

Estimation of Atmospheric Aerosol Emissions from North Oil Company Baba Region Gas Flare Stacks in Kirkuk Province Using a Gaussian Model (Case Study)

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Abstract

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Concentrations of fine 2.5 μ m Aerosols particulate matter (PM) containing black carbon (soot) are considered to have significant harmful health effects, especially those resulting from the combustion of petroleum derivatives during crude oil extraction operations, whether for workers in the oil sector or citizens residing in nearby areas. The current study provides an assessment and calculation of PM_{2.5} concentrations in the Baba Industrial Area resulting from the emission of flares burning through extraction field operations. The study relied on the analysis of the components of five samples of associated gas which, is pumped to the flares before combustion using a chromatograph (GC). Based on the samples' analysis, the emission coefficient and emission ratios were calculated and applied as a case study in the Gaussian diffusion model after calculating the horizontal and vertical diffusion coefficients (σ_y, σ_z) and the Pasquill stability classes during the gas sample analysis periods. The Gaussian diffusion equation was also modified to apply on (PM), relying on calculations of deposition velocity instead of gaseous materials at different distances from the extraction fields. The results did not indicate high concentrations of carbon particles, while there was a noticeable increase in concentrations under stable conditions, although wind direction and distance sometimes had the greatest impact on the recorded concentrations. Overall, this study will be important in assessing air quality in oil industry facilities and evaluating the impact of atmospheric treatments on it, in addition to identifying the quantities of black carbon (soot) deposited around the study area.

Keywords: PM_{2.5}; Oil field; Black carbon; Deposition velocity; Gaussian equation model

1. Introduction

Natural gas exists either independently in gas reservoirs or alongside crude oil, and its composition mainly consists of short-chain alkanes (Hamiza, 2021). During the separation process, a portion of the natural gas is collected for residential and industrial uses, while the remainder is typically flared at an open flame (Saleh and Hassoon, 2024). The term "fuel gas" refers to natural gas that undergoes flaring (Saleh and Hassoon, 2024). The amount of pollutants released during this stage of processing is influenced by several factors, including the technology used, the volume of crude oil processed, the design and structure of the flare, the current weather conditions, and the chemical composition of the flared gas (Abu et al., 2023). Gas flaring is a significant producer of volatile organic compounds (VOCs),

carbon monoxide (CO), carbon dioxide (CO₂), sulfur dioxide (SO₂), polycyclic aromatic hydrocarbons (PAHs), nitrogen oxides (NO_x), and soot or (BC), all of which are critical pollutants that interact, both directly and indirectly, with the Earth's climatic processes (Fawole et al., 2016). Gas flaring is a major source of BC, which, with other, such as sources aviation and shipping, contributes about 9% of global BC emissions (Chen et al., 2022).

Gas flaring is considered one of important sources for BC sources, which is characterized by open fires with flames reaching 8-10 m in length and temperatures as high as 2000 K (Bond et al., 2013). There are many studies dealing with estimated pollutants (gas oxides and particulate matter) resulting from the combustion of crude oil wastes in stacks according to the Gaussian model, for example Gzar and Kseer (2009) investigated the release and atmospheric dispersion of contaminants from elevated flaring systems at the South Gas Company, a producer of Liquidated Petroleum Gas (LPG) located in Al-Basrah Governorate, Iraq. Gas composition analysis and new EPA estimating methodologies determined emission rates. The results show that unstable atmospheric conditions and wind speed cause the highest ground-level pollution concentrations.

Baker (2018) studied the composition of associated gases in the Khabaz Oil Field, which is affiliated with the North Gas Company, using a GC instrument (Varian CP-3800). The analysis of the associated gas samples showed that methane (CH₄) constitutes 75%, while hydrogen sulfide (H₂S) constitutes 2%. The associated gas burned in a flare at the Khabaz Oil Field is 4 mm scf/day, and the flaring rate is equivalent to 104 tons/day, which is sufficient to generate 8.4 megawatts of electrical energy (Baker, 2018). Saleh and Hassoon (2021) studied the effect of atmospheric stability on CO emissions from eight units at the Kirkuk refinery in 2019, using Turner's method to classify atmospheric stability based on meteorological factors. CO emissions from 11 stacks were estimated using the Gaussian model for January and July. Results showed that CO levels decreased with distance 1000–10,000 m (Saleh, 2021).

