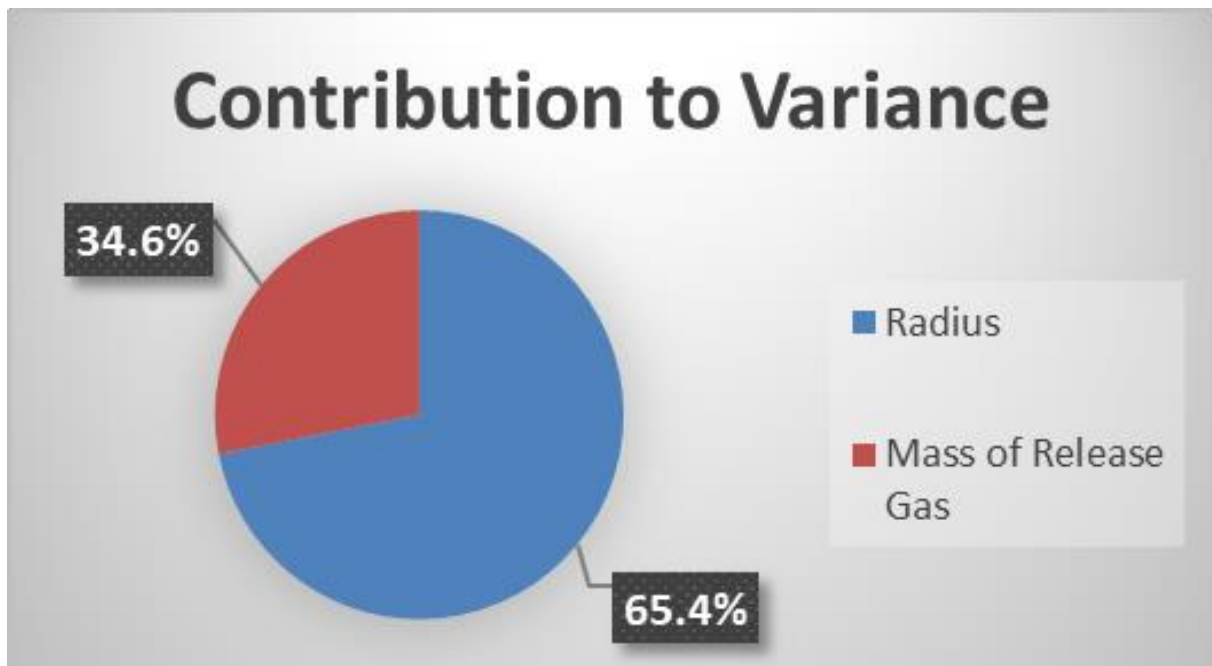


Figure 5 Sensitivity Data View of Overpressure

Figure 6 shows the sensitivity parameters to heat-flux, and Figure 7 shows the sensitivity parameters to overpressure. Sensitivity analysis is carried out by numerical analysis method because the parameters that affect the results are more than 3 [18]. The analysis uses a crystal ball in Microsoft Excel by entering parameter data and heat-flux and overpressure results. Each parameter varies at the specified limit and simulates 100,000 times of variation.

Discussion

The calculation of heat-flux results shows that the heat-flux value decreases as the radius from the fire point increases. Figure 2 shows a uniqueness at a radius of 100 m. All curves move away significantly differently from another radius; differences in the maximum diameter of the fireball in each scenario cause it.

Each maximum diameter for scenarios 1, 2, 3, and 4 is 74.42 m, 93.77 m, 118.14 m, 135.24 m. This means that a radius of 100 m for scenarios one and two is outside the fire, while for scenarios 3 and 4, the radius of 100 m is still inside the fire confinement. It causes the heat flux in scenarios 3 and 4 not to decrease significantly at a radius of 100 m.

The overpressure calculation results shown in [Figure 4](#) show that the overpressure also decreases with the increase in radius from the explosion point. The overpressure value decreases significantly from a radius of 50 m to 100 m. It means that the overpressure distribution relates to the energy distribution law.

When the distance is increased by two times, the resulting energy value decreases by 1/4. Theoretical modeling of heat flux with fireball modeling provides accurate results, as tested in previous research by Kang Wang [9], comparing modeling outcomes with actual field occurrences.

The hazard zone category in Table 3 shows the hazard zone due to heat flux. The red zone causes lethality at a radius of 200 m for an operating pressure of 250 Psi and 350 m for an operating pressure of 500 Psi. It proves that the operating pressure affects the value of heat flux.

The red zone has a heat flux value greater than $>25 \text{ kW/m}^2$ and possibly caused 100% of lethality. The yellow zone has a heat flux range of $2 - 12.5 \text{ kW/m}^2$ and caused injury and minor damage to structure, the green zone can be categorized as a safe zone and has a heat flux value less than 2 kW/m^2 . A safe zone is at a radius of 500 m. This result is not much different from research conducted by Wang, who found that the danger zone due to heat-flux from fireballs is up to a radius of 322 m [14].

The hazard zone category in Table 4 shows the hazard zone due to overpressure. The red zone that potentially caused 100% lethality is at a radius of 100 m for each scenario. This is because overpressure is different from heat flux. Overpressure does not have thermal radiation, which can spread quickly and far. The red zone has an overpressure value greater than 7 kPa and possibly caused 100% of lethality.

Yellow zone has an overpressure range of $2 - 7 \text{ kPa}$ and caused injury and minor impact on the structure. The green zone is a safe area with an overpressure value of less than 2 kPa. The resulting overpressure and impact were similar to the actual natural gas explosion incident in Murcia, Spain, in 2011—the explosion of a natural gas truck with a capacity of 10000 kg. A safe zone is obtained at a radius of 600 m.

Numerical analysis is carried out to determine the parameters that most influence the resulting impact. It was found that the radius from the accident point contributed the most to the impact for both fire and explosion scenarios. [Figure 6](#) shows the contribution of each input to the heat-flux generated. The highest contribution is given by the radius, which is 86.1%, meaning that the heat-flux value is strongly influenced by the distance of the receptor from the heat source point.

Meanwhile, the contribution of release volume is higher than the operating pressure. [Figure 7](#) shows the contribution of each input to the perceived explosion strength. The results show that the overpressure is strongly influenced by the distance of the receptor from the explosion point, with a contribution of 65.4%. The effects received by receptors due to fires and explosions are sensitive to the receptor's distance from the accident's point.

CONCLUSION

The radius, release volume, and operating pressure affect the consequences of fire and explosion. The safe distance from the point of occurrence of the new accident is obtained within a radius of more than 500 m. The danger radius for causing instant death is in the range of 100 m to 350 m. The consequences of an explosion at a radius far from the source of

the explosion are smaller than the consequences of a fire at the same radius. This is because fire has heat flux or the effect of thermal radiation that propagates in large quantities, so the range of the danger radius from the consequences of fire is more significant. The most influential parameter to heat-flux and overpressure is the distance of the receptor from the accident point, which contributed 86.1% for heat-flux and 65.4% for overpressure.

For further researchers to do consequence modeling with different fire models, the current research only focuses on modeling fireballs. So, if all fire scenarios have been modeled, the resulting consequences will be more accurate.

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