

Article

Analysis of the Environmental and Safety Aspects of a Routine Utility Flare Using Computational Fluid Dynamics

Mohammed H. S. Zangana 

Department of Petroleum Engineering, Faculty of Engineering, Koya University, Daniel Mitterrand Boulevard, Koya KOY45 AB64, Kurdistan Region—F.R., Iraq; mohammed.zangana@koyauniversity.org

Abstract: The CFD code C3d was used to investigate the operation of a routine utility flare at low and high gas firing rates in an oil field in Iraq. This code was developed for the analysis of transient flares, enables the simulation of flare operation, and offers detailed estimates of the flame shape and the emissions produced. In this work, the numerical simulations included two flare gas rates, 9 t/h (2.5 kg/s) and 45 t/h (12.5 kg/s), under three crosswind conditions (4 m/s, 8 m/s, and 14 m/s) and using three stack heights (35 m, 45 m, and 55 m). The results of this work provided insights into the flame shape and size, pollutant types and dispersion, and ground heat radiation levels from the flare. The safety analysis found that ground-level heat increased with higher flare gas rates and decreased with higher stack heights. The stack height of 55 m and the lower gas firing rate of 9 t/h were identified as the safest operating conditions, as they provided lower ground-level heat compared to the higher flare gas rate of 45 t/h. The heat radiation at a stack height of 55 m during normal firing rates remained below 1600 W/m², which was within the safe continuous exposure limit for personnel not wearing protective clothing. This limit is in accordance with the recommended safety guidelines for personnel and equipment as outlined in API 521. Likewise, the environmental analysis showed that the plume size increased with increasing flare gas rate, while pollutant dispersion intensified with stronger crosswinds. When comparing the two gas firing rates, in the case of 9 t/h, there was a smaller plume and less pollutant dispersion, which illustrated a relatively lower impact on the environment.



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1. Introduction

Gas flaring is the controlled combustion of waste gases that cannot be processed due to technical or economic constraints. It safely disposes of gases from sources like associated gas, gas processing plants, and well testing using specialized flare systems. These systems collect waste gas in piping headers and direct it to a flare stack, where it is ignited [1,2]. The flame's height reflects the gas volume, while its brightness and color depend on the gas composition. A complete flare system includes the flare stack and the piping network that collects and directs waste gases for flaring [3], as shown in Figure 1.

The flare tip at the top of the stack enhances air entrainment to improve the combustion efficiency, while seals prevent flame flashback. A vessel at the stack's base collects liquids from the gas flow. Depending on process needs, multiple flares may be required to manage waste gases effectively. Flares produce light, noise, and heat, with combustion primarily generating water vapor and CO₂. Efficient combustion relies on the proper

mixing of fuel gas with air or steam to ensure complete combustion and minimize pollutant emissions [4–8].

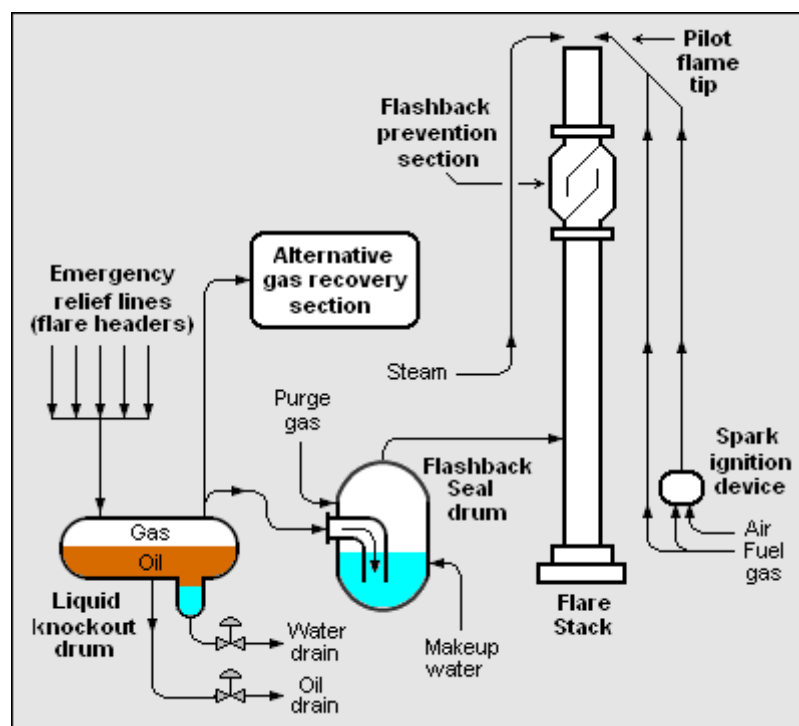


Figure 1. Typical gas flare system [3].

Flaring processes are categorized into three main types: emergency flaring, process (routine) flaring, and production flaring [9]. Emergency flaring occurs during events like fires or equipment failures, burning large volumes of gas at a high velocity for short durations. Process flaring involves lower flaring rates, typically during the removal of waste gases in petrochemical processes, with volumes ranging from a few cubic meters per hour in normal operations to thousands during plant failures [10]. Production flaring happens in the oil and gas exploration and production sectors, where large volumes of gas are burned during tests to assess a well's production capacity [3].

Flaring is a major source of energy loss in industries such as oil and gas production, chemical plants, refineries, coal industries, and landfills, leading to the waste of gases like process gases, fuel gas, and natural gas [11–13]. Flaring systems are used in various locations, including onshore and offshore production fields, transport ships, port facilities, storage tank farms, and distribution pipelines. Gas flaring is a disposal method for excess hydrocarbons. Although its composition resembles natural gas, flaring wastes chemical energy and primarily serves to reduce methane emissions, rather than generating usable energy [14].

The significance of flare gas has increased recently, as concerns grow about the large amounts of gas being wasted, driven by rising gas prices since 2005 and fears over the limited availability of oil and gas resources. Studies suggest that if the gas flared were utilized as an energy source, it could meet 50% of Africa's electricity needs [15]. As global priorities shift toward energy conservation and emission reduction, minimizing flaring and maximizing fuel gas usage are crucial for improving energy efficiency and mitigating climate change [16].

Gas flaring poses significant energy and environmental challenges, with serious local health impacts due to its noise, heat, and visible emissions [11]. The release of greenhouse gases like CO_2 and CH_4 into the atmosphere contributes to climate change, with CO_2

playing a major role in global warming [17]. Flaring has rendered large areas uninhabitable, and the combustion of fossil fuels accounts for 75% of CO₂ emissions. CH₄, often released during incomplete combustion, is particularly harmful, having a global warming potential 25 times greater than CO₂, raising concerns about its environmental impact [18,19].

During the flaring process, pollutants such as sulfur oxides (SO_x), nitrogen oxides (NO_x), and volatile organic compounds (VOCs) are released [11,20–22]. A study by Ezersky and Lips in 2003 [21] on oil refinery flare emissions found significant amounts of total organic compounds and SO_x, ranging from 2.5 to 55 tons per day. These pollutants contribute to overall SO₂ and VOC emissions, with SO₂ leading to acid deposition and harmful effects on both the environment and human health [23]. SO_x and NO_x are key contributors to acid rain, while ozone formed from VOC and NO_x reactions worsens the environmental impact by promoting the formation of toxic sulfuric and nitric acids. Reducing VOC and NO_x emissions is crucial to lower ozone levels [24].

A smoking flare can significantly contribute to particulate emissions, as untreated or unprocessed flared gas creates challenging conditions. These conditions can lead to issues like condensation, fouling (due to paraffin wax and asphaltene deposits), corrosion (from H₂S, moisture, or air), and abrasion (from debris, dust, and corrosion products in pipes, especially at high flow velocities) [25]. The quantity of emissions from flaring is primarily determined by the combustion efficiency, which is influenced by factors such as the heating value, gas velocity, and meteorological conditions. Properly operated flares can achieve combustion efficiency levels of at least 98%, meaning that less than 2% of the gas stream consists of hydrocarbons and CO. Well-designed and well-operated industrial flares are highly efficient, but flare efficiencies can vary significantly, ranging from 62% to 99% [26].

The aim of this paper is to evaluate a routine utility flare (55 m in height and 0.61 m in diameter) operation in one of the oilfield sites in Iraq at two gas firing rates, low with 9 t/h and high 45 t/h, under different operational conditions using CFD code C3d version (5-20-24). This includes the environmental and safety aspects of the flare operation under different operational conditions by studying the effects of the stack height and crosswind on the amount of thermal radiation and pollution released from the burning flare gas at both firing rates. Moreover, this work evaluates the number of pollutants in the plume generated at both gas firing rates.

2. Methodology

This paper uses CFD code C3D based on LES approach version (5-20-24) to analyze the operation of a routine utility flare at low and high firing rates in the summer in Iraq. The analysis focuses on both safety and environmental reviews of the flare operation under different gas firing conditions: a low rate of 9 t/h and a high rate of 45 t/h. The study also examines the impacts of three different crosswind speeds (4 m/s, 8 m/s, and 14 m/s) and three different stack heights (35 m, 45 m, and 55 m) to understand how these factors affect radiation rates to the ground and pollution dispersion. These crosswind speeds were chosen based on wind speed data in Iraq during the summer and winter at the flare operation site. The wind speed is approximately 4 m/s in the summer and 8 m/s in the winter. A speed of 14 m/s was applied to account for the worst-case flare operation scenario under high wind conditions like storms.

The chosen gas flow rates reflect practical and safety considerations for routine operations. The low gas firing rate represents the typical operational rate during routine flare activities. The high gas firing rate, while below the maximum allowable rate of 250 t/h, was selected because it is more likely to occur under routine conditions compared to the maximum rate, which is typically associated with emergency flare operations. The flare

height and diameter used in this study were 55 m and 0.61 m (24"), respectively. Table 1 shows the flare gas composition used in this study.

Table 1. Case study flare gas composition.

Basis = 100 kg Mole					
Components	Mole (%)	Mole (kg Mole)	MWt (kg/kg Mole)	Mass (kg)	Mass (%)
CH ₄	16.44	16.44	16	263.0	0.074
C ₂ H ₆	8.80	8.80	30	264.0	0.074
C ₃ H ₈	12.5	12.5	44	550.0	0.155
C ₄ H ₁₀	20.35	20.35	58	1180.3	0.333
C ₅ H ₁₂	14.37	14.37	72	1034.6	0.292
H ₂ S	2.96	2.96	34	100.6	0.028
H ₂	20.58	20.58	2	41.2	0.012
N ₂	4.00	4.00	28	112.0	0.032
Total	100	100.0		3545.8	1.00

Additionally, ParaView software 5.12.1 was used to visually represent the flare operation at both gas firing rates. The software enables the visualization of ground radiation and allows for the extraction of combustion products, which are essential for evaluating the pollution rate from burning flare gas. This integrated approach helps to assess the environmental impact of flare operation under various conditions and provides a clear representation of the flare's behavior during routine and maximum operation scenarios.

2.1. CFD Code C3d

C3d is a computational fluid dynamics (CFD) and heat transfer software developed by the USDOE Sandia National Laboratory that is designed to tackle a wide range of fluid mechanics and heat transfer problems, including flare and fire analyses. It uses the Large Eddy Simulation (LES) methodology to perform transient analyses of flare operations. In flare studies, C3d is commonly applied to estimate flame shapes and the associated emissions. The software includes several optional sub-models that simulate various processes, such as deposition, radiation heat transfer, aerosol transport, chemical reactions, combustion, and material decomposition.

For fire and flare scenarios, C3d models important phenomena such as fuel vapor transport, liquid fuel evaporation, combustion products, heat release, and chemical reactions. It also accounts for soot and intermediate species formation and destruction, diffusion radiation within the fire, and radiation view factors from the fire's edge to nearby objects. The software selects soot radiation and reaction rates based on comparisons with experimental data from flare and fire studies. To model fluid flow around solid objects, C3d employs a body-fitted geometry method, combined with a structural orthogonal Cartesian grid. This approach allows for both fine and coarse discretization while accurately representing the curvature of objects within the flow domain.

The C3d code has been widely used in various studies [27,28], including those evaluating flare performance and fire safety. Originally developed as a CFD tool called ISIS-3D, it was validated for simulating pool fires and assessing the thermal performance of nuclear transport packages [29–31]. The C3d code has been applied in multiple studies to analyze different types of flares, such as utility flares, air-assisted flares, and large multipoint ground flares [32–35]. Its combustion model has been enhanced and validated for a variety of flare gases like propane, methane, ethylene, ethane, propylene, and xylene. The code helps estimate the flame size, shape, and the impact of smoking tendencies, as well as heat flux to the ground [35].

C3d has also been employed in studies involving multipoint ground flares to assess the effect of surrounding wind fences on flame height and shape under high firing conditions [34]. It has proven useful in determining the optimal spacing between flare tips to ensure sufficient airflow during operation, thus preventing smoke under maximum firing conditions. Moreover, the code has been used to investigate the impacts of discrete and continuous ignition systems on flare operation [33].

2.2. CFD Models

In this simulation, the governing equations are discretized using a finite volume method with orthogonal Cartesian coordinates, which makes the discretization closely resemble a finite difference approach. Vector quantities, such as momentum, are defined at the cell interfaces, while scalar variables like pressure and temperature are defined at the cell centers. The flow equations in the C3d code are solved using a compressible, pressure-based solution algorithm [36]. Additionally, turbulence is modelled using the Large Eddy Simulation (LES) approach. In this simulation, air is treated as incompressible with minimal temperature variations. The momentum equation is solved using a conservative form of the momentum flux vector (ρu).

2.3. Physical Model

In all simulations, the LES turbulence model was employed to simulate fluid flow, while radiation effects were incorporated into the energy equation. To monitor the distribution and concentration of the fuel, soot, intermediate species, and combustion products (such as H_2O and CO_2), individual species equations were solved. The combustion model provided the sink and source terms for these species' equations based on the local gas temperature, species concentrations, and turbulent diffusivity.

The code predicted flame emissivity using various models that considered factors such as the soot volume fraction, molecular gas composition, flame size, shape, and the temperature profile of the combustion effluent. These factors were derived from the solutions to the momentum, mass, species, and energy equations. Additionally, a radiation transport model was used to predict the radiation flux from the flame to the ground and to provide the sink and source terms for the energy equation, allowing for the prediction of the flame's temperature distribution.

2.4. Chemical and Soot Model

A combination of Arrhenius and Eddy breakup reaction time scales has been used to define the rate of combustion equations.

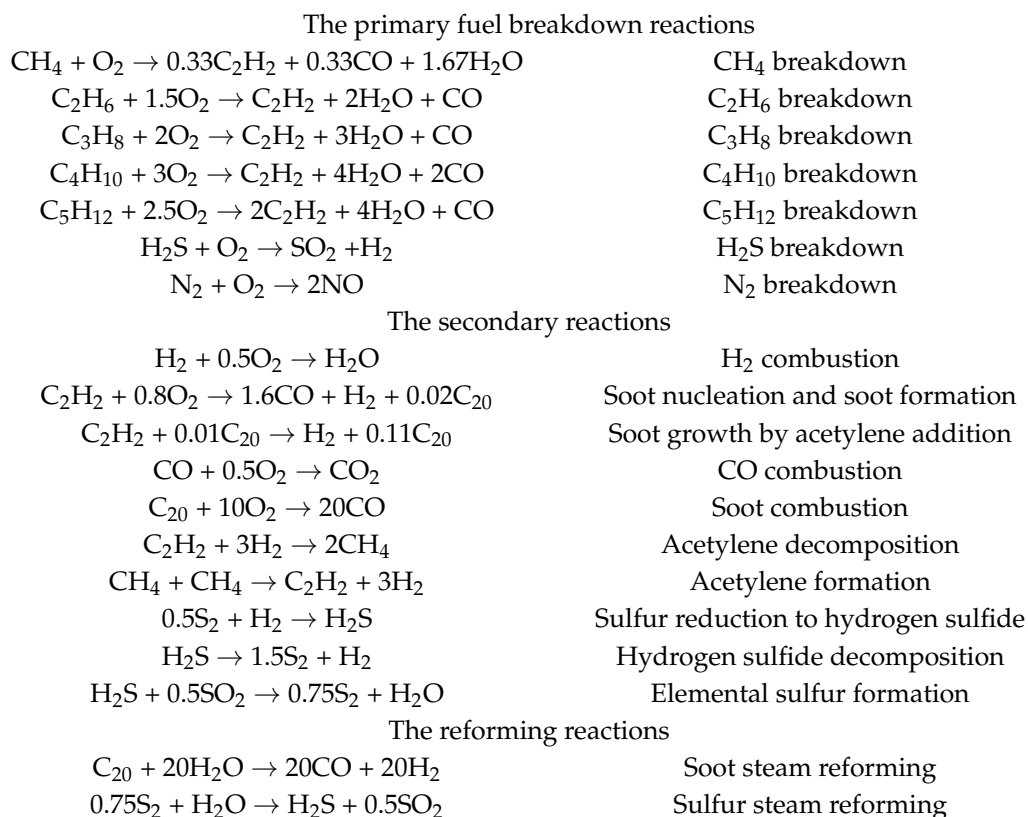
$$t_{total} = t_{reaction} + t_{turb} = \left(\frac{1}{A_k T^b e^{-\left(\frac{T_A}{T}\right)}} \right) + \frac{C_{eb} dx^2}{\varepsilon_{diff}} \quad (1)$$

(T) = the local gas temperature, (A_k) = a pre-exponential coefficient, (b) = a global exponent, (C_{eb}) = the eddy breakup scaling factor, (T_A) = activation temperature, (dx) = the characteristic cell size, (t_{turb}) = the turbulence time scale, and (ε_{diff}) = the eddy diffusivity from the LES module [32].

Combustion chemistry consists of several critical reactions. Initially, primary fuel breakdown reactions generate intermediate combustion products such as C_2H_2 , H_2 , CH_4 , soot, and CO . These intermediate products undergo secondary reactions that further combust, contributing to soot formation. Additionally, reforming reactions that involve hydroxyl (OH) radicals play a significant role in the process. In this scenario, oxidizing species are simplified to water vapor. To promote soot formation, equilibrium reactions

involving acetylene, methane, hydrogen, sulfur, and hydrogen sulfide are also included in the model [32].

The primary fuel breakdown, secondary, and reforming reactions of the flared gas mixture are shown below.



A global Arrhenius rate mode is used for these reactions. The consumption of fuel, soot, and intermediate species are evaluated by

$$\frac{df_{R_i}}{dt} = -C \left[\prod_i^N f^{PA_i} \right] T^b e^{-(T_A/T)} \quad (2)$$

(N) = number of reactants, (T_A) = effective activation temperature, (f_{R_i}) = moles of each reactant, (i) and (c) = pre-exponential coefficients, and (b) = the temperature exponent.

2.5. Computational Domain and Flare Geometry

Three different computational domain sizes were used to simulate various cases with different stack heights at both low and high gas firing rates. The first domain size had dimensions of 65 m in height, 50 m in length, and 50 m in width, and was used for a stack with a height of 35 m and a diameter of 0.61 m. The second domain size was 75 m in height, 50 m in length, and 50 m in width, corresponding to a stack height of 45 m and the same stack diameter of 0.61 m. The third domain size was 85 m in height, 50 m in length, and 50 m in width, with a stack height of 55 m and a diameter of 0.61 m. In all three cases, the computational domain's height (z -axis) extended from -0.1 m to 0 m, defining the ground level (dry sand) for the flare, and then from 0 m to the top of the domain. The domain's length (x -axis) ranged from -5 m to 45 m, and its width (y -axis) spanned from -25 m to 25 m. By positioning the x and y domains at -5 m and -25 m, the flare's center was strategically placed to ensure that the crosswind would blow from the x -axis. The flare model was constructed from carbon steel using a dedicated flare modeler.

This approach allowed for the simulation of various stack configurations and operational scenarios. Figure 2 shows the three computational domain sizes with the corresponding mesh configurations used for the different simulation cases in this study. These domain sizes were selected to represent various operational scenarios, allowing for a detailed analysis of the flare. Moreover, Figure 3 illustrates the three flare stack heights within the domain, along with the mesh for both the stack and the ground. This figure provides a clear representation of the stack configurations and their relationship to the computational domain, highlighting the precision of the mesh distribution around key components to ensure accurate simulation results. The total number of hexahedral cells for the simulations varied depending on the stack height. In the case of the 35 m tall stack, there were 1,335,288 cells ($138 \times 118 \times 82$). For the 45 m tall stack, the number of cells increased to 1,498,128 ($138 \times 118 \times 92$), and for the 55 m tall stack, there were 1,660,968 cells ($138 \times 118 \times 102$). In all cases, the mesh was refined near the flare tip to accurately capture the flame shape and the transient nature of the flow. This finer mesh ensured that the complex interactions in the flame region were simulated with a high level of detail, improving the accuracy of the results.

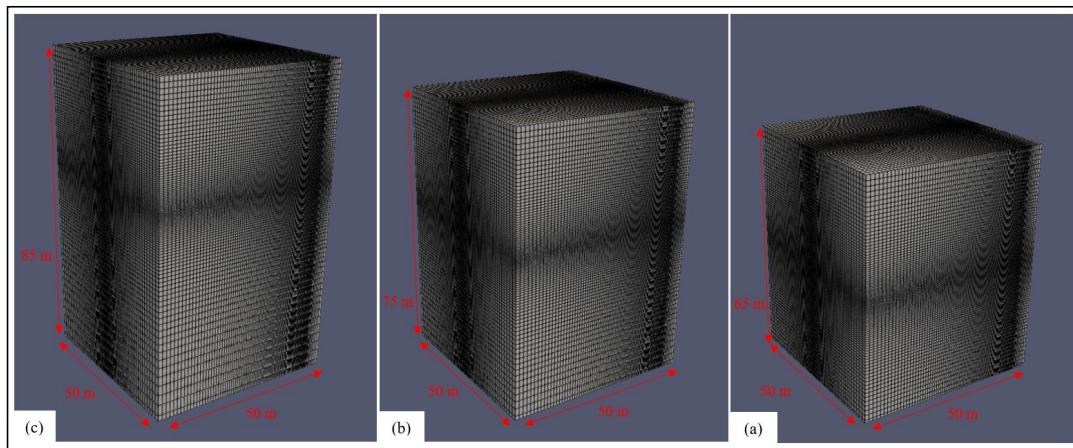


Figure 2. Computational size and mesh: (a) 65 m (z-axis), 50 m (x-axis), and 50 (y-axis); (b) 75 m (z-axis), 50 m (x-axis), and 50 (y-axis); and (c) 85 m (z-axis), 50 m (x-axis), and 50 (y-axis).

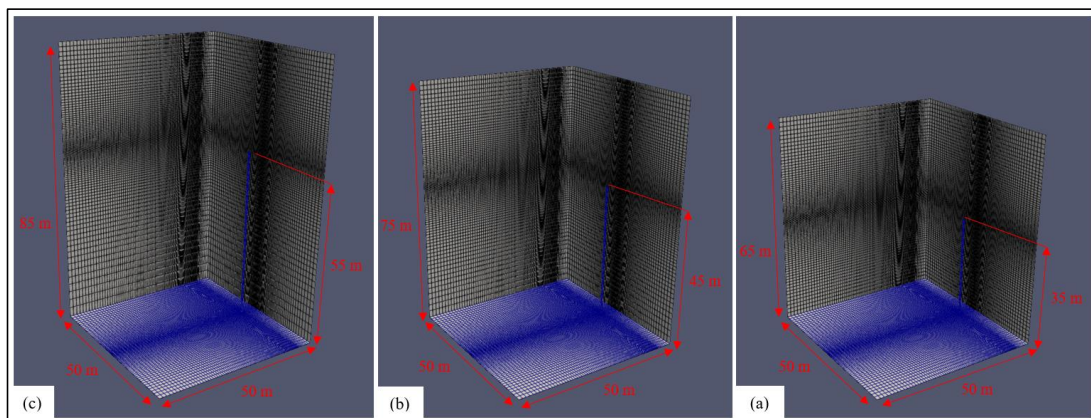


Figure 3. Flare model and ground mesh: (a) 35 m stack height, (b) 45 m stack height, and (c) 55 m stack height.

2.6. Mesh Independence Study

A mesh independence study was conducted by monitoring the change in carbon dioxide emissions during a 9 t/h gas firing operation. Since three different stack heights

(35 m, 45 m, and 55 m) with corresponding domain sizes were applied in this study, a separate mesh independence analysis was performed for each case. For each stack height, two different mesh configurations were tested: one with a lower cell number and another with a higher cell number.

Figures 4–6 show the specified probe locations used to monitor the carbon dioxide emissions in the plume during the mesh independence study. The probe used in this study had a radius of 0.3 m and was employed to record 10 datasets for each monitoring location. The average of these datasets was then calculated and used in the analysis.

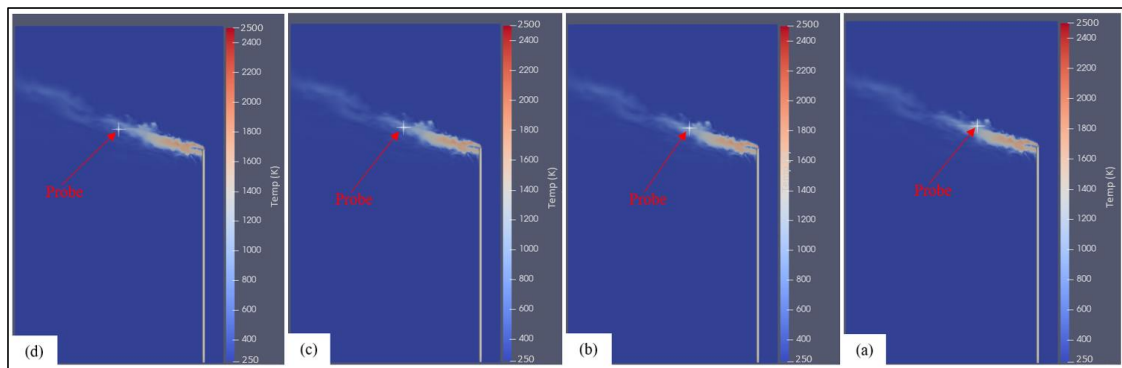


Figure 4. Data sampling locations for the mesh independence study at a 9 t/h firing rate using a stack height of 55 m: (a) 14 m (x-axis), 0 m (y-axis), and 60 m (z-axis); (b) 16 m (x-axis), 0 m (y-axis), and 60 m (z-axis); (c) 18 m (x-axis), 0 m (y-axis), and 60 m (z-axis); and (d) 20 m (x-axis), 0 m (y-axis), and 60 m (z-axis).

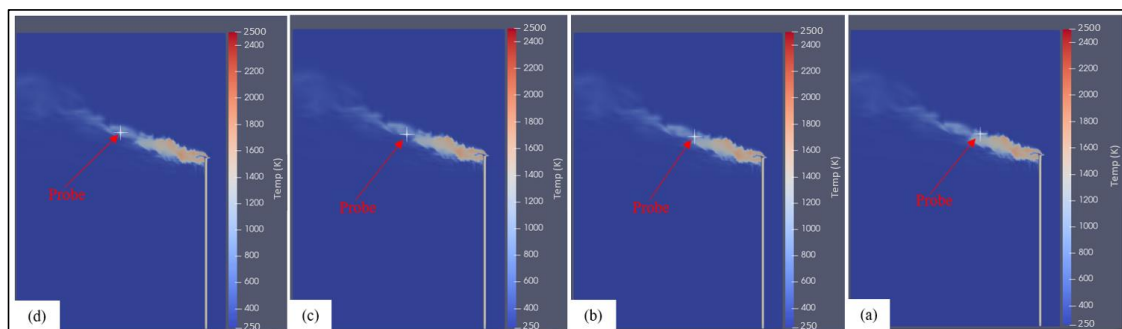


Figure 5. Data sampling locations for the mesh independence study at a 9 t/h firing rate using a stack height of 45 m: (a) 14 m (x-axis), 0 m (y-axis), and 50 m (z-axis); (b) 16 m (x-axis), 0 m (y-axis), and 50 m (z-axis); (c) 18 m (x-axis), 0 m (y-axis), and 50 m (z-axis); and (d) 20 m (x-axis), 0 m (y-axis), and 51 m (z-axis).

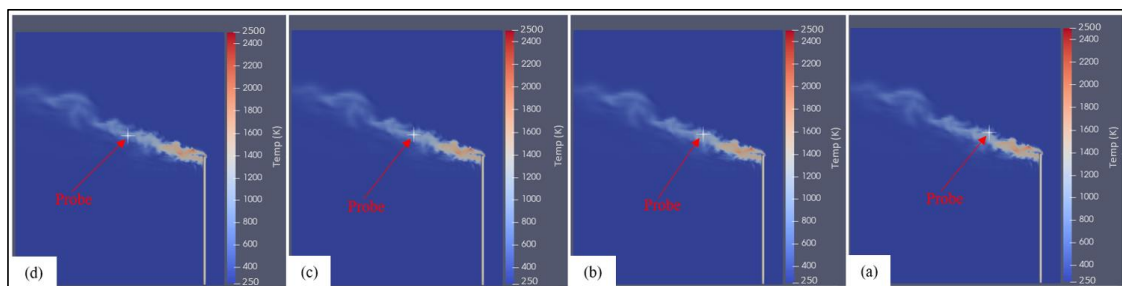


Figure 6. Data sampling locations for the mesh independence study at a 9 t/h firing rate using a stack height of 35 m: (a) 12 m (x-axis), 0 m (y-axis), and 40 m (z-axis); (b) 14 m (x-axis), 0 m (y-axis), and 40 m (z-axis); (c) 16 m (x-axis), 0 m (y-axis), and 40 m (z-axis); and (d) 18 m (x-axis), 0 m (y-axis), and 40 m (z-axis).

Figures 7–9 show the results of the mesh independence study for the 35 m stack height, 45 m stack height, and 55 m stack height cases, respectively. According to these figures, there is a slight difference in the carbon dioxide mass fraction between the lower and higher cell numbers for each case. This indicates that the mesh refinement has a minimal effect on the results, demonstrating mesh independence. Therefore, the chosen mesh configurations of 1,335,288 cells for the 35 m stack height, 1,498,128 cells for the 45 m stack height, and 1,660,968 cells for the 55 m stack height were deemed appropriate for the simulations, as they provided reliable and consistent results.

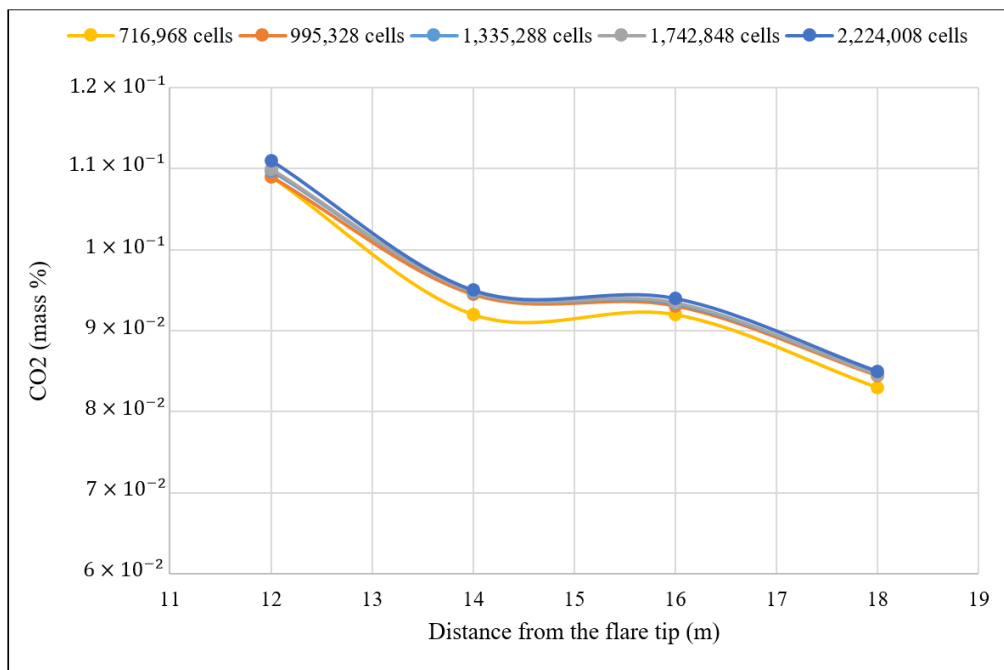


Figure 7. Mesh independence study of the 35 m tall stack case at a 9 t/h firing rate and 8 m/s crosswind.

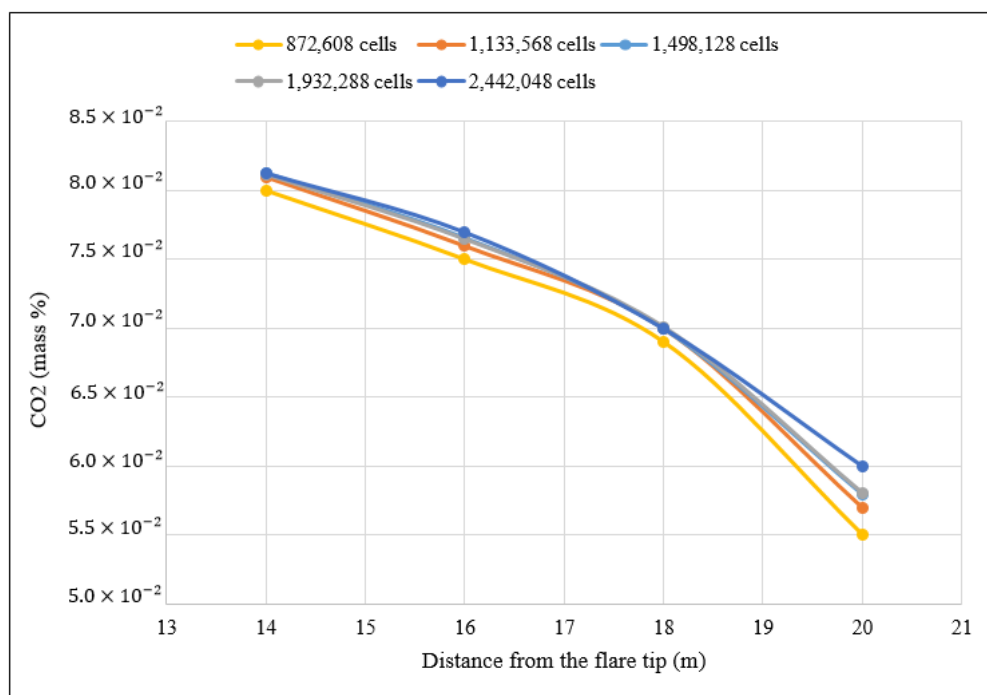


Figure 8. Mesh independence study of the 45 m tall stack case at a 9 t/h firing rate and 8 m/s crosswind.

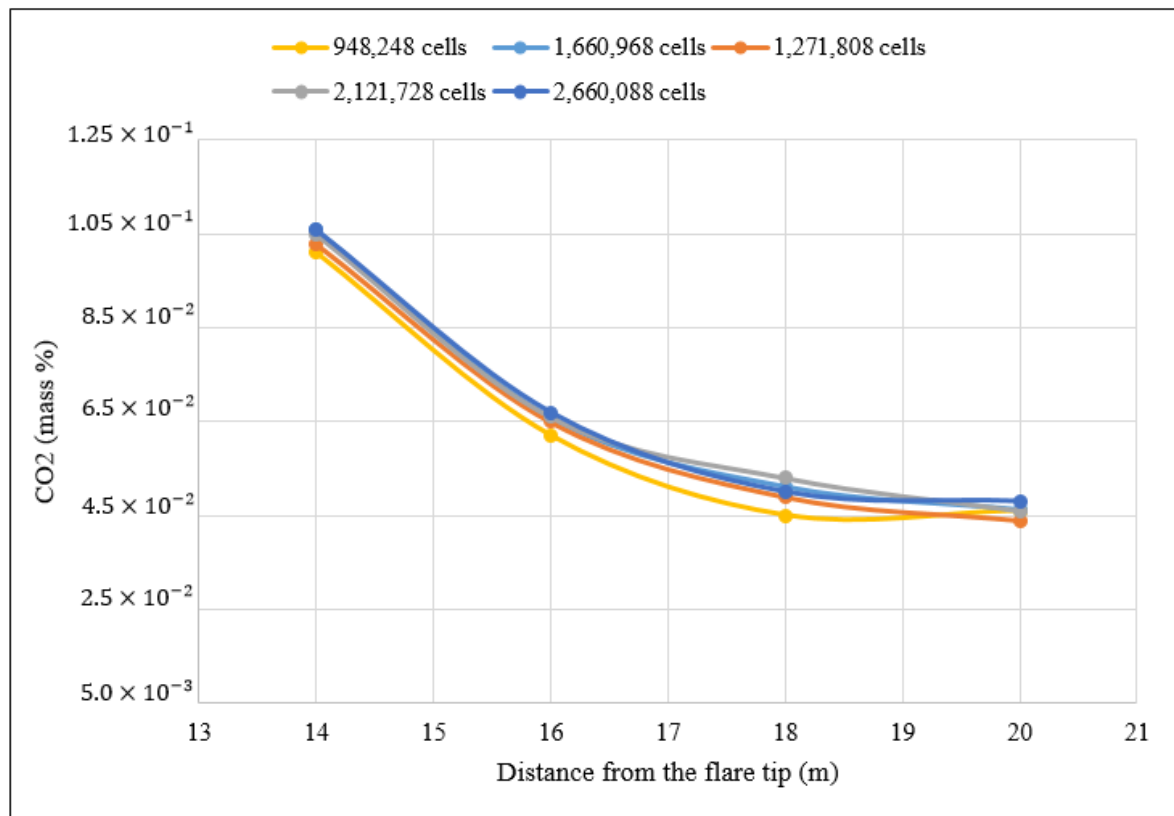


Figure 9. Mesh independence study of the 55 m tall stack case at a 9 t/h firing rate and 8 m/s crosswind.

2.7. Boundary Conditions

The boundary conditions implemented in this work included three crosswind cases with speeds of 4 m/s, 8 m/s, and 14 m/s at a temperature of 300 K, flowing from the x-axis toward the flare. Hydrostatic pressure was defined throughout the computational domain to ensure an accurate simulation of pressure variations. To model the specific components of the flare system, three one-dimensional subgrids were established: one for the ground, one for the flare wall, and one for the flare tip. In the ground subgrid, dry sand was selected as the material, representing the ground beneath the flare. In the flare wall subgrid, carbon steel was chosen as the material for the flare stack, reflecting the typical construction material for such systems.

For the flare tip subgrid, the mass flux and temperature of the gas were specified for both low and high gas firing rates. The mass flux values were 8.4 kg/m².s (equivalent to 9 t/h or 2.5 kg/s) at the low gas firing rate and 42 kg/m².s (equivalent to 45 t/h or 12.5 kg/s) at the high gas firing rate, with the gas temperature maintained at 300 K. Finally, the flare exit was defined as a three-dimensional pressure outlet, ensuring a proper representation of gas flow and pressure conditions at the flare tip.

2.8. Postprocessing and Transient Calculation

Initially, the simulation ran for 100 timesteps to calibrate the gas mass flow rate injected through the flare in all cases, which was set to 2.5 kg/s (equivalent to 9 t/h) and 12.5 kg/s (equivalent to 45 t/h). This initial phase allowed the system to adjust and ensure an accurate gas flow representation. Following the calibration, the simulation parameters were adjusted, with the timestep set to 1,000,000 and the total simulation time extended to 10 s. This longer duration was necessary to allow the system to stabilize and accurately reflect the operational characteristics of the flare under the specified conditions.

To check the simulation stability and validate the gas firing rate, the net reaction energy source was used in all simulation cases. The net reaction energy source consists of the reaction power (MW), which changes with time. This power can be calculated for each case by multiplying the gas flow rate (kg/s) by the LHV of the gas (MJ/kg). For instance, in the case of a 2.5 kg/s gas firing rate, the reaction power is approximately 113 MW, calculated as 2.5 kg/s times 45 MJ/kg. Similarly, for the 12.5 kg/s gas firing rate, the reaction power is approximately 563 MW, calculated as 12.5 kg/s times 45 MJ/kg. At the start of the simulation, the initial combustion of a significant amount of gas causes a small peak in the reaction power curve. However, after a few seconds, this value drops and stabilizes, indicating that the simulation has reached a steady state. Figure 10 shows the net reaction energy source and time step size for the 2.5 kg/s gas firing rate cases, while Figure 11 displays the net reaction energy source and simulation time step size for the 12.5 kg/s gas firing rate cases.

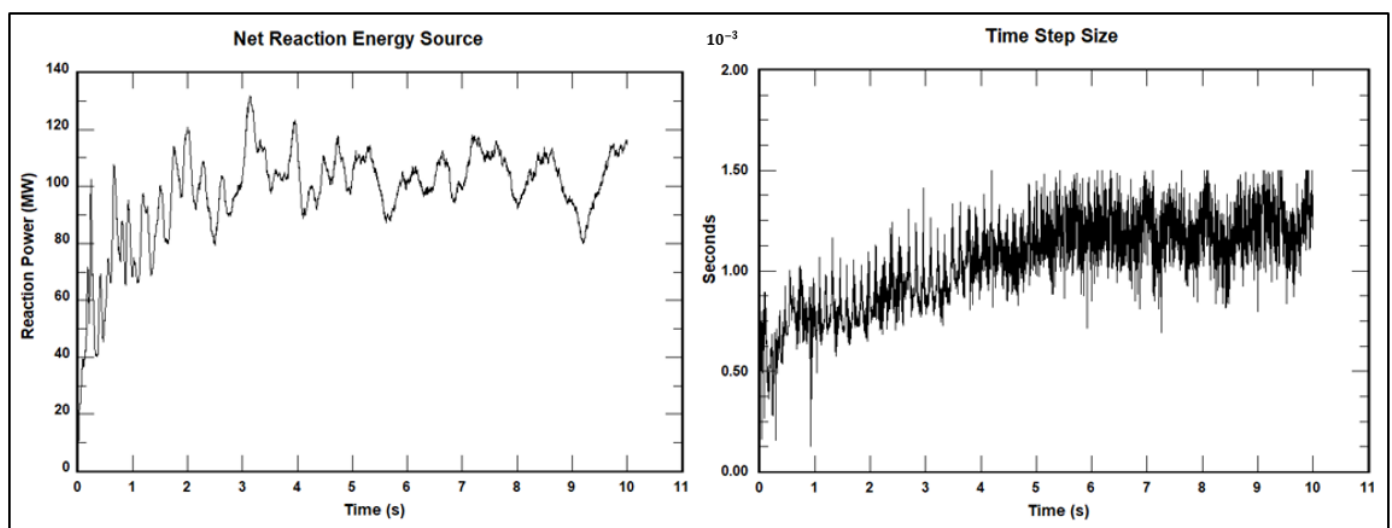


Figure 10. Net reaction energy source and simulation time step size for 2.5 kg/s gas firing rate cases.

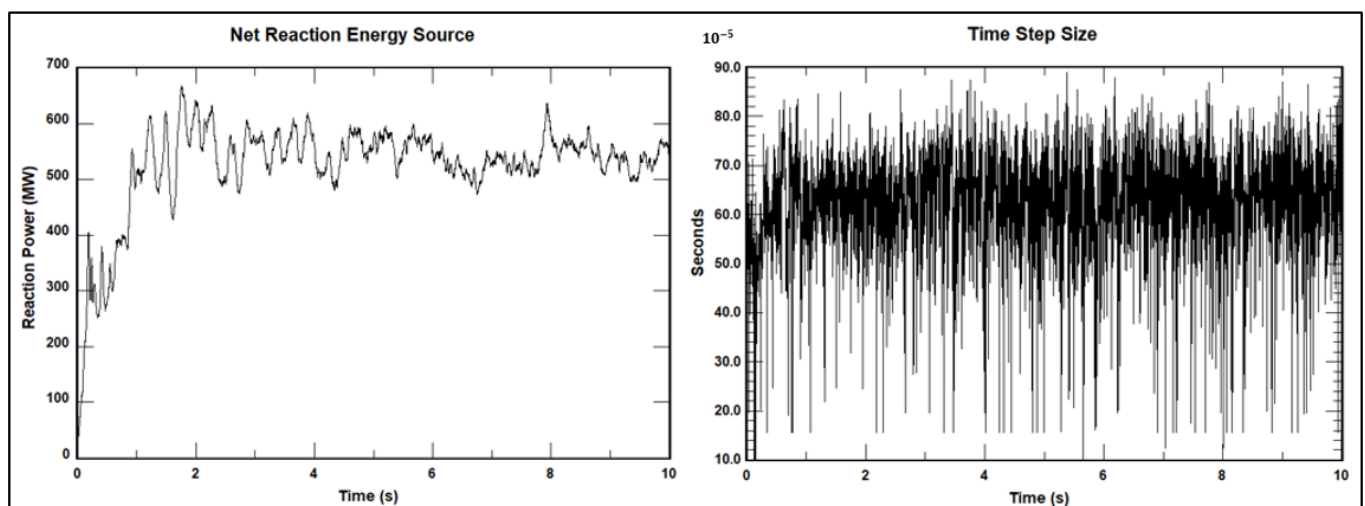


Figure 11. Net reaction energy source and simulation time step size for 12.5 kg/s gas firing rate cases.

3. Results

ParaView version 5.12.1 was used to extract the results for this study, which includes comparing the flare operation at low and high gas firing rates. This includes comparing the flame size and shape, soot formation, and combustion products. Moreover, the results

include studying the effects of a crosswind on pollution dispersion and wake stabilization. Finally, the results demonstrate the relation between the stack height and ground heat at both firing rates.

3.1. Flame Shape and Size vs. Crosswind

The flame size and shape at low and high gas firing rates using a flare stack with a height of 55 m and a diameter of 0.61 m were visualized using the CFD code C3d (version 2-19-24) and ParaView software (version 5.11.2). To study the changes in the flame angle and pollution dispersion, three different crosswind speeds (4 m/s, 8 m/s, and 14 m/s) were applied. Figures 12 and 13 illustrate the effects of the crosswind on flare operation at low and high gas firing rates, respectively.

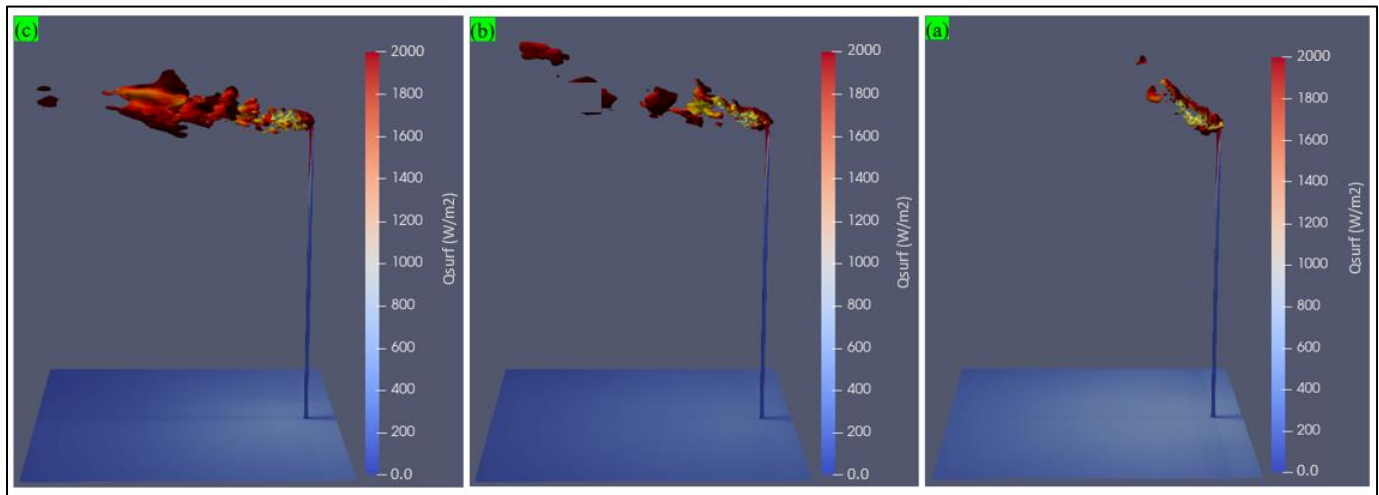


Figure 12. Low gas firing rate (9 t/h) flare operation with three different crosswind speeds: (a) 4 m/s, (b) 8 m/s, and (c) 14 m/s.

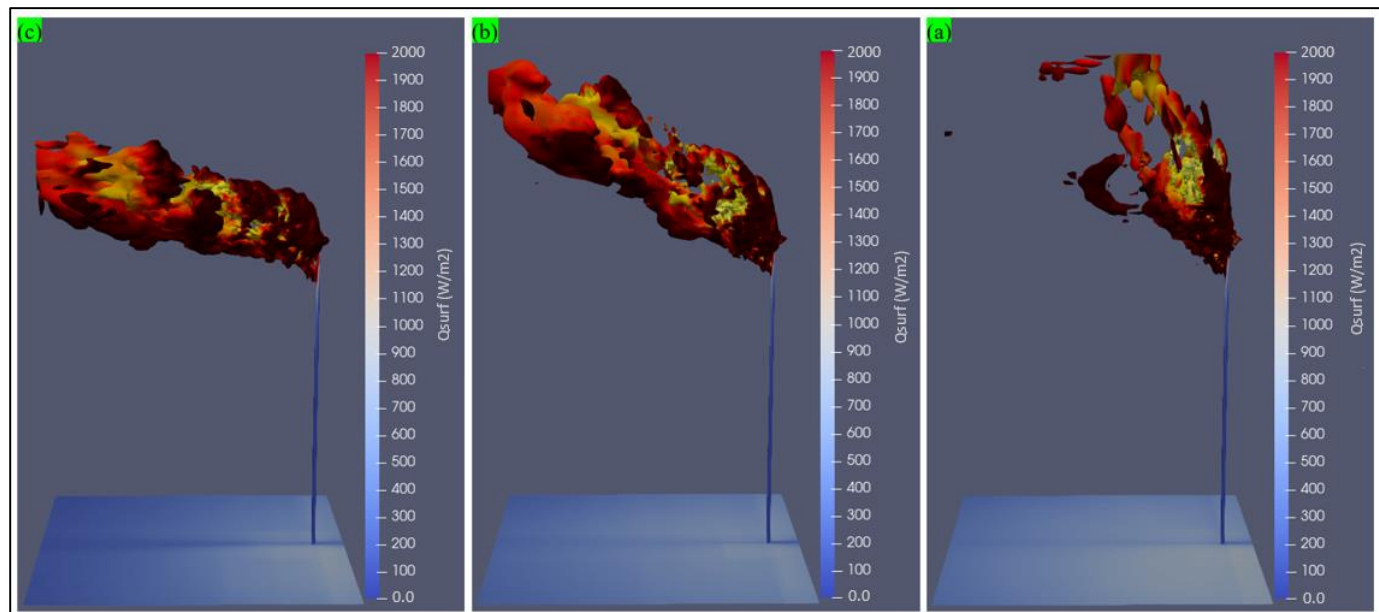


Figure 13. High gas firing rate (45 t/h) flare operation with three different crosswind speeds: (a) 4 m/s, (b) 8 m/s, and (c) 14 m/s.

The figures demonstrate that as the gas firing rate increases, the flame size and shape also expand, leading to higher heat radiation toward the ground and greater pollutant

emissions. In both low and high gas firing rate scenarios, an increase in crosswind speed stabilizes the wake and elongates the flame. Additionally, ground heat radiation rises with the flare gas firing rate but decreases with higher crosswind speeds due to the cooling effect of the wind on the flame.

Figures 14 and 15 illustrate the impacts of the crosswind on flame stability and size at low and high gas firing rates.

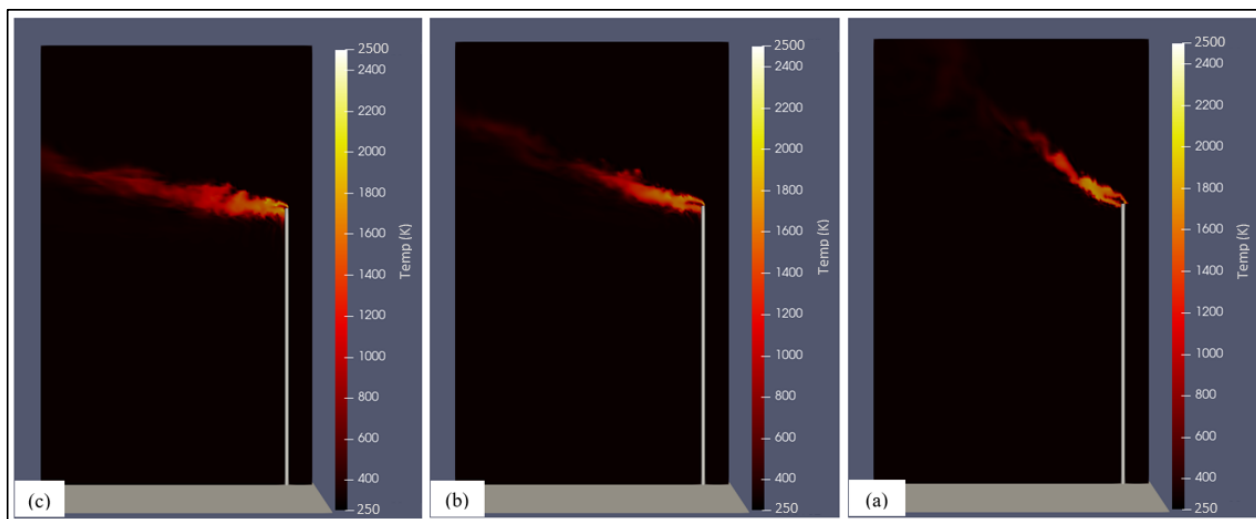


Figure 14. Flame temperature at a normal gas firing rate (9 t/h) with different crosswind speeds: (a) 4 m/s, (b) 8 m/s, and (c) 14 m/s.

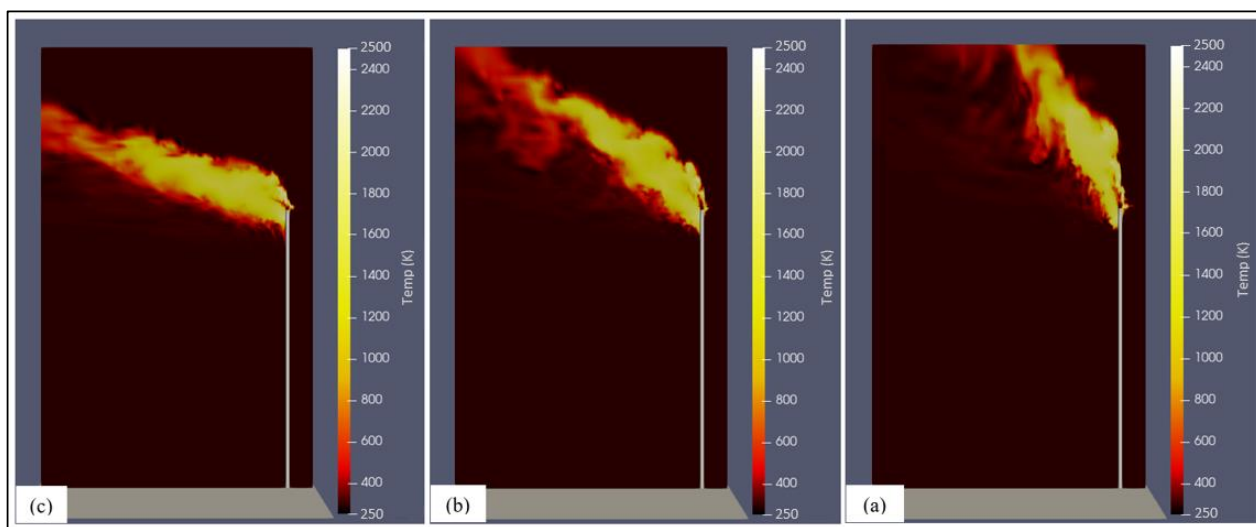


Figure 15. Flame temperature at a high gas firing rate (45 t/h) with different crosswind speeds: (a) 4 m/s, (b) 8 m/s, and (c) 14 m/s.

From these figures, it is clear that as the gas rate increases, the flame heat radiation also increases due to the larger flame size. The larger flame retains heat for a longer duration, reducing cooling effects and sustaining high temperatures over a larger region. Furthermore, the figures clearly demonstrate wake stabilization, especially at high gas firing rates. This phenomenon has important implications for flare operation, not only in maintaining safe operation but also in reducing the lifetime of the flare tip. In other words, increased wake stabilization causes the flame to remain attached to the tip, and with the higher temperatures, the flare tip's lifetime becomes shorter and it becomes more susceptible to deformation.

3.2. Combustion Products vs. Crosswind

The environmental consequences of flare operation have always been a topic of interest, and understanding the types of emissions produced by a flare is a critical aspect when analyzing its operation. This paper shows and compares the combustion products of the flare at low and gas firing rates and using a flare stack height and diameter of 55 m and 0.61 m, respectively. To demonstrate the effect of the crosswind on pollution dispersion, three crosswind speeds (4 m/s, 8 m/s, and 14 m/s) were applied.

3.2.1. Soot Formation

Soot formation is one of the main pollutants produced during flare operation, and studying this pollutant is essential for evaluating the environmental performance of the flare. Figures 16 and 17 illustrate the soot formation rate from the flare at normal and high gas firing rates under different crosswind conditions.

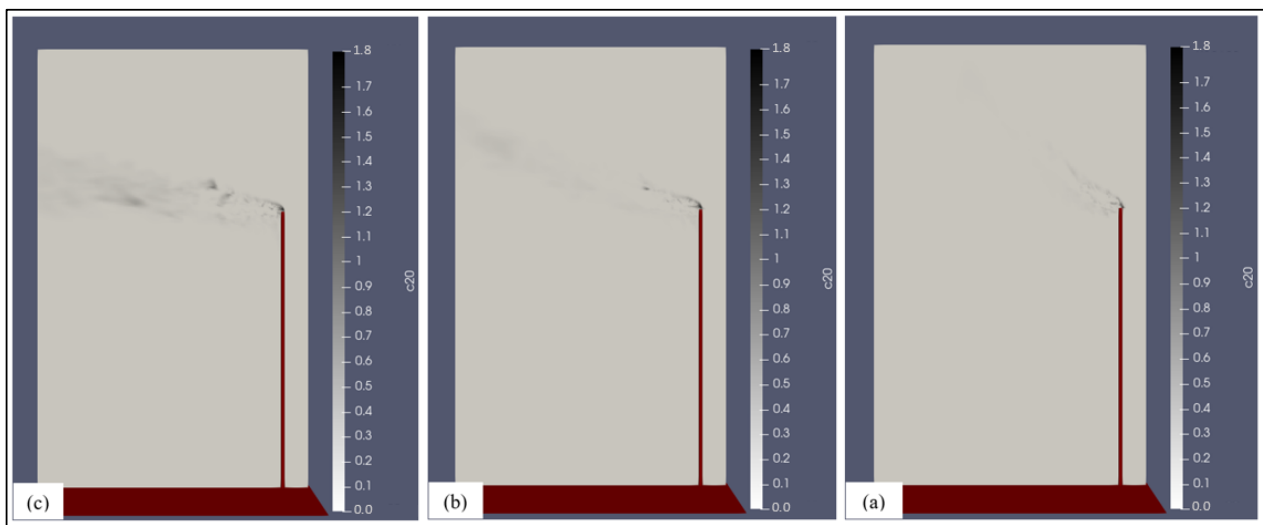


Figure 16. Soot formation at a normal gas firing rate (9 t/h) with different crosswind speeds: (a) 4 m/s, (b) 8 m/s, and (c) 14 m/s.

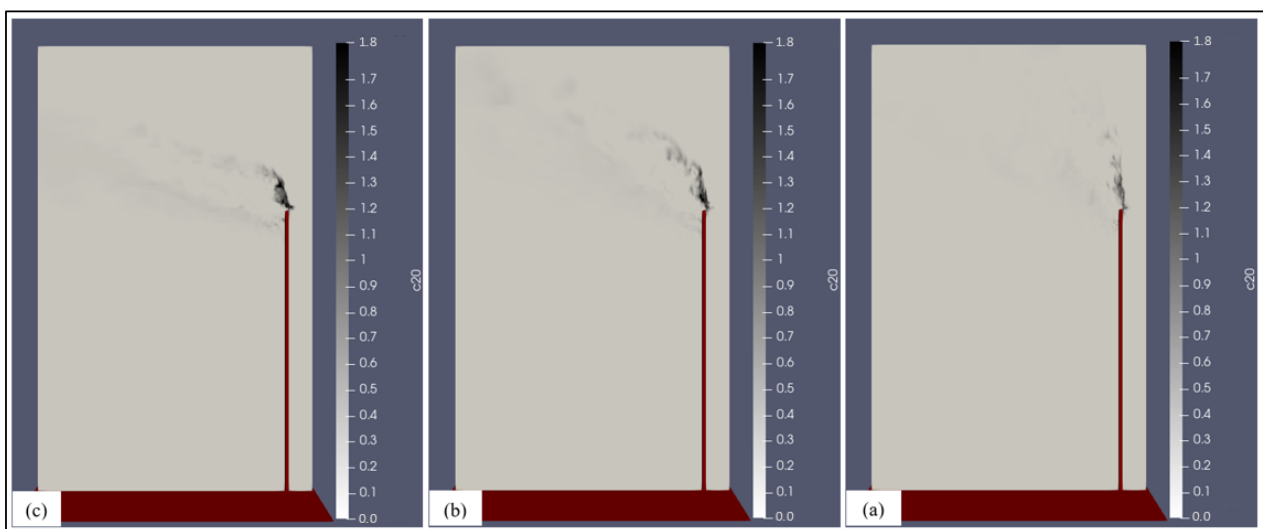


Figure 17. Soot formation at a high gas firing rate (45 t/h) with different crosswind speeds: (a) 4 m/s, (b) 8 m/s, and (c) 14 m/s.

According to these figures, soot formation at high gas firing rates is significantly higher than at normal gas firing rates. In the case of normal flare gas operation, soot formation

ranged from 1 to 1.3 ppmv, while at higher flare gas operation, it exceeded 1.4 to 1.5 ppmv. The effect of wind was evident in both operational cases, with soot dispersion increasing as the crosswind speed rose.

3.2.2. Carbon Dioxide and Carbon Monoxide Emissions

The important combustion products that indicate the quality of combustion at the flare tip are carbon dioxide (CO_2) and carbon monoxide (CO). Figures 18 and 19 show the emissions of carbon dioxide (CO_2) at normal and high gas firing rates of the flare, considering different crosswind speeds. Moreover, Figures 20 and 21 demonstrate the emissions of carbon monoxide (CO) at normal and high gas firing rates with various crosswind speeds.

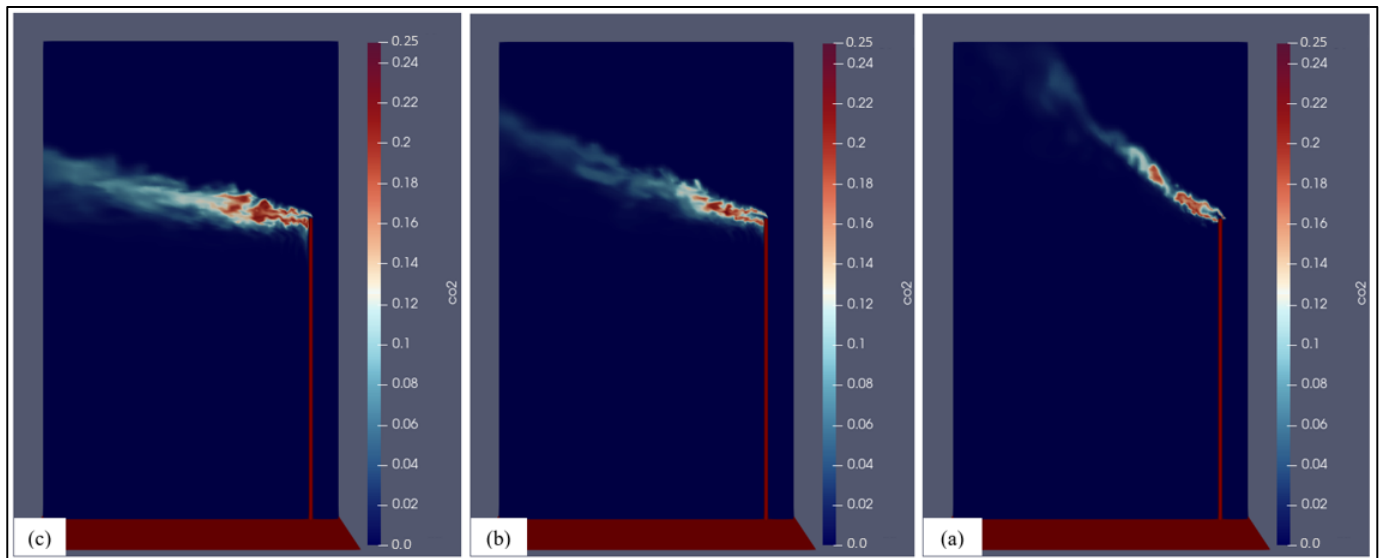


Figure 18. Carbon dioxide emissions at a normal gas firing rate (9 t/h) with different crosswind speeds: (a) 4 m/s, (b) 8 m/s, and (c) 14 m/s.

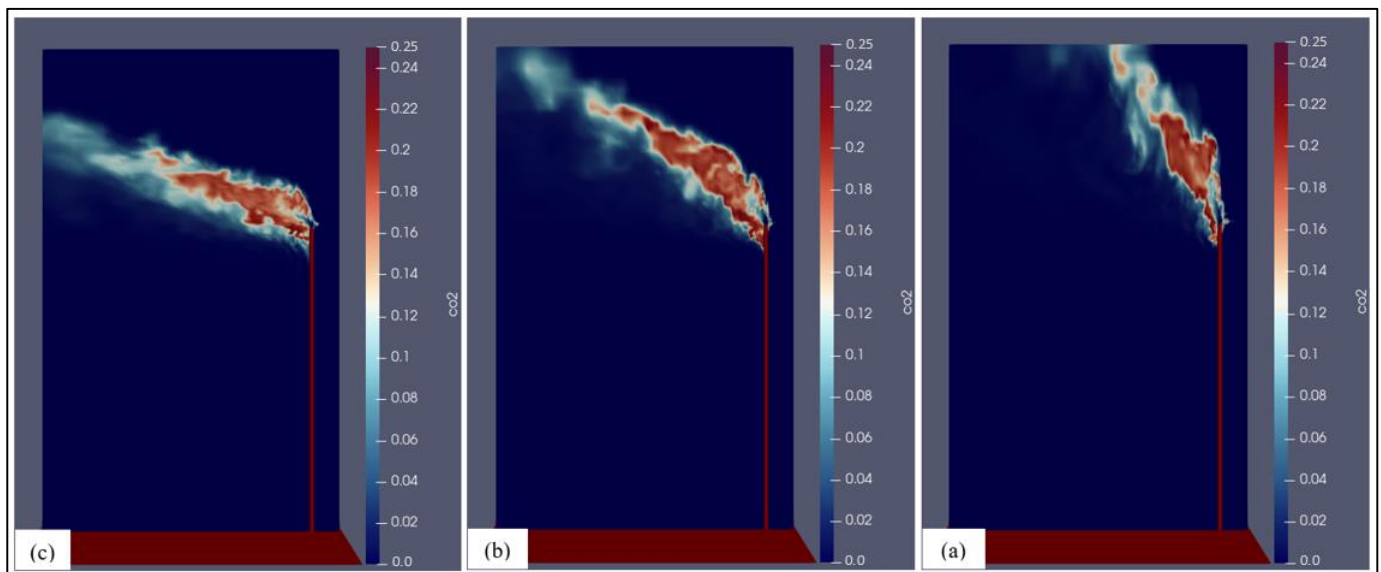


Figure 19. Carbon dioxide emissions at a high gas firing rate (45 t/h) with different crosswind speeds: (a) 4 m/s, (b) 8 m/s, and (c) 14 m/s.

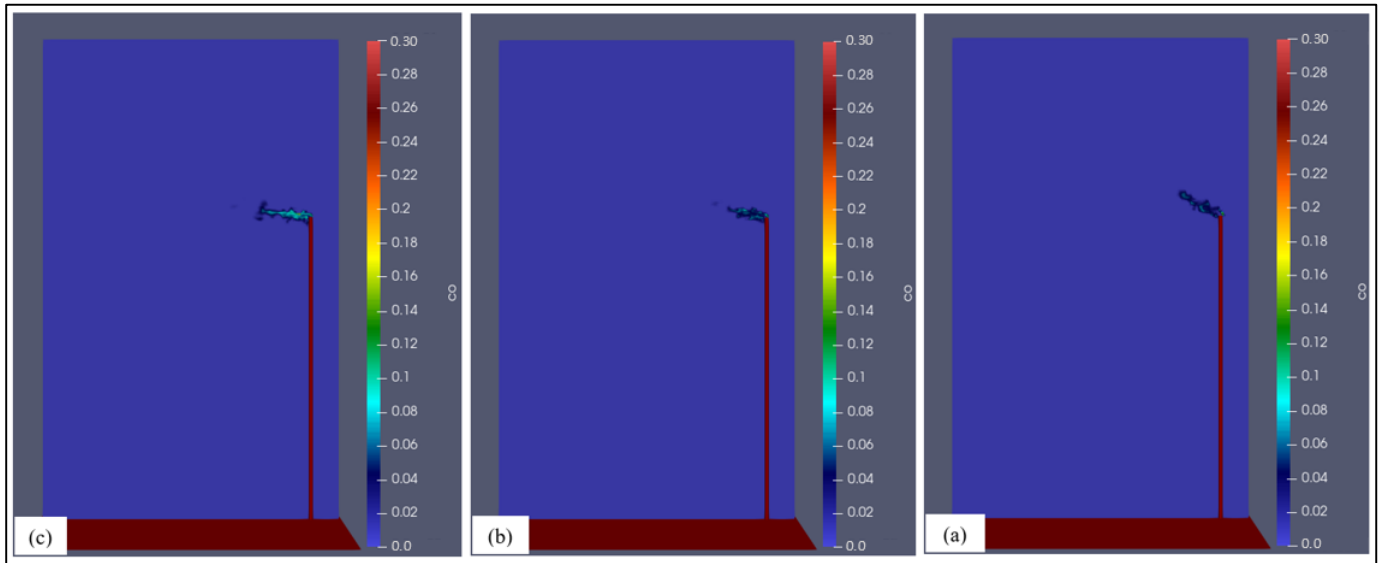


Figure 20. Carbon monoxide emissions at a normal gas firing rate (9 t/h) with different crosswind speeds: (a) 4 m/s, (b) 8 m/s, and (c) 14 m/s.

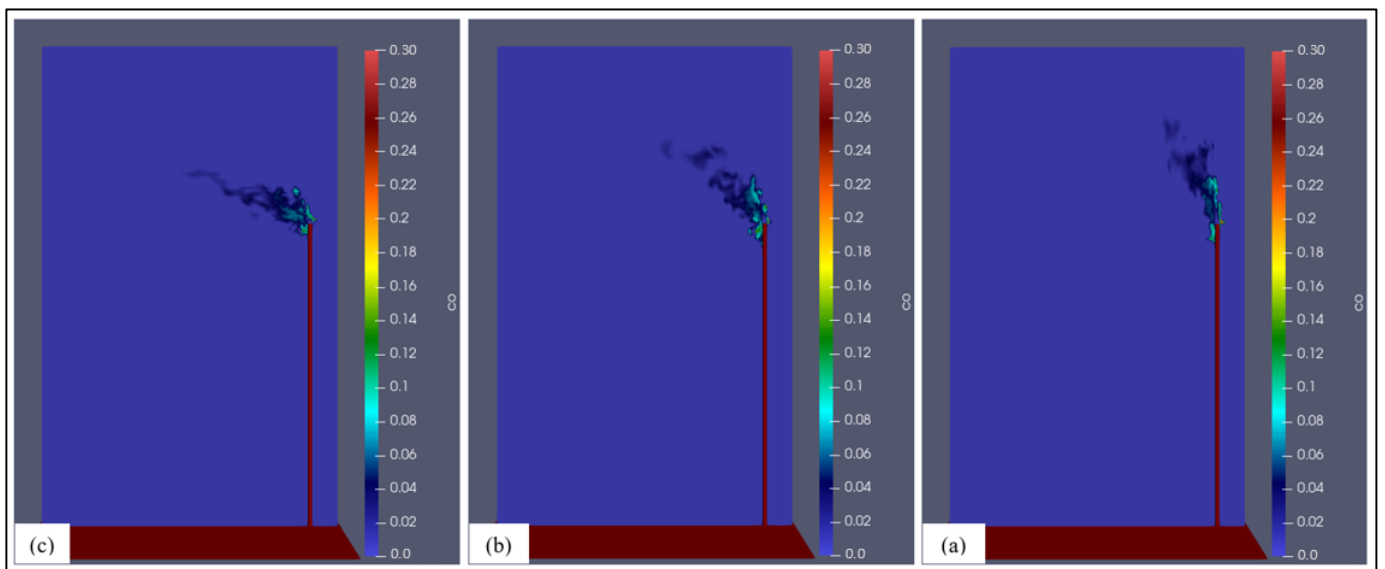


Figure 21. Carbon monoxide emissions at a high gas firing rate (45 t/h) with different crosswind speeds: (a) 4 m/s, (b) 8 m/s, and (c) 14 m/s.

The CO₂ emissions in Figures 18 and 19 show that crosswind significantly affects the dispersion of this pollutant. By comparing these two figures, it is clear that a high flare gas rate produces more CO₂ than a normal flare gas rate.

Generally, the CO emissions in Figures 20 and 21 are much lower than the CO₂ emissions, indicating that the operation was acceptable to some extent, especially at normal gas firing rates. In fact, the low CO emissions at low gas firing rates, compared to high gas firing rates, explain the lower soot formation in the low gas firing rate case. In other words, at low gas firing rates, the flare gas combustion is more stable, allowing most of the flare gas to convert to CO₂ instead of CO, which results in less soot formation. In contrast, at high gas firing rates, more CO is produced, leading to increased soot formation.

3.2.3. Sulphur Dioxide and Nitric Oxide Emissions

Sulphur dioxide (SO_2) and nitric oxide (NO) are hazardous combustion products of flare operation. Since the flare gas contains hydrogen sulfide (H_2S) and nitrogen, the presence of these emissions after combustion is expected. Figures 22 and 23 show the sulfur dioxide (SO_2) emissions at normal and high gas firing rates with different crosswind speeds. Similarly, Figures 24 and 25 illustrate the nitric oxide (NO) emissions from flare operation at normal and high gas firing rates with various crosswind speeds.

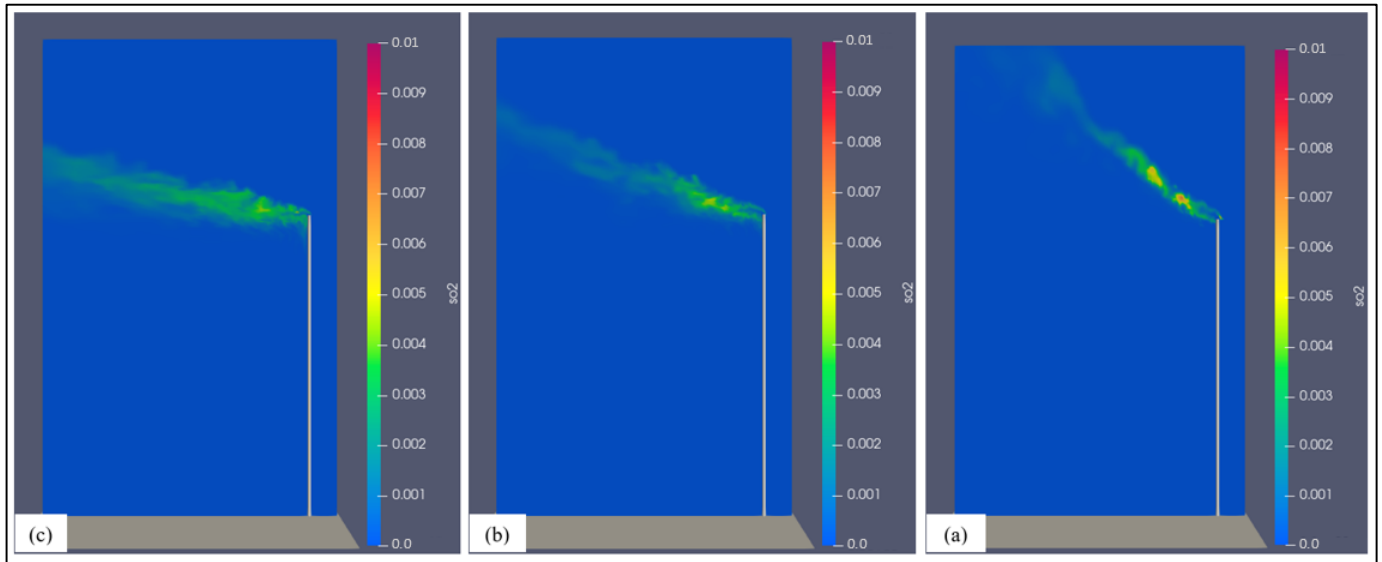


Figure 22. Sulphur dioxide emissions at a normal gas firing rate (9 t/h) with different crosswind speeds: (a) 4 m/s, (b) 8 m/s, and (c) 14 m/s.

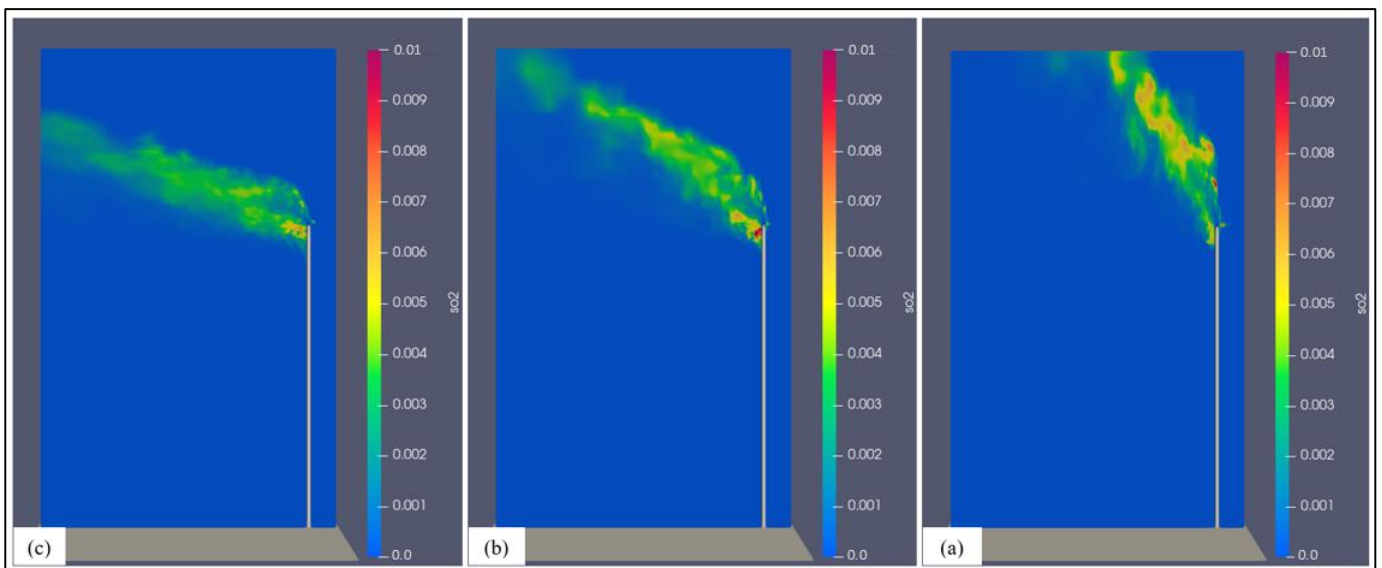


Figure 23. Sulphur dioxide emissions at a high gas firing rate (45 t/h) with different crosswind speeds: (a) 4 m/s, (b) 8 m/s and (c) 14 m/s.

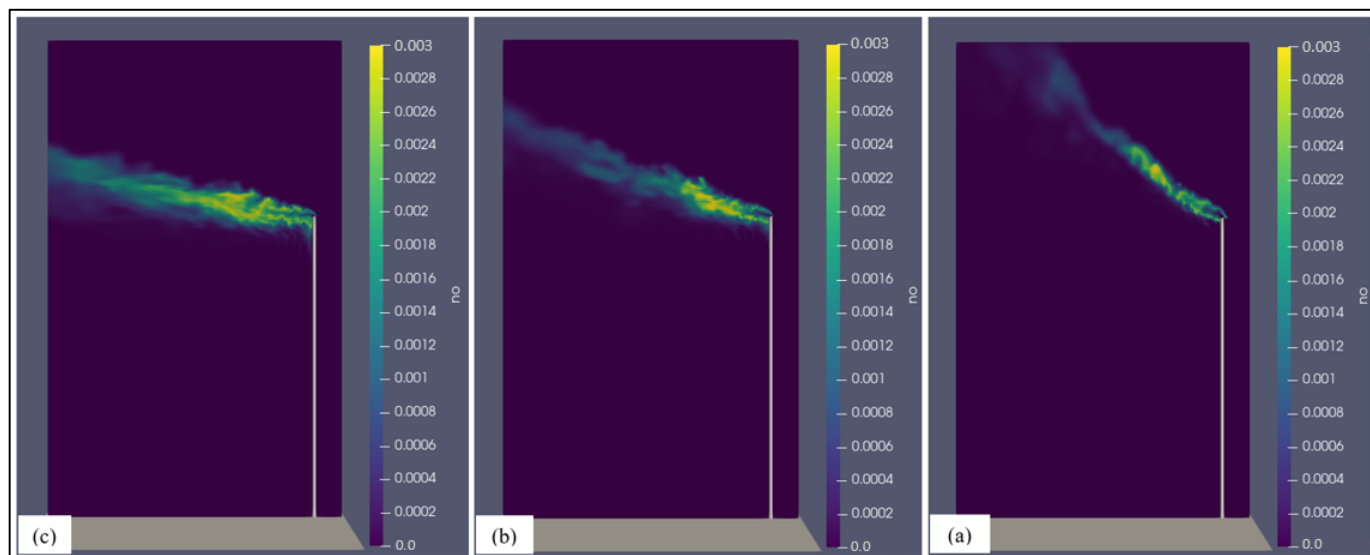


Figure 24. Nitric oxide emissions at a normal gas firing rate (9 t/h) with different crosswind speeds: (a) 4 m/s, (b) 8 m/s, and (c) 14 m/s.

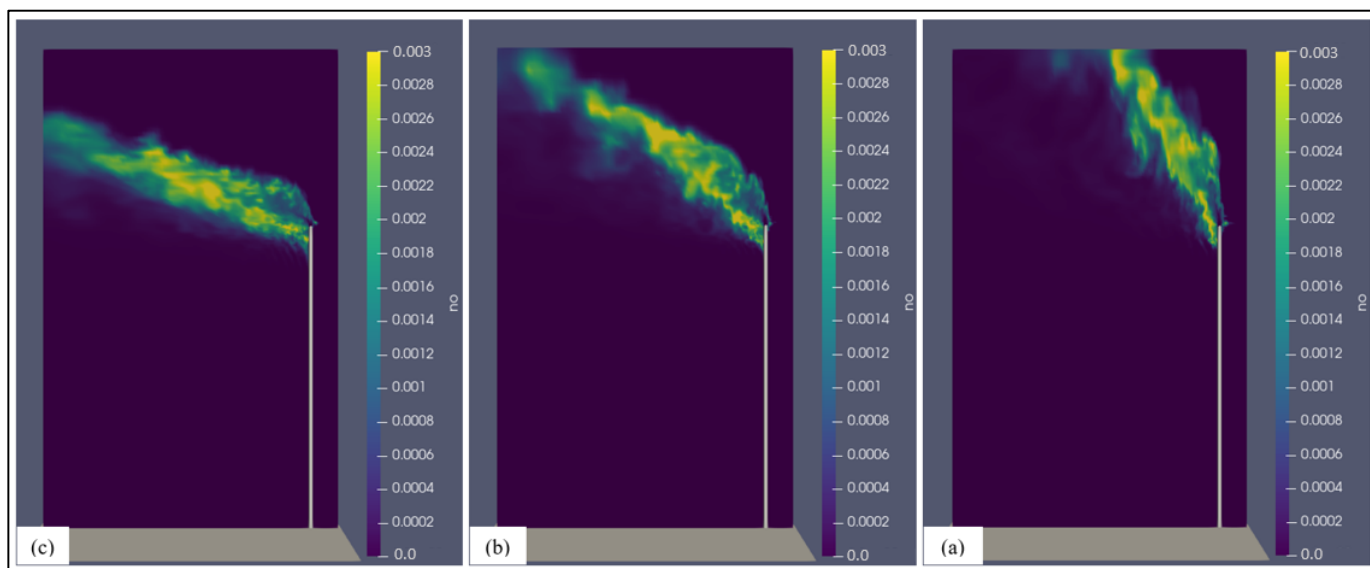


Figure 25. Nitric oxide emissions at a high gas firing rate (45 t/h) with different crosswind speeds: (a) 4 m/s, (b) 8 m/s, and (c) 14 m/s.

Comparing sulfur dioxide (SO_2) emissions at a normal gas firing rate in Figure 22 with SO_2 emissions at a high gas firing rate in Figure 23, it is clear that the rate of emissions increases as the flare gas rate increases due to the larger amount of gas being burned. Furthermore, these figures clearly demonstrate that the crosswind significantly affects the dispersion of this pollutant. An increase in crosswind speed enhances the dispersion of SO_2 , allowing it to spread to greater distances.

Regarding nitric oxide (NO) emissions, similar to other combustion products, the emission rate is higher at a high gas firing rate than at a normal gas firing rate. Additionally, the dispersion of nitric oxide due to the crosswind follows the same pattern as SO_2 and other emissions. Finally, the dispersion increases with rising crosswind speeds, ranging from 4 m/s to 14 m/s. Generally, at higher gas flow rates, NO production increases due to a larger flame size and improved air mixing, which leads to higher combustion temperatures

and promotes thermal NO_x formation. Conversely, at lower gas flow rates, the reduced flame size and lower temperatures result in less NO production.

3.3. Heat Radiation vs. Stack Height

One of the critical safety factors in flare operation is the heat radiation to the ground. This study examines the effect of the stack height on ground heat radiation using three stack heights: 55 m, 45 m, and 35 m. In all cases, the crosswind speed was kept constant at 9 m/s. Figures 26 and 27 illustrate the ground heat radiation for different stack heights at low and high gas firing rates, respectively, under constant crosswind conditions.

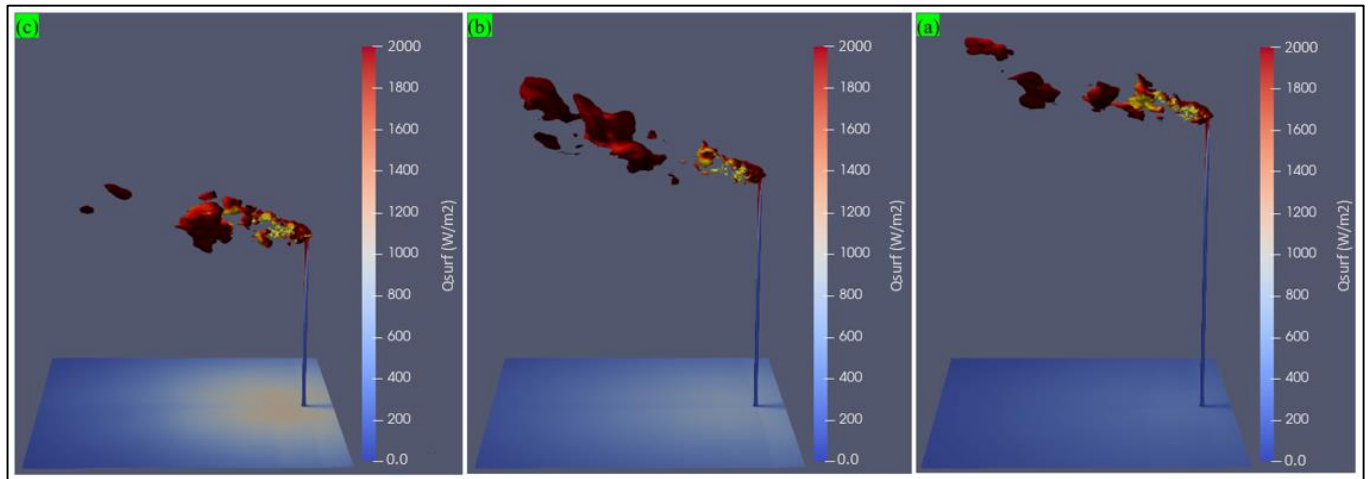


Figure 26. Low gas firing rate (9 t/h) flare operation using three different stack heights: (a) 55 m, (b) 45 m, and (c) 35 m.

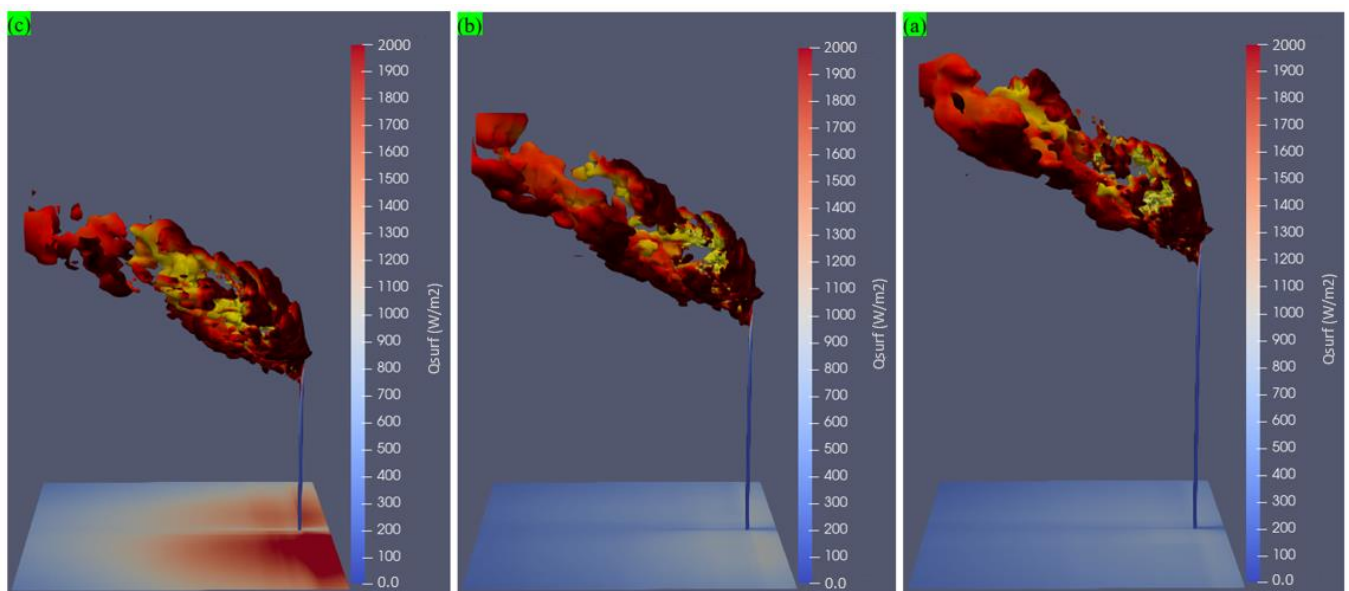


Figure 27. High gas firing rate (45 t/h) flare operation using three different stack heights: (a) 55 m, (b) 45 m, and (c) 35 m.

The figures clearly show that a decrease in stack height leads to an increase in ground heat due to greater heat radiation from the flame to the ground. A shorter flare stack brings the flame closer to the ground, resulting in more heat being absorbed by the surface. Additionally, an increase in the amount of flare gas amplifies ground heat as it generates a larger flame. This is evident from the figures, where for the same scenario, the heat

radiation from a high gas firing rate is significantly greater than that from low or normal firing rates.

For instance, in the case of low firing rates with a shorter 35 m flare stack, the ground heat reaches 1000 W/m^2 within a 20 m radius. In contrast, with the same stack height and a high gas firing rate, ground heat exceeds 2000 W/m^2 within a 25 m radius. This demonstrates that as the gas firing rate increases, the radius of ground heat expands, necessitating additional precautions to ensure safe operation at the site.

Generally, the heat radiation level at a higher stack height of 55 m during normal firing rates is below 1600 W/m^2 , which is within the continuous exposure limit for personnel without protective clothing. According to API 521, this is the recommended safe exposure limit for personnel and equipment.

3.4. Sampling Locations

As explained earlier, the increase in the amount of gas being flared affects the rate of emissions. Four locations in the domain were defined for both gas firing rates with a crosswind speed of 8 m/s to extract combustion product data. The flare's hydraulic limits in this study were a height of 55 m and a diameter of 0.61 m. Figure 28 shows the probe locations used for monitoring combustion products at normal gas firing rates, while Figure 29 illustrates the probe locations used for monitoring combustion products at high gas firing rates. The probe size in both gas firing cases had a radius of 0.3 m and ten datasets were recorded at each location. The average of these ten datasets was taken and represented.

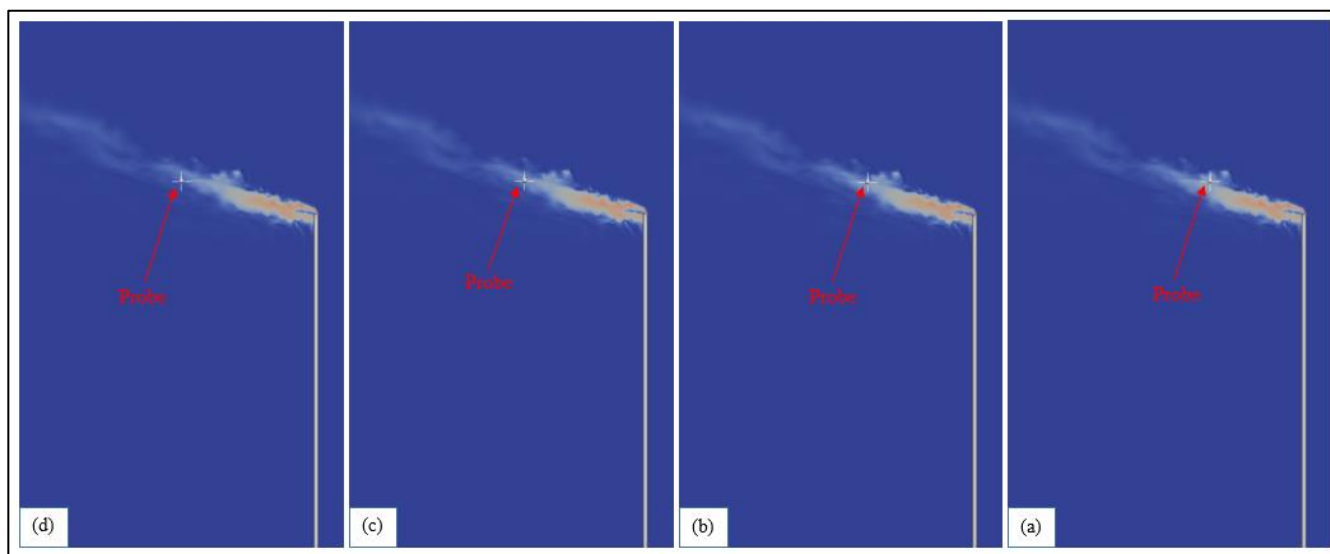


Figure 28. Probe locations at a normal gas firing rate (9 t/h) of the flare using a stack height of 55 m: (a) 14 m (x-axis), 0 m (y-axis), 60 m (z-axis); (b) 16 m (x-axis), 0 m (y-axis), 60 m (z-axis); (c) 18 m (x-axis), 0 m (y-axis), 60 m (z-axis); and (d) 20 m (x-axis), 0 m (y-axis), 60 m (z-axis).

The following tables show the main combustion products and fuel compounds in the plume at both gas firing rates. Additionally, they provide the locations of the probes in the domain, as well as the sizes of the probes used to extract combustion products and fuel compounds from the plume. Tables 2 and 3 demonstrate the mass fractions of the main pollutants in the plume as well as the main fuel compounds at normal gas firing rate.

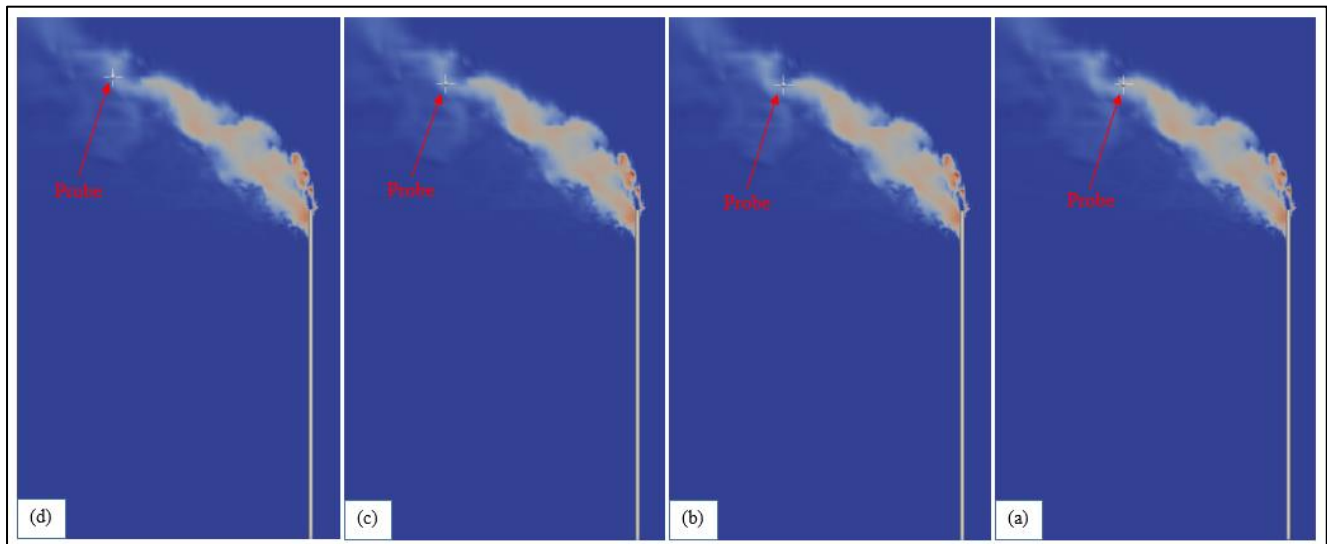


Figure 29. Probe locations at a high gas firing rate (45 t/h) of the flare using a stack height of 55 m: (a) 25 m (x-axis), 0 m (y-axis), 74 m (z-axis); (b) 27 m (x-axis), 0 m (y-axis), 74 m (z-axis); (c) 29 m (x-axis), 0 m (y-axis), 74 m (z-axis); and (d) 30 m (x-axis), 0 m (y-axis), 75 m (z-axis)..

Table 2. Main combustion products at a normal gas firing rate (9 t/h).

Probe Location				CO (Mass%)	CO ₂ (Mass%)	Soot (Mass%)	SO ₂ (Mass%)	NO (Mass%)
x-Axis (m)	y-Axis (m)	z-Axis (m)	Radius (m)					
14	0	60	0.3	6.31×10^{-9}	1.06×10^{-1}	1.90×10^{-4}	2.49×10^{-3}	2.33×10^{-3}
16	0	60	0.3	3.26×10^{-7}	6.58×10^{-2}	9.90×10^{-5}	1.60×10^{-3}	1.47×10^{-3}
18	0	60	0.3	4.52×10^{-9}	5.10×10^{-2}	1.42×10^{-4}	1.22×10^{-3}	1.14×10^{-3}
20	0	60	0.3	1.28×10^{-6}	4.61×10^{-2}	2.51×10^{-4}	1.11×10^{-3}	1.02×10^{-3}

Table 3. Main fuel compounds in the plume at a normal gas firing rate (9 t/h).

Probe Location				CH ₄ (Mass%)	C ₂ H ₆ (Mass%)	C ₃ H ₈ (Mass%)	C ₄ H ₁₀ (Mass%)	C ₅ H ₁₂ (Mass%)
x-Axis (m)	y-Axis (m)	z-Axis (m)	Radius (m)					
14	0	60	0.3	8.43×10^{-9}	7.42×10^{-9}	7.51×10^{-9}	7.63×10^{-9}	7.59×10^{-9}
16	0	60	0.3	7.83×10^{-9}	6.04×10^{-9}	6.14×10^{-9}	6.32×10^{-9}	6.31×10^{-9}
18	0	60	0.3	7.80×10^{-9}	5.30×10^{-9}	5.41×10^{-9}	5.62×10^{-9}	5.62×10^{-9}
20	0	60	0.3	6.96×10^{-9}	4.72×10^{-9}	4.83×10^{-9}	5.01×10^{-9}	5.00×10^{-9}

Moreover, Tables 4 and 5 show the mass fractions of the main pollutants and fuel compounds in the plume at a high gas firing rate.

Table 4. Main combustion products at a high gas firing rate (45 t/h).

Probe Location				CO (Mass%)	CO ₂ (Mass%)	Soot (Mass%)	SO ₂ (Mass%)	NO (Mass%)
x-Axis (m)	y-Axis (m)	z-Axis (m)	Radius (m)					
25	0	74	0.3	1.45×10^{-5}	1.24×10^{-1}	1.76×10^{-5}	3.39×10^{-3}	2.39×10^{-3}
27	0	74	0.3	1.16×10^{-8}	1.38×10^{-1}	7.06×10^{-5}	3.91×10^{-3}	2.76×10^{-3}
29	0	74	0.3	2.66×10^{-8}	1.27×10^{-1}	3.82×10^{-5}	3.82×10^{-3}	2.67×10^{-3}
30	0	75	0.3	2.83×10^{-7}	7.78×10^{-2}	1.05×10^{-4}	2.27×10^{-3}	1.67×10^{-3}

Table 5. Main fuel compounds in the plume at a high gas firing rate (45 t/h).

Probe Location				CH ₄ (Mass%)	C ₂ H ₆ (Mass%)	C ₃ H ₈ (Mass%)	C ₄ H ₁₀ (Mass%)	C ₅ H ₁₂ (Mass%)
x-Axis (m)	y-Axis (m)	z-Axis (m)	Radius (m)					
25	0	74	0.3	7.59×10^{-8}	1.04×10^{-6}	1.61×10^{-6}	4.93×10^{-6}	4.38×10^{-6}
27	0	74	0.3	9.47×10^{-9}	9.60×10^{-9}	9.52×10^{-9}	9.83×10^{-9}	9.69×10^{-9}
29	0	74	0.3	9.06×10^{-9}	8.39×10^{-9}	8.44×10^{-9}	8.59×10^{-9}	8.68×10^{-9}
30	0	75	0.3	8.69×10^{-9}	6.29×10^{-9}	6.40×10^{-9}	6.60×10^{-9}	6.59×10^{-9}

From these figures, it is evident that the selected locations for data extraction at both firing rates provide almost identical data. This similarity can be attributed to the crosswind effect, which causes pollutant dispersion at points farther from the flare tip. In other words, soot formation near the flare tip is lower for the low gas firing rate compared to the higher gas firing rate (see Figures 16b and 17b). However, due to the crosswind effect and dispersion, soot formation decreases at locations farther from the tip.

Finally, Tables 6 and 7 present the primary gas compounds in the plume and fuel, highlighting the results of fuel consumption and destruction. These tables demonstrate that the majority of the carbon was consumed during combustion at both firing rates.

Table 6. Main flare gas compounds in the fuel and the plume at a normal gas firing rate (9 t/h).

Plume				CH ₄ (Mass%)	C ₂ H ₆ (Mass%)	C ₃ H ₈ (Mass%)	C ₄ H ₁₀ (Mass%)	C ₅ H ₁₂ (Mass%)
Probe Location								
x-Axis (m)	y-Axis (m)	z-Axis (m)	Radius (m)					
14	0	60	0.3	8.43×10^{-9}	7.42×10^{-9}	7.51×10^{-9}	7.63×10^{-9}	7.59×10^{-9}
16	0	60	0.3	7.83×10^{-9}	6.04×10^{-9}	6.14×10^{-9}	6.32×10^{-9}	6.31×10^{-9}
18	0	60	0.3	7.80×10^{-9}	5.30×10^{-9}	5.41×10^{-9}	5.62×10^{-9}	5.62×10^{-9}
20	0	60	0.3	6.96×10^{-9}	4.72×10^{-9}	4.83×10^{-9}	5.01×10^{-9}	5.00×10^{-9}
Fuel				7.40×10^{-2}	7.40×10^{-2}	1.55×10^{-1}	3.33×10^{-1}	2.92×10^{-1}

Table 7. Main flare gas compounds in the fuel and the plume at a high gas firing rate (45 t/h).

Plume				CH ₄ (Mass%)	C ₂ H ₆ (Mass%)	C ₃ H ₈ (Mass%)	C ₄ H ₁₀ (Mass%)	C ₅ H ₁₂ (Mass%)
Probe Location								
x-Axis (m)	y-Axis (m)	z-Axis (m)	Radius (m)					
14	0	60	0.3	7.59×10^{-8}	1.04×10^{-6}	1.61×10^{-6}	4.93×10^{-6}	4.38×10^{-6}
16	0	60	0.3	9.47×10^{-9}	9.60×10^{-9}	9.52×10^{-9}	9.83×10^{-9}	9.69×10^{-9}
18	0	60	0.3	9.06×10^{-9}	8.39×10^{-9}	8.44×10^{-9}	8.59×10^{-9}	8.68×10^{-9}
20	0	60	0.3	8.69×10^{-9}	6.29×10^{-9}	6.40×10^{-9}	6.60×10^{-9}	6.59×10^{-9}
Fuel				7.40×10^{-2}	7.40×10^{-2}	1.55×10^{-1}	3.33×10^{-1}	2.92×10^{-1}

4. Conclusions

This paper analyzed the operation of a routine utility flare, 55 m in height and 0.61 m in diameter, located in an oilfield in Iraq at two different gas firing rates: low and high. The analysis focused on evaluating the environmental and safety aspects of the flare operation by varying the crosswind and stack height.

The numerical testing results concluded that increasing the flare gas flow rate not only results in a larger flame and plume size but also raises the overall heat radiation intensity. This increased heat load can pose risks to nearby equipment and personnel, emphasizing the need for an adequate stack height and safe operational limits. Moreover, stronger crosswinds improve the dispersion of combustion products, potentially reducing localized pollutant concentrations. However, excessive wind speeds can also lead to flame deflection, increasing unburned hydrocarbons and soot formation.

The safety analysis demonstrated that operating with a taller stack height of 55 m significantly enhances safety by reducing ground-level heat radiation compared to the shorter 35 m stack, which exhibited the highest heat intensity at ground level. This reduction in heat exposure helps mitigate risks for personnel and nearby equipment, aligning with API 521 safety guidelines. Additionally, measurements of pollutant concentrations at various locations within the computational domain at both low and high gas firing rates showed minimal variation. This consistency is primarily attributed to the wind-driven dispersion of pollutants, which effectively distributes emissions across the domain, preventing the localized buildup of harmful combustion byproducts. These findings highlight the role of crosswind conditions in reducing near-field pollutant accumulation while emphasizing the importance of optimizing the stack height and flare tip design for improved safety and environmental performance.

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Conflicts of Interest: The authors declare no conflicts of interest.

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