Balancing Relief Gas and Assist Gas Flows for Efficient Flare Gas Combustion in Onshore Gas Facility

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Abstract. This study investigates the interplay between relief gas and assists gas flows in onshore gas facilities, focusing on their impact on flare gas combustion efficiency. The primary objectives of this study are to analyze how relief gas flow rate, CO_2 and H_2S compositions, and the mixed-gas flow ratio influence the assist gas requirement, the mixed-gas calorific value, the flare gas composition, and the overall gas mix ratio. Additionally, the study evaluates flare gas monitoring to ensure compliance with environmental regulations. The comprehensive analysis aims to enhance the understanding of these variables' interactions and their effects on gas systems, contributing to improved industrial sustainability and efficiency. Increasing relief gas flow reduces assist gas demand, raises the mixed-gas calorific value and SO_2 concentration, and lowers CO_2 levels. Higher CO_2 content in the relief gas decreases the calorific value and increases CO_2 concentration without significantly affecting relief gas flow. Increasing H_2S content raises the calorific value and SO_2 concentration while reducing CO_2. A higher gas-mix flow ratio also lowers CO_2 and increases SO_2, with the minimum LHV of 300 BTU/SCF occurring at a ratio of 10.69. Monitoring results confirm that all flare emissions remain within government regulatory limits.

Keywords: Calorific Value, Carbon Dioxide, Environmental Compliance, Hydrogen Sulfide, Mixture Gas Ratio

INTRODUCTION

The current energy system is progressively adapting to address society's growing challenges. The primary success factors for electricity generation have been altered by uncontrolled urbanization, changes in social structures, new energy markets, and competitive conditions (Halim *et al.*, 2019). In addition, both demand and supply are affected by interest in cleaner, more flexible, and more affordable energy sources, necessitating the development of new technologies and decision-making processes to address these challenges (Liu *et al.*, 2021).

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The attention of sustainable solutions to significant issues of our generation, including energy shortages and global warming, has been motivated by the environmental impact of energy use (Bonneuil *et al.*, 2021). The accelerated development of renewable technologies to address the issue has been facilitated by growing global awareness of climate change over the past few decades. Fortunately, this has been the case. The primary constraints of renewable sources, which differ by three orders of magnitude from non-renewable sources, are their non-programmability and reduced power density (Olabi *et al.*, 2022). Nevertheless, their implementation is consistent with sustainability objectives.

Starting with the need to enhance the efficacy of thermodynamic systems to reduce fuel consumption, environmental concerns have posed new challenges for the energy production sector (Meo *et al.*, 2022). As a result of the ongoing increase in the average temperature of the Earth's atmosphere, oceans, and land, the global surface temperature has increased by 0.74 ± 0.18 °C. Carbon dioxide (CO_2) emissions have the greatest impact on air quality (Raymond *et al.*, 2016). The most significant contributor to global warming is CO_2 gas, which accounts for 50%. This CO_2 gas absorbs and reflects radiation pulses emitted by the Earth, thereby storing heat at the Earth's surface (Frolicher *et al.*, 2014).

The global and sectoral assessment diagrams, as well as examples of regional main risks, demonstrate fluctuations in the levels of impact and risk associated with global warming of 0-5 °C, which is the relative surface temperature change over the pre-industrial period between 1850 and 1900 (Song *et al.*, 2022). Therefore, it is imperative to mitigate CO_2 and other greenhouse gas emissions to address the additional climate change resulting from the inefficient use of fossil fuels and the heat generated by their combustion (Van Asselt *et al.*, 2021). In addition to reducing the combustion of flare gas, which is primarily composed of methane (80% of the total composition), propane, butane, ethane, and trace quantities of other hydrocarbons, inert gases, H_2S, SO_2, and other sulfur compounds.

Flare gas is burnt in the oil and gas industry for a variety of purposes. Initially, investors are hesitant to build production facilities because flare gas is typically not economically attractive, as it yields only a small income. Second, flare gas is designed to be combusted for emergency pressure relief in order to mitigate the risk of detonation that may result from the discharge of significant quantities of reactive gas. Third, the environment is more adversely affected by the direct release of excess gas into the open air. This is because methane, the primary component of hydrocarbon gas, is more hazardous than CO_2. Methane, in particular, has a global warming potential approximately 25 times that of CO_2 on a mass basis.

Flare gas products are composed of water and CO_2, with volatile organic compounds burning at over 98% (Daun & Spinti, 2025). This is the reason why flare gas is considered safer from a toxicity standpoint. Nevertheless, the utilization of flare gas is one of the most difficult issues in the energy and environmental sectors. The environmental consequences of flare gas combustion have a substantial impact on local residents' health, often leading to severe health issues (Obi *et al.*, 2021). Furthermore, the CO_2 emissions from flare gas combustion have a significant global warming potential and contribute to climate change. Consequently, numerous studies have demonstrated that the use of flare gas mitigates emissions. The present energy transition from fossil fuels to low-carbon fuels will be further supported by the utilization of flare gas, which will also ensure the national natural gas supply and prevent natural gas shortages.

The Ministry of Energy and Mineral Resources Regulation No. 30 of 2021 (Peraturan ESDM, 2021) on Procedures for Determining the Allocation, Utilization and Pricing of Flare Gas regulation specifies that flare gas may be converted into liquefied natural gas (LNG), compressed natural gas (CNG), and dimethyl ether (DME). LNG is more advantageous than other fuels due to its reduced storage capacity and shortened travel distance. This implies that LNG is more convenient to store and transport in an archipelagic nation such as Indonesia (Putiastuti *et al*, 2021). When combustion occurs in the flare, assist gas is required, which is typically natural gas. Assist gas is supplemental natural gas supplied to the flare tip to support stable combustion (Ismail & Umukoro, 2016). Therefore, optimizing flare gas will increase sales gas and improve the efficiency of assist gas use. The assist gas flow in the LP (low pressure) flare system is controlled at 0% opening when the gas flowing to the flare is 0.3-3 MMSCFD. Additionally, the auxiliary gas that is employed is 27 MMSCFD in the event of an operational failure or if the flow rate exceeds 3 MMSCFD (Abdollahi *et al.,* 2017). Current low-BTU flare tip technology requires flare gas with a lower heating value (LHV) of approximately 200 BTU/SCF. In contrast, advancements in CO_2 removal membrane technology have produced very low BTU waste gas with an LHV of about 140 BTU/SCF (Lou *et al*., 2022).

Factors influencing a flare encompass relief gas flow rate, assist gas flow rate, calorific value, and gas mix ratio. This is directly associated with combustion efficiency, emission control, and the plant's operational safety. Relief gas flow refers to gas emitted through a flare for combustion as a component of a safety system or process control. This gas typically originates from deliberately released high-pressure gas to prevent overpressure within the system. Excessive gas flow can lead to incomplete combustion, increasing gas emissions. The specific type of gas released, including light hydrocarbons, CO_2, and H_2S, influences the quality of combustion and the resulting emissions, such as NO_x and SO_x. Assisting gas flow rate facilitates combustion in flares, typically as additional air or as auxiliary gases such as natural gas, which is often regarded as a fuel gas. This facilitates the complete combustion of relief gas, thereby minimizing emissions of unburned gases, including carbon monoxide and unsaturated hydrocarbons. The flame temperature is increased while the flare flame stability is maintained, thereby enhancing combustion rate and reducing the emission of unwanted by-products.

The combustion process yields a calorific value, indicating the energy produced from the combustion of relief gas and assist gas. The value depends on the composition of the mixed gas. A higher calorific value of gas correlates with greater energy output from combustion, leading to higher temperatures and greater combustion efficiency. Gases with low calorific values may necessitate supplementary assist gas to achieve sufficient combustion. If the calorific value is low, the gas combustion is inefficient, leading to increased emissions. An incorrect ratio of relief gas to assist gas will lead to increased emissions of hazardous and greenhouse gases.

Combustion efficiency is significantly affected by flow relief, assist gas flow rate, calorific value, and gas mix ratio in the flare. The appropriate combination will result in optimal combustion, reducing hazardous gas emissions. Improper adjustment of any of these factors may lead to combustion instability, resulting in explosions, flare outages, or unsafe combustion conditions. These four factors are interrelated and contribute to maintaining combustion stability in the flare, maximizing energy efficiency, and minimizing harmful gas emissions. Optimizing combustion in the flare is also necessary to ensure that undesirable gases are fully consumed during operation. Failure to do so will result in substantial environmental and health issues. Lou *et al.* conducted research on a nontoxic combustion approach that demonstrated combustion efficiency, as well as devastation and eradication efficiency, across all types of flames in the refinery (Bai *et al.*, 2014).

The flare system is equipped with a purge system that uses oxygen-free gas to prevent issues that may arise during operation, such as burnback and stack explosions. The gas prevents air from entering the flare stack, which would otherwise form a flammable mixture. To mitigate purge gas consumption, velocity seals are implemented. The purge gas flow rate is the velocity seal's most critical operating parameter. An excessively high purge rate can increase operational expenses, while a too-low purge rate can lead to burnback and a detonation in the stack. During an emergency relief operation that involved a hydrotreating unit in April 2008, a detonation occurred in a flare system at a refinery in China. The reason was the low eradication rate (Sarkari *et al.*, 2022).

The objective of this investigation is to examine the impact of various variables on the efficacy and performance of gas relief and assist gas systems in industrial processes. The objectives of this study are to evaluate how relief gas flow rate, CO_2 and H_2S composition, and gas-mix flow ratio influence the assist gas requirement, the mixed-gas calorific value, and the resulting flare gas composition. Additionally, the study assesses flare exhaust gas at adjacent locations to verify compliance with applicable environmental regulations. The originality of this study lies in its comprehensive analysis that integrates these variables to provide a more complete understanding of the interactions and their effects on the relief gas and assist gas systems. Consequently, it is anticipated that the findings of this investigation will make substantial contributions to enhancing the sustainability and efficiency of industrial operation, as well as to advancing more effective flare gas monitoring and control strategies.

MATERIALS AND METHOD

Flare Gas System

The research was conducted at the Onshore Gas facility in Bojonegoro Regency, East Java Province. The Onshore Gas flare system has two types: low-pressure (LP) and high-pressure (HP). This study examines the utilisation of a low-pressure flare system, as shown in Figure 1. The flare system was designed to gather and safely discharge exhaust gases from relief valves, blowdown valves, and pressure control valves associated with different equipment in the facility. This gas comprised a blend of hydrocarbon gases, including non-volatile liquids. These gases cannot be directly emitted into the atmosphere due to their toxicity (H_2S and CO_2), possible explosiveness, and detrimental environmental effects such as acid rain

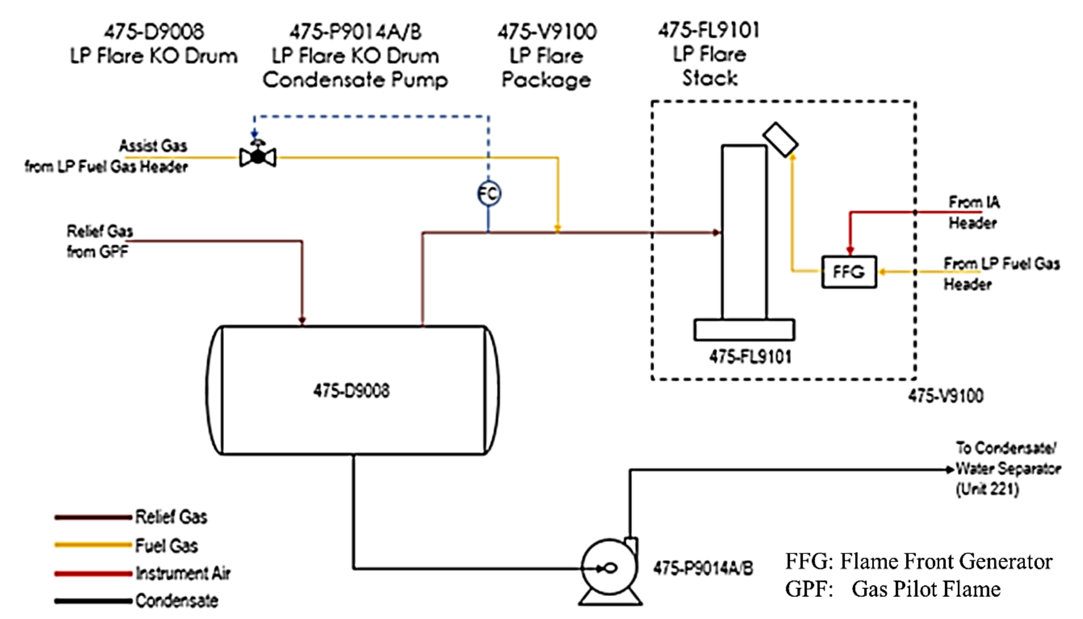

Fig. 1: Low Pressure (LP) Flare System in Onshore Gas Facility.

formation, increased greenhouse gas emissions, and local air-quality degradation (Shahab-Deljoo *et al.*, 2023). Functions to eliminate liquid from gas and securely dispose of gas by combustion. The LP Flare System was designed to manage gas relief from flash gas and regeneration sections, originating from continuous and/or specific-time gas discharges, emergency gas discharges, plant maintenance and Turn Around (TAR) operations, as well as scheduled or unexpected shutdowns. LP Flare was engineered with a capacity of 106.58 MMSCFD and includes a 36-inch pipe segment from the LP flare header, the LP Flare KO drum (475-D9008), LP Flare KO drum condensate pumps (475-P9014A/B), the LP Flare package (475V9100) comprising the pilot flare panel and LP Flare stack and tip (475-FL9101), along with an LPG bottle skid supplied as the initial fuel during start-up. LP Flare Tip was a sonic attachment designed to diminish heat radiation. The operational principle of the LP Flare Header involves the conveyance of hydrocarbons from the relief system to the LP Flare KO Drum (475-D9008), facilitating the separation of condensed liquid from gas prior to its entry into the combustion system at the Flare Tip. This system was designed to accommodate a discharge duration of 20 minutes at the maximum rate, with a maximum operating pressure of 4.2 psig, a temperature of 63 °F, and a maximum liquid level of 25%. The liquid accumulated in the vessel will be transferred using two 100% LP Flare KOD Condensate Pumps (475-P9014A/B) to the Condensate/Water Separator (221-D9002) during standard operations or to the Closed Drain System maintenance. Normal pump suction pressure was 4.9 psig, whereas discharge pressure was 188 psig. Upon verifying the proper operation of the LP Flare KOD Condensate Pumps, observe the gas flow via the Flow Indicator 475-FI9008-01 to ascertain the assist gas from the LP Fuel Header necessary to maintain a BTU value of no less than 300 BTU/SCF for the gas mixture. To ensure the effective combustion of high H_2S and CO_2 gas (acid gas) emitted by the H_2S

Recycle Compressor System Unit and Membrane Permeate Incinerator. The amalgamation of relief gas with assist gas proceeds to the flare stage, where a pilot flame or an automated ignition system ensures the effective combustion of the discharged gas. The LP Flare ignition system comprises a dual-ignition mechanism: High Energy Ignition (HEI) as the Primary Ignition and Flame Front Generator (FFG) as the Secondary Ignition. Additionally, it was outfitted with diverse flow and pressure regulators to ensure efficient combustion and prevent excessive pressure within the system, along with control mechanisms such as flame arrestors to inhibit fire propagation to the gas source, and a monitoring system to ensure safe operations in compliance with environmental regulations.

Relief Gas - Assist Gas Data Collection and Flare Gas Analysis

The Central Control Room (CCR) generates primary data on H_2S and CO_2 concentrations, as well as flow, temperature, and pressure for assist gas and relief gas. The data were collected over a 2-month operational period. The procedure for determining the concentrations of relief gas, assist gas, and mix gas using gas chromatography (GC) was outlined as follows. Gas samples were extracted from the system or process using a cylinder boom or gas bag. Additionally, the sample was introduced into the Gas Chromatography (GC) apparatus with a manual or automated injection system that ensures precise gas volume. The gas entering the gas chromatograph was partitioned between columns, resulting in varying elution times for each gas component. Utilizing a gas chromatography (GC) detector, each gas eluting from the column will be transformed into electrical signals. The signals were then captured and converted to concentration units by juxtaposing them with signals from the reference gas. Upon completion of the analysis, the concentrations of each component were expressed as percentages, parts per million (ppm), or parts per billion (ppb). The manufacturer's software calculates LHV, GHV, specific gravity, and other parameters based on the concentration of each component. Furthermore, the LHV of mixed gas was computed using Equation (1).

$$LHV_{mix} = \sum (y_i \times LHV_i) \quad (1)$$

where y_i is the mole fraction or mass fraction of the i-th component in the mixture, and LHV_i is the LHV value of the i-th component.

RESULTS AND DISCUSSION

Effect of Relief Gas Flow Rate on Assist Gas Flow, Mixed-Gas Calorific Value, Flare Gas Composition, and Gas Mix Ratio

Assuming that the combustion process is 100% converted and that the process occurs in optimal gas conditions. Therefore, the results in the appendix table were derived from the primary data. In the interim, Figures 2a-d illustrate the impact of the relief gas flow rate on the assist gas flow rate by combining flare gas in the form of SO_2 and CO_2 with gas heat. When data is collected with the assumption that the relief gas flow varies with a similar composition, and the assist gas composition is nearly identical. A graph of the relationship between relief gas flow and assist gas flow, expressed in MMSCFD units, is shown in Figure 2a. The graph shows a downward trend in assist gas flow as relief gas flow increases, and vice versa, suggesting that assist gas flow tends to decrease as relief gas flow increases. Certain factors may result in a decrease in assist gas flow while increasing relief gas flow. The need for assist gas may be influenced by operational conditions, such as the composition of the gas being processed or increased production. If the relief gas flow increases, it may be necessary to adjust the assist gas to ensure it meets the combustion requirements, which require approximately 300 BTU/SCF. In the processing facility, allowed combustion is unavoidable due to standard operating conditions, and the quantity is typically greater than that of unallowed combustion (Khalili *et al.*, 2021). Combustion in the flare burner may be ineffective if the assist gas is not optimal. This can lead to a reduction in calorific value and subpar performance. Nevertheless, the excessive use of assist gas, which is also a production gas, will result in its inefficient utilization. Therefore, it is imperative to regulate the use of assist gas, particularly to prevent the emission of greenhouse gases (Du *et al.*, 2019).

A graph of the relationship between the mixed-gas heat and the relief-gas flow is shown in Figure 2b. As the relief gas flow increases, the mixed gas heat also increases until it reaches a plateau (saturation). The graph illustrates an increasing trend. The rise in the gas mixture's temperature as the relief gas flow increases can be attributed to several factors. The total energy released when the gas is consumed is typically higher because the relief gas contains more combustible components. For instance, methane, ethane, propane, and other combustible gases (Perry, 1950). The combustion process can become more efficient, producing more heat per unit of gas as the gas flux increases. The energy available to fuel the combustion of flare gas is determined by calculating its calorific value using thermodynamic tables. The heat content of a gas propellant depends on the gas composition in the flare, as well as its molar mass and density (Beychok *et al.*, 2005). The combustion efficiency of the heat in the gas mixture can be influenced by variations in system pressure and temperature, which can result from increased gas fluxes. The LP Flare operates at a normal operating pressure of 100 psig, with a maximum flare stage temperature of 365 °F. The maximum flare point temperature is 960 °F, and its maximum capacity is 106.58 MMSCFD (International, 2021).

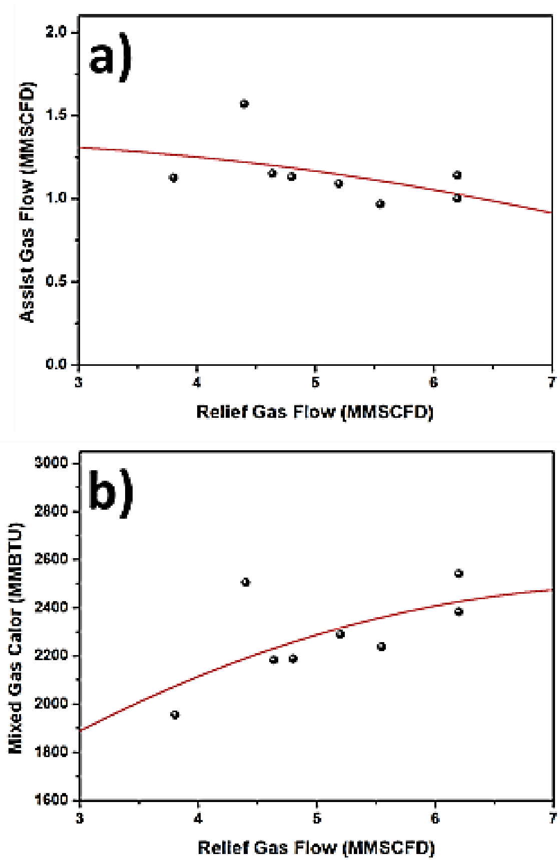

Fig. 2: Relationship curves between relief gas flow and a) assist gas flow, b) mixed gas calor

The correlation between flare gas concentration and relief gas flow rate is illustrated in Figure 3a. The SO_2 concentration initially increases as the relief gas flow rate increases, while the CO_2 concentration tends to continue to decrease as the relief gas flow rate increases. As the relief gas flow rate increases, the CO_2 content decreases, and the SO_2 content increases. This phenomenon may be attributed to several factors. The combustion efficiency can be enhanced by increasing the gas flow if the relief gas flow rate is derived from the combustion process. Consequently, a greater amount of CO_2 can be converted to SO_2 (Mirrezaei *et al.*, 2019). The presence of additional sulfur compounds in the relief gas flow rate may result in SO_2 production when the relief gas is ignited. In the interim, the carbon content may be lower, potentially leading to reduced CO_2 (Flagan *et al.*, 2012). Chemical reactions can be influenced by changes in operating conditions, such as temperature and pressure, leading to shifts in the ratios of CO_2 and SO_2 production. Consequently, standard emission factors are frequently insufficiently precise to accurately depict all operating conditions (Martin *et al.*, 2003).

The relationship between gas relief flow and gas mix flow ratio is illustrated in Figure 3b. The yellow line shows a nearly linear, increasing trend, indicating a positive correlation between the gas-mix flow ratio and the gas-relief flow. In other words, the gas mix flow ratio is higher when the gas relief flow is greater. As the gas relief flow increases, the gas mix flow ratio also increases, as the two variables are positively correlated. The following are a few of the primary reasons. This is intended to enhance system efficiency by increasing the gas-mix flow rate while maintaining the gas-assist flow rate. The system pressure also increases as the gas relief flow increases. The flow ratio increases due to the greater efficiency of systems designed to manage larger gas volumes. The flow ratio is directly influenced by the increase in system flow capacity resulting from increased gas relief flow. By increasing the flow of gas relief, the system's resistance can be reduced, resulting in a gentler flow at the flare.

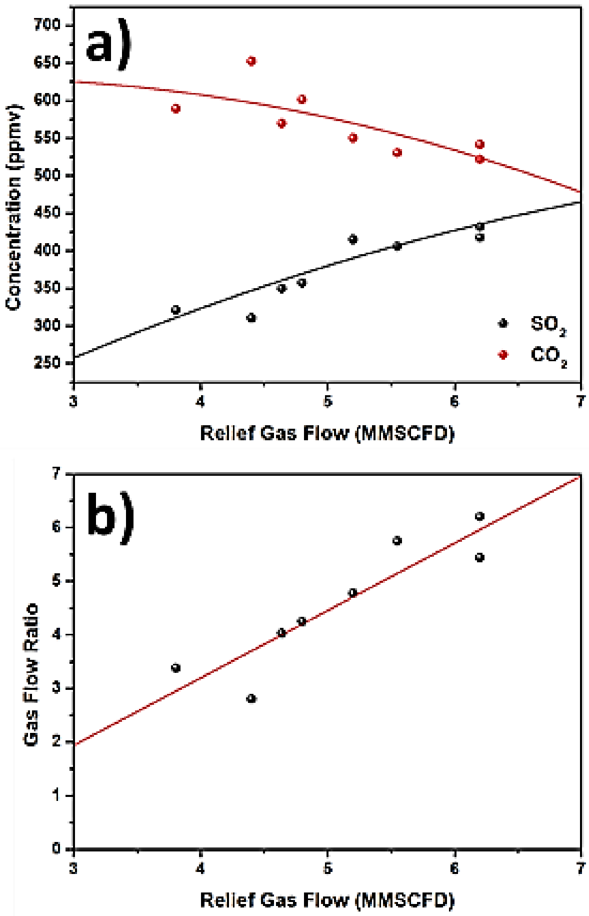

Fig. 3: Relationship curves between relief gas flow and a) SO_2 and CO_2 concentration in flare gas, b) gas low ratio

Effect of CO_2 Composition in Relief Gas on Assist Gas Flow, Mixed-Gas Calorific Value, Flare Gas Composition, and Gas Mix Ratio

In this section, data is collected under conditions of nearly identical relief gas flow and assist gas composition, simulating variations in CO_2 composition within the relief gas. Figure 4a illustrates the correlation between CO_2 composition and relief gas flow rate. This graph indicates that with nearly identical relief gas flow and assist gas composition, the CO_2 composition remains stable, averaging around 50-60% mol, with minimal variation. This may be attributed to multiple factors, including the design of the gas relief system, which aims to maintain a constant flow irrespective of gas composition to ensure operational safety and efficiency. Additionally, an automatic control mechanism is in place to regulate gas flow consistently, despite variations in gas composition, provided the gas flow mixture remains unchanged. The properties of CO_2 gas may not substantially influence the pressure or volume under specific conditions, thereby maintaining stable flow.

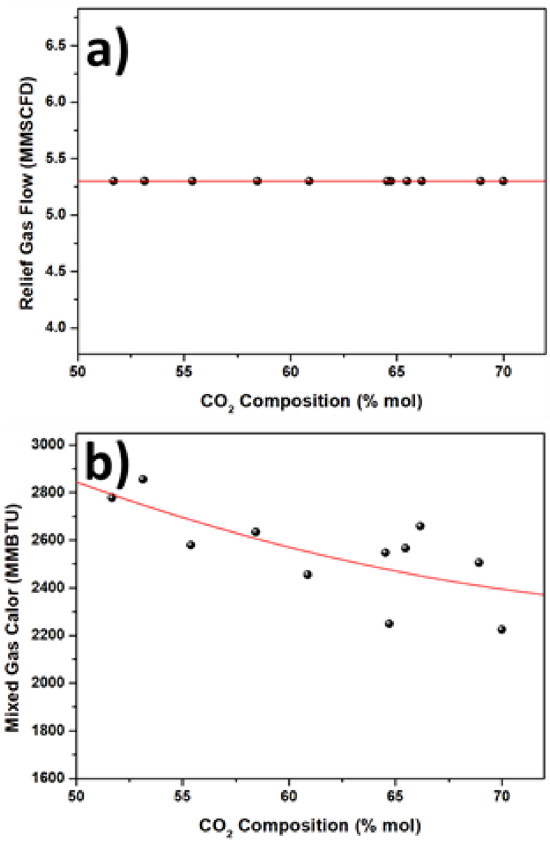

Fig. 4: Relationship curves between CO_2 composition in relief gas and a) relief gas flow, b) mixed gas calor

Figure 4b illustrates the correlation between CO_2 composition and heat mix gas. A negative relationship exists between CO_2 composition and heat mix gas. An increase in the CO_2 content of the gas mixture decreases the gas's calorific value. CO_2 is a non-flammable gas with a low calorific value. Consequently, an increase in CO_2 concentration in the gas mixture reduces the proportion of combustible gas, thereby decreasing the heat energy (calories) generated by gas combustion. This elucidates the reduction in the gas mixture's thermal energy as the CO_2 concentration increases. The reduction in the thermal energy of the gas mixture with increasing CO_2 content in the relief gas is attributed to CO_2's low calorific value. Gases with high calorific values, such as methane, yield more energy per unit mass in combustion. An increase in CO_2 content decreases the proportion of combustible gas, thereby reducing the total energy output of the gas mixture. The LHV of CO_2 is 0 BTU/SCF, CH_4 is 1000 BTU/SCF, and H2S is 279 BTU/SCF. As CO_2 concentration increases, the values of other gas components decrease, resulting in a reduced calorific value (Gas Processors Association, 1986).

Figure 5a displays the correlation between CO_2 levels and the composition of flare gases. As the concentration of CO_2 gas increases, the amount of CO_2 in the flare gas increases as well. Conversely, a decrease in H_2S composition reduces SO_2 gas formation, as SO_2 formation is primarily influenced by CO_2 levels. There exists an inverse relationship between the concentrations of CO_2 and H_2S in the flare gas. This phenomenon can be attributed to several factors. An enhanced combustion process may elevate CO_2 emissions while decreasing SO_2 emissions. SO_2 typically originates from sulfur in the fuel, and improved combustion can mitigate sulfur emissions. Combustion efficiency in a flare quantifies the effectiveness of gas decomposition into safe end products, including CO_2 and H_2O. High efficiency reduces emissions of harmful pollutants, including volatile organic compounds (VOCs), CO, and SO_2, into the atmosphere (Pohl *et al.*, 1986). Emission control technologies, including scrubbers, can effectively decrease SO_2 emissions while leaving CO_2 emissions unchanged. Currently, technology is being developed for real-time and continuous monitoring to assess combustion efficiency in flare gas. This involves gas- and temperature-sensor-based monitoring using optical sensing technology, specifically infrared spectroscopy and a flame ionization detector (FID). It includes automatic control and feedback systems with real-time data processing, as well as the application of IoT and integration with monitoring and data acquisition systems (Tao *et al.*, 2024).

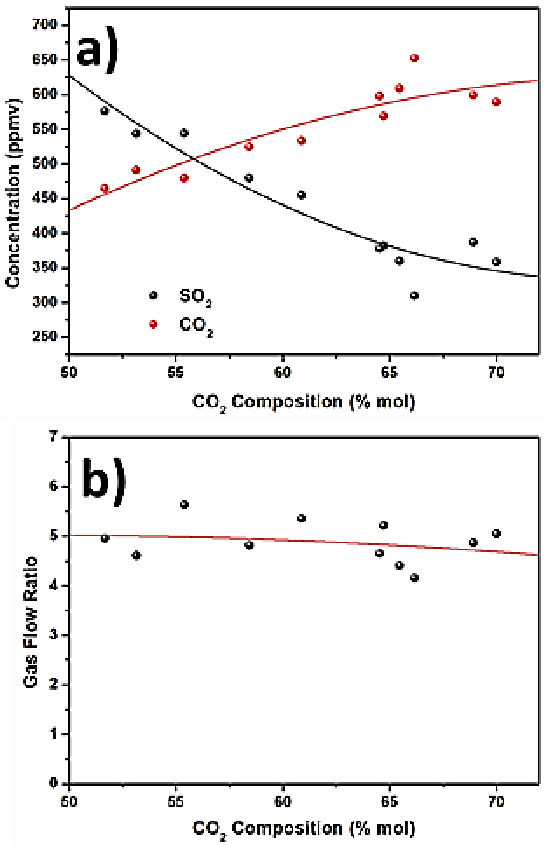

Fig. 5: Relationship curves between CO_2 composition in relief gas and a) SO_2 and CO_2 concentration in flare gas, b) gas low ratio

Figure 5b shows the correlation between CO_2 composition and the gas mixture flow ratio. As the concentration of CO_2 gas increases, the ratio of other gases decreases. The reduction in the flow ratio of relief gas to assist gas is attributed to multiple factors, including variations in gas density, with CO_2 exhibiting a higher density compared to other gases. As the concentration of CO_2 in the gas mixture increases, the mixture's overall density rises. The change affects the relief gas volumetric flow rate, resulting in a decrease in the relief gas ratio relative to the assist gas. The increase in CO_2 concentration may indicate a more efficient operational process, wherein reduced flare gas is directed to the relief gas while the quantity of assist gas remains constant. Carbon dioxide exhibits a greater density relative to numerous other gases. Under standard conditions, the density of CO_2 is approximately 1.98 kg/m^3, whereas the density of H_2S is about 1.54 kg/m^3. If the composition of flare gas is predominantly CO_2, the concentrations of other primary components, such as H_2S, will decrease, lowering the density. The viscosity of CO_2 gas at standard conditions is 0.07 cP, indicating a relatively high viscosity. The increase in viscosity may lead to heightened resistance to flow, consequently diminishing the flow ratio. The thermodynamic properties of CO_2, including heat capacity and thermal conductivity, influence gas flow within the system (Perry, 1950).

Effect of H_2S Composition in Relief Gas on Assist Gas Flow Rate, Mixed-Gas Calorific Value, Flare Gas Composition, and Gas Mix Ratio

Data in this section is collected under conditions of nearly identical gas relief flow and assist gas composition, simulating variations in H_2S composition within the gas relief. Figure 6a shows the correlation between H_2S composition and gas relief flow. This graph indicates that under nearly identical gas relief flow and assist gas composition conditions, the H_2S composition remains stable, fluctuating between approximately 0-50% mol with minimal variation. This indicates that there is no substantial correlation between variations in gas relief flow and H_2S composition. This phenomenon may be explained by several factors. The gas relief system can be engineered to accommodate fluctuations in gas composition while maintaining a constant flow rate. This suggests that the system has sufficient capacity to manage elevated H_2S levels without affecting overall flow (Zoeir et al., 2019). Operational conditions, including pressure and temperature, may remain stable, resulting in a constant gas flow rate despite an increase in H_2S composition. This arrangement is essential to prevent hazards in the flare system, including overfilling, liquid accumulation, flameouts, and air ingress (Denham *et al.*, 2015). H_2S may not significantly impact on the overall volume of gas released. The presence of other gases in the mixture may significantly influence the flow rate (Papailias *et al.*, 2018). The control system can be configured to sustain a constant flow rate for safety or operational efficiency, irrespective of variations in gas composition. Figure 6b illustrates the correlation between H_2S composition and the thermal properties of the gas mixture. A positive correlation exists between H_2S composition and the thermal properties of gas mixtures. An increase in H_2S content in the gas mixture correlates with an increase in the calorific value produced by the gas. The temperature of the gas mixture rises as the H_2S content in the relief gas increases, due to H_2S's high calorific value during combustion. An increase in H_2S composition correlates with a rise in the total energy released during combustion. The LHV of H_2S at standard condition is 587 BTU/SCF, whereas the LHV of CO_2 is 0 BTU/SCF. As H_2S concentrations rise, the levels of CO_2 and other components will decline, thereby increasing the combined LHV. The reaction of H_2S with other gas components yields more energetic products.

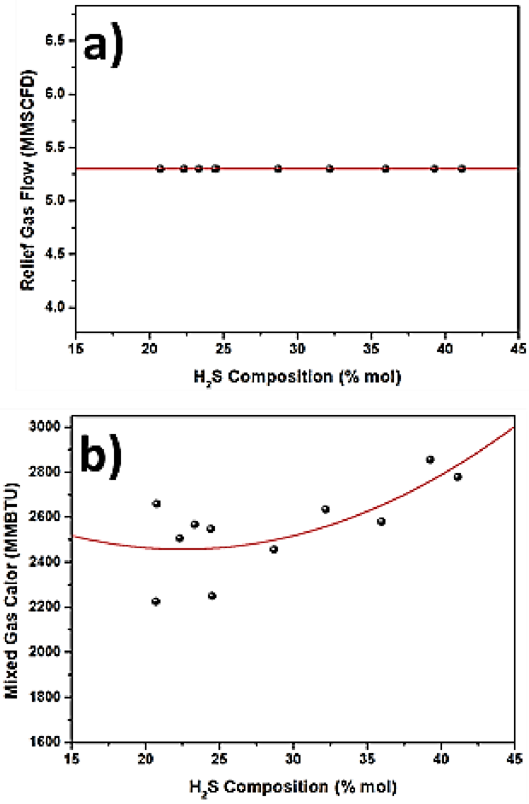

Fig. 6: Relationship curves between H_2S composition in relief gas and a) relief gas flow, b) mixed gas calor

Figure 7a indicates the correlation between H_2S composition and flare gas concentration. As the concentration of H_2S gas increases, the amount of SO_2 gas in the flare also rises. Conversely, a decrease in H_2S concentration reduces SO_2 formation, as SO_2 is primarily influenced by H_2S. There exists a unidirectional balance between the concentrations of SO_2 and H_2S in the flare gas. This shows an inverse relationship with the CO_2 concentration in the flare gas composition. H_2S can react with oxygen to produce SO_2. The increase in H_2S concentration correlates with a rise in SO_2 formation. Elevated H_2S levels may replace CO_2 in the gas mixture, reducing CO_2 concentration. In the combustion process, H_2S is more readily oxidized to SO_2 than CO_2, which is already in a stable state. Combustion efficiency may decline due to a rapid increase in the volume of gas combusted, reducing the heat content of the combusted gas. Under these conditions, it is proposed that gas with a lower calorific value may exhibit an efficiency as low as 90% (Blackwood, 2000). Figure 7b illustrates the correlation between H_2S composition and the ratio of relief gas flow to assist gas flow. As the concentration of H_2S gas increases, the gas ratio also increases. The increase in the flow ratio, alongside the rising H_2S composition in the relief gas, may be due to the greater presence of H_2S in the relief gas, which contains significant amounts of acid gases, including H_2S and CO_2. The increase in relief gas in the gas mixture will affect the ratio of relief gas flow to assist gas. H_2S has a higher density than many other gases; thus, an increase in its composition results in a greater number of H_2S molecules in the gas mixture, potentially enhancing the gas flow rate. The presence of H_2S can influence the thermodynamic parameters of the system, including temperature and pressure. This alteration can enhance the kinetic energy of gas molecules, subsequently increasing the flow ratio.

The combustion reaction of H_2S is exothermic, releasing heat into the system (Jasim et al., 2022). The elevated H_2S concentration poses significant safety risks and affects reaction kinetics, as H_2S is highly flammable under specific conditions. An increase in its concentration heightens the risk of explosion at elevated temperatures and pressures. The reaction between H_2S and oxygen occurs rapidly, leading to a sudden rise in temperature and pressure that may cause accidents in closed systems. The reaction rate increases with increasing H2S concentration. In certain instances, this may elevate the thermal risk within the system, potentially leading to thermal runaway, characterized by an uncontrolled reaction, as the temperature rises more rapidly than the cooling system can manage (Bunker *et al.*, 2023).

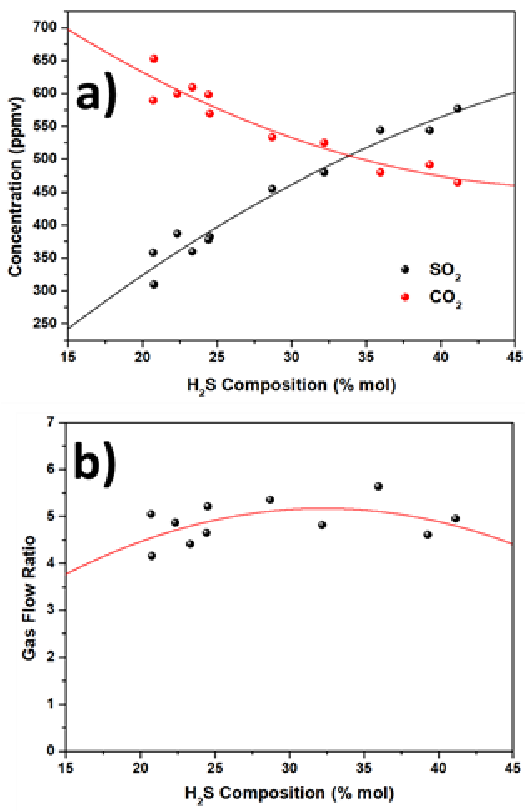

Fig. 7.: Relationship curves between H_2S composition in relief gas and a) SO_2 and CO_2 concentration in flare gas, b) gas flow ratio

Effect of Mix Gas Flow Ratio on Mix Gas LHV and Flare Gas Concentration

Figure 8a-b illustrates the impact of the flow mix gas ratio on the LHV of both the mix gas and flare gas. The data was obtained considering the relief gas flow rate and assist gas, which are nearly identical in composition. Figure 8a illustrates the correlation between the flow mix gas ratio and the LHV of the mix gas. This graph indicates that at the highest relief gas flow rate ratio, the mixed gas achieved a minimum LHV of 300 BTU/SCF at a flow mix gas ratio of 10.69. This aligns with the provisions outlined in the licensor's operation development procedure (OPD), ensuring that flare gas is maintained and that the mixed gas is combusted effectively (International, 2021). A lower level increases the risk of extinguishing the flare fire, thereby posing a threat to the dispersion of gas into the surrounding environment. The decrease in the LHV of the mixed gas, coupled with the increase in its flow ratio, can be explained by several scientific factors. An increase in the flow mix gas ratio may result in a predominance of lighter gases with lower calorific values in the mixture. Hydrogen and nitrogen exhibit a lower LHV than methane. Assist gas, defined as a gas that facilitates the combustion process, typically possesses an LHV exceeding 900 BTU/SCF. A reduction in the flow mix gas ratio results in a decrease in the assist gas flow rate, which has a higher methane concentration than the relief gas. As the flow mix gas ratio increases, the composition of the mixed gas shows higher concentrations of H_2S and CO_2 (Parivazh *et al.*, 2022). Increasing the flow mix gas ratio may lead to decreased combustion efficiency. Gas with a lower LHV yields reduced energy output per unit volume, resulting in decreased overall system efficiency. Combustion Efficiency (CE) is a metric expressed as a percentage that quantifies the effectiveness of equipment in burning a specific fuel (Shahab *et al.*, 2023).

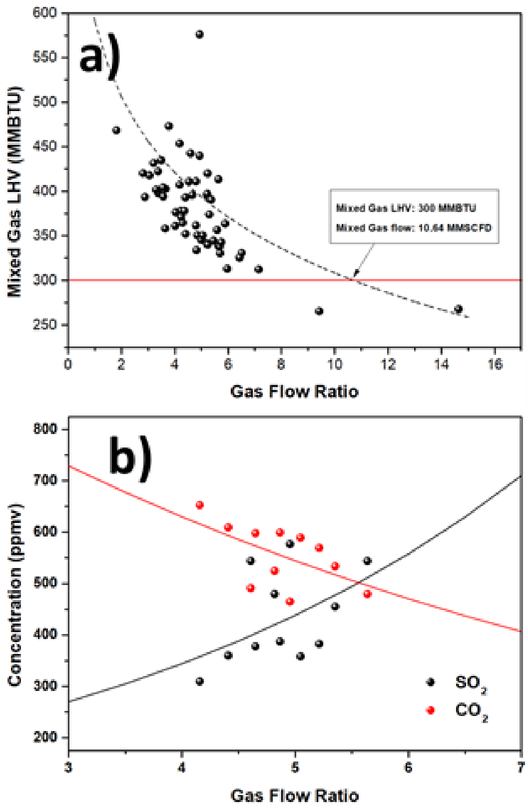

Fig. 8.: Relationship curves between gas flow ratio and a) mixed gas LHV, b) SO_2 and CO_2 concentration in flare gas.

Figure 8b illustrates the correlation between the flow-mix gas ratio and flare gas. As the gas ratio increases, the concentration of SO_2 gas rises while the concentration of CO_2 gas decreases in the flare. Altering the flow mix gas ratio can modify the conditions of chemical reactions within the system. SO_2 is produced through the oxidation of sulfur present in the fuel, whereas CO_2 results from the combustion of carbon. Increasing the gas flow ratio enhances sulfur oxidation efficiency relative to carbon, leading to higher SO_2 concentrations and lower CO_2 levels. The increased H_2S content in the gas mixture is also converted to SO_2 during flaring. The increase will be inversely related to the CO_2 gas content in the flare (Desrina *et al.*, 2007). Increasing the gas flow ratio can alter the system's temperature and pressure. The elevation of SO_2 concentrations may exhibit greater stability under elevated temperatures or pressures, whereas CO_2 may be more readily decomposed or transformed into alternative compounds. Furthermore, an increase in the gas flow ratio may influence the distribution of gases within the system. Increased gas flows may increase the rate of SO_2 formation or decrease the rate of CO_2 formation, resulting in corresponding changes in the concentrations of each gas.

Monitoring of Exhaust at Adjacent Locations

Emission factors are widely used to estimate exhaust emissions. Emission factors represent average values that estimate the quantity of pollutants released into the atmosphere from the activities associated with the pollutant source. Emission factors are provided for various air pollutants, including carbon dioxide, methane, sulfur oxides, and nitrogen oxides. Emission factors are determined for each fuel type and specific operation prior to combustion, expressed in units of pollutant mass relative to the mass of the fuel source, per calorific value of the exhaust gas, or per unit of oil produced (Soltanieh *et al.*, 2016).

Environmental monitoring and fixed gas detectors will be implemented in Q3 and Q4 of 2023, as outlined in Table 1. The laboratory analysis results for ambient air quality samples indicate that the concentrations of all parameters across all monitored factory locations remain below the ambient air quality standards established by Government Regulation No. 22 of 2021 (Peraturan Pemerintah, 2021), Chapter on Ambient Air Quality Standards.

The dispersion of exhaust gases from the flare is significantly influenced by factors such as wind speed and direction; stronger winds affect both the dispersion distance and the trajectory of pollutants (Burtt *et al.,* 2022). The air temperature influences the vertical flow of gas; higher temperatures facilitate mixing with a denser atmosphere, hence decreasing the concentration of gas near the ground surface. Stable air conditions, such as colder surface temperatures at night, impede the vertical dispersion of SO_2, resulting in elevated pollution concentrations around the source (flare) (Mirrezaei, 2019). Flare gas emissions may produce visible smoke despite combustion efficiency of up to 99%, since a small amount of soot may absorb and release visible smoke (Castineira *et al.*, 2006). Nonetheless, several hazards associated with gas and particulate matter pose risks to both health and the environment (Beychok, 2005).

Table 1. Flare gas monitoring in surrounding area

No.	Parameters	Unit	Value at 2023		Threshold
			Q3	Q4	
1	SO_2	mg/Nm^3	< 19.7	< 19.7	60
2	CO	mg/Nm^3	71.60	117.40	100
3	NO_2	mg/Nm^3	5.04	5.04	10
4	O_3	mg/Nm^3	44.70	22.80	120
5	HC	mg/Nm^3	< 5	< 5	-
6	TSP	mg/Nm^3	60.70	57.60	-
7	Pb	mg/Nm^3	< 0.54	< 0.54	2
8	PM_{10}	mg/Nm^3	26.60	20.00	150
9	$PM_{2.5}$	mg/Nm^3	17.50	10.40	65
10	NH_3	ppm	< 0.043	< 0.043	-
11	H_2S	ppm	< 0.003	< 0.003	-

SO_2, CO, NO_2, O_3, HC, TSP, Pb, PM_{10}, $PM_{2.5}$, NH_3, and H_2S can induce respiratory tract irritation, exacerbate asthma and bronchitis symptoms, and result in pulmonary damage. They may disrupt the blood's oxygen transport capacity, leading to headaches, dizziness, loss of consciousness, and potentially fatal outcomes at elevated concentrations (Motte *et al.*, 2021). In relation to the environment, it generates acid rain that harms vegetation, soil, water, and structures, diminishes air quality, facilitates the development of tropospheric ozone, poses risks to wildlife, and produces an unpleasant odor in the vicinity (Mousavi *et al.*, 2021). Emission reduction may also be achieved by minimizing flaring, namely by using flared gas for alternative uses. Including power plants, methanol, ammonia, hydrogen, and gas compression for industrial applications (Jokar *et al.,* 2021). However, gas relief has a significantly elevated H_2S concentration, rendering it unsuitable for industrial use.

CONCLUSIONS

Based on the results of this study, an increase in relief gas flow rate is inversely proportional to the assist gas flow rate, thereby increasing the mixed-gas calorific value and SO_2 concentration while reducing CO_2 concentration. Variations in CO_2 composition within the relief gas do not significantly affect the relief gas flow rate, but they lower the calorific value of the mixed gas, increase CO_2 concentration, and decrease SO_2 concentration. Conversely, increasing the H_2S composition elevates the mixed-gas calorific value and SO_2 concentration while reducing CO_2 concentration, without influencing the relief gas flow rate. Changes in the mixed-gas flow ratio also affect combustion behavior; higher ratios reduce CO_2 concentration while increasing SO_2 concentration, with the lowest LHV (300 MMBTU) occurring at a ratio of 10.69. These findings highlight that inappropriate gas composition or flow-ratio conditions may require higher assist-gas consumption, thereby reducing the economic efficiency of flare operation, as more assist gas—typically a saleable product—must be supplied to meet the minimum combustion requirement (≥300 BTU/SCF). Environmental monitoring confirms that flare exhaust emissions remain below the national ambient air-quality thresholds. The monitored parameters include SO_2, CO, NO_2, O_3, hydrocarbons (HC), total suspended particles (TSP), Pb, PM_{10}, $PM_{2.5}$, NH_3, and H_2S. All measured values comply with Indonesian Government Regulation No. 22 of 2021 (PP 22/2021) concerning ambient air quality standards, ensuring regulatory compliance at the monitoring locations.

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