Anad et al. (2022) used Gaussian equations modeled in MATLAB to study the effect of pollutant NO₂ on the area around the Durra refinery located southwest of Baghdad City; the program also evaluates factors, such as wind and stability and their effect on stack height. Results show that the most NO₂ polluted areas are concentrated in Al-Jadriyah and Al-Karada, located about 3-5 kilometers from the refinery, where NO₂ levels exceed the national ambient air quality standard (Anad et al., 2022). The aim of this article is to estimate the amount of PM created as BC a size of 2.5µm and the estimated emission rate resulting from burning of associated gas in Baba Industrial, using a Gaussian model according to many samples tested by a GC instrument, for associated gas before burning in these flares.

2. Materials and Methods

2.1. Location (Baba Industrial Area)

Baba Dome, or the Baba industrial region, lies to the northwest of Kirkuk City. The region is geographically located between the latitudes 35° 31' 20" N - 35° 20' 20" N and longitudes 44° 26' 10" E - 44° 16' 30" E (Mahmood et al., 2021). The Kirkuk Governorate is an oil-rich province located among the Zagros Mountains, the Lower Zab and Tigris rivers, and the Himreen hills and it ranks as the fifth-largest oil field in the world in terms of capacity (Saleh, 2021). The three domes extend from the southeast to the northwest, but two main domes (Baba and Avana) are located in Kirkuk province, while the third one (Khurmala) is in Erbil Province (Fig. 1) (Sahib, 2019).

The daily crude oil output from the Baba Dome stations is estimated to be around 67,900 barrels, which includes 8,700 barrels of dry oil and 49,200 barrels of wet oil (Fig. 2) (Mahmood et al., 2021). Baba Dome consists of seven stations under the North Oil Company, including five main stations for

gas-oil separation: Qutan Gas Separation Station, Jabal Bour Gas Separation Station, Hanjira Gas Separation Station, Shoraw Gas Separation Station, and Baba Gas Separation Station.

Furthermore, there are two corresponding natural gas compression stations, specifically AB2 Gas Compression Station and AB3 Gas Compression Station. The gas is transported to the North Gas Company (NGC) via compression stations, where it undertakes processing to reject sour gases and sulfur, yielding both fluid and dry gas. This method meaningfully diminishes gas flaring, thereby lessening environmental pollution (Al-Kazwini et al., 2009).

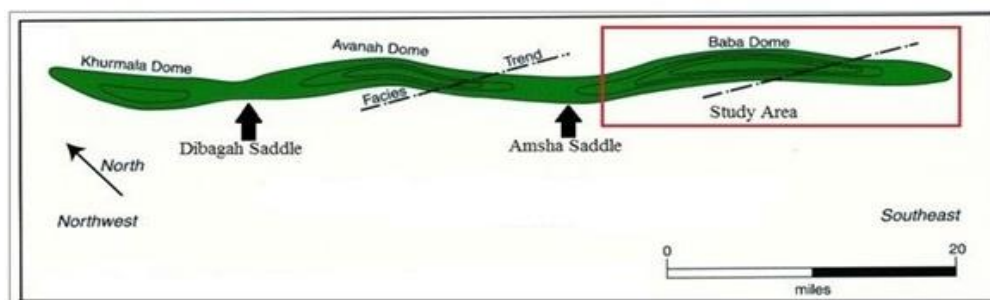


Fig. 1. The Baba Dome study area is depicted in a schematic longitudinal cross-section of the Kirkuk structural formation (Sahib, 2019)

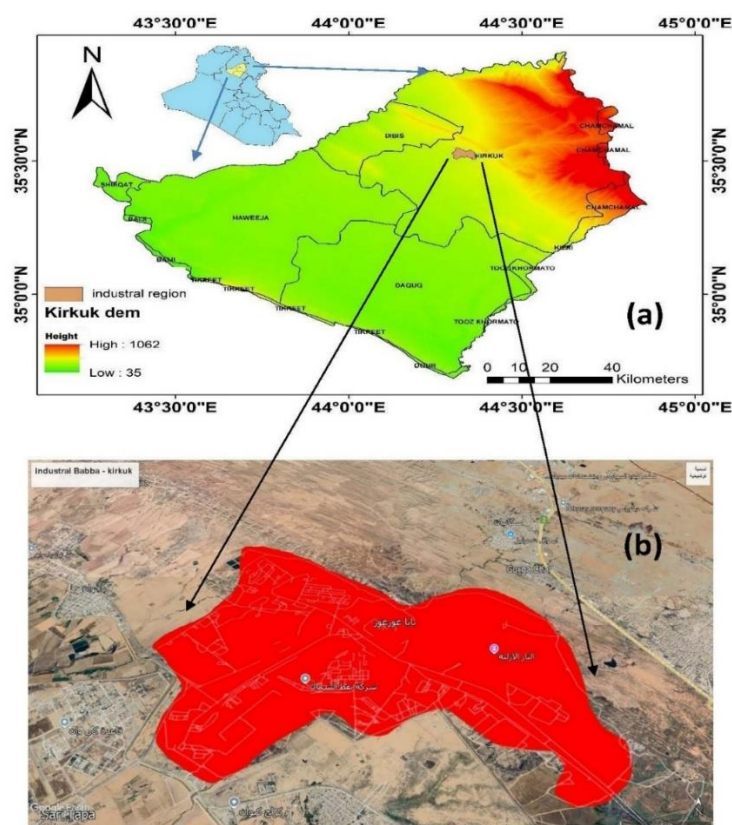


Fig. 2. Location of the study area shows (a) a map of Iraq and Kirkuk Province and (b) Baba industry oil field

2.2. Gas Flare Stacks

Flaring is the controlled burning of undesirable or associated natural gas or gas produced during oil and gas extraction, processing, refining, petrochemical operations, landfill gas extraction, and coalbed

methane production (Abu et al., 2023). The flare system design depends on the flare type (raised or ground) and the burning improvement method (steam contribution, air assist, pressure assist, or no support) (Ali, 2014). The process encompasses the following steps:

1. Directed gases to the process unit that is linked to the flare stack via a collection header and piping system.
2. A liquid knockout container separates and collects condensates and liquids from the gas flow, preventing them from entering the flare system.
3. A flashback seal container with purged gas prevents flashbacks.
4. The stack contains multiple burner parts and a pilot flame for continuous ignition.
5. A spark ignition device generates a spark to ignite the waste gas-air mixture at the flare tip, ensuring safe and reliable operation.
6. Steam purge gas (natural fuel, inert gas, or nitrogen) assists with combustion and flare stability.

The characteristics of these flares vary depending on the type of station and its processing units. Table 2 provides details on design characteristics of the flare system at five stations.

Table 2. Design characteristics of the flare system at five stations in Baba Dome Area, (NGC), including flare type, number, height, diameter, and volume of gas in the study area. (Production Department and Oil Processing Department, 2020)

Stations	Flare Type	Number of Flares	Flare Stack Height (m)	Flare Stack Diameter (m)	Volume of Gas Burned in Flares (m ³ /hr)	Molecular Weight (Mole%)	Gas temperature (°C) entering the flare stack
Wet Crude Oil Treatment Unit	Elevated L.P.	1	12	0.41	1765.8	19.76	10 - 20
Baba Degassing Station	Elevated H.P.	1	8	0.15			
Shoraw Degassing Station	Ground L.P. finger (12 tips)	2	1.5	0.1	588.6	22.65	10 - 20
AB3 Compressing Station	Elevated L.P.	2	6	0.3	588.6	23.5	10 - 20
Old Process Units	Elevated L.P.	1	50	0.74	58.9	22.25	34
	Blowdown L.P.	1	1.5-2.5	0.2			
	Burn Pit Ground L.P. finger (12-14 tips)	3	2-3	0.15			
	Elevated H.P.	2	6	0.3	659.2	37.32	40
						29.55	

2.3. Aerosols (Black Carbon) Emission Rate

The nature and quantity of any emission depend on the amount and composition of the fuel burned, as well as the flare geometry and design (Torres et al., 2012). Pollutants such as PM_{2.5}, including soot from flaring, are typically estimated using simplified emission factors (EFs) that relate pollutant quantities to the volume of fuel consumed. However, flare emissions can vary significantly due to

fluctuations in meteorological conditions, fuel composition, flow rates, flare size, and design (McEwen and Johnson, 2012). The United States (U.S.) Environmental Protection Agency (EPA) determines emission factors for PM_{2.5} from flare systems based on a standardized fuel heating value of 87 MJ/m³. These EFs are classified into three value sets, as summarized in Table 3 (U.S. Environmental Protection Agency, 2009). According to the U.S. EPA's FIRE 6.25 (2009) and U.S. Environmental Protection Agency (1995), flare emission factors are further categorized into four concentration levels based on flare smoking intensity: Non-smoking flares: 0 (μg/m³), lightly smoking flares: 40 (μg/m³), average smoking flares: 177 (μg/m³), and heavily smoking flares: 274 (μg/m³). These classifications are illustrated in Table 3.

Variations in the volumetric heating value (VHV) during the combustion of hydrocarbons affect soot emissions. The higher heating value (HHV) usually correlates to the volumetric heating value (VHV), which is expressed in kJ·mol⁻¹. The heat emitted from water vapor condensation during combustion is included in the HHV, which is the overall enthalpy of the entire combustion reaction for a gas mixture (Fawole et al., 2016).

Table 3. Comparison of soot emission factor values (U.S. Environmental Protection Agency, 2009)

Standard	Emission Factor	Fuel Gas type
U.S. EPA Fire 6.25	53 lb PM per 10 ⁶ ft ³ gas	Landfill gas
(U.S. Environmental Protection Agency, 2009)	17 lb PM per 10 ⁶ ft ³ gas	Methane
CAPP guide (CAPP, 2007)	0, 40, 177, 274 lb PM per 10 ⁶ BTU*	80% propylene 20% propane
U.S. EPA AP-42 Vol. I, section 13.5 (U.S. Environmental Protection Agency, 1995)	2.5632 kg PM per 10 ³ m ³ fuel	Associated gas
	0, 40, 177, 274 μg PM per 10 ³ m ³ exhaust gas	80% propylene 20% propane

* 1 BTU = 1055.06 Joules.

In gas flaring, the HHV serves as a critical parameter; it can be calculated using standard thermodynamic data. It determines flare buoyancy and emission dispersion characteristics (Beychok, 2005). The energy content of the discharged gas (represented by HHV) is determined by the complete gas composition, calculated using the Equation 1.

$$HHV = X_{CH_4} * HHV_{CH_4} + X_{ethane} * HHV_{ethane} + X_{propane} * HHV_{propane} + X_{butane} * HHV_{butane} + X_{pentane} * HHV_{pentane} \quad (1)$$

In this equation, X denotes the mole fraction for each constituent in the associated gas, namely methane, ethane, propane, butane, and pentane. At the same time, HHV_x indicates the heat content of each respective constituent (Chen et al., 2022). McEwen and Johnson used a lab-based experiment in their studies to investigate BC emissions from the combustion of hydrocarbons, they varied the VHV value of the fuel gas and measured the soot yield for each combustion process experiment. The relationship between the two variables (soot yield and HHV) obtained from another study is given in Equation 2 (McEwen and Johnson, 2012).

$$EF_{soot} = 0.0578(VHV) - 2.09 \quad (2)$$

The soot emission output in g/m³ from hydrocarbon combustion can be estimated using Equation 1. However, this method is only effective for complete or nearly complete combustion processes. Based on Böttcher's tests, the BC emissions factor (g/m³) for flares can be estimated through a nonlinear correlation with the heat content of the gas (higher heating value, HHV, in MJ/m³) by applying Equation 3 as referenced by Chen et al. (2022).

$$EF = 0.0112 (\ln(HHV - 37.6))4.612 + 0.194 \quad (IF \ HHV > 38.6 \frac{MJ}{m^3}) \quad (3)$$

$$EF = 0.194 \text{ If HHV} < 38.6 \frac{\text{MJ}}{\text{m}^3}$$

Flared gas heat content (higher heating value, HHV) is estimated using gas composition data reported by oil and gas producers to the EPA Greenhouse Gas Reporting Program (GHGRP) Subpart W (EPA, 2014). In most cases, BC constitutes at least 90% of the carbon-based species found in flare emissions. However, when sour gas is burned, significant amounts of sulfur dioxide, carbon dioxide, and hydrogen sulfide are also released (Koyanbayev et al., 2022). The emission rates of BC as PM_{2.5} aerosols from the flare are calculated in kg/hr using the following equation (4) (Gzar and Kseer, 2009).

$$Q_{BC} = \sum_{i=1}^n EF_{pm} * V \quad (4)$$

where: Q_p : Emission rate of aerosol particles (PM), (kg/hr). EF_{pm} : Emission factor of aerosol particles (PM), (kg/10⁶ kJ). V: volume of gases flared (m³/hr).

To estimate BC emissions from flaring, the emission factor was multiplied by the gas flaring volume at each flare stack, using Equation 4. Flaring processes release pollutants into the atmosphere, and the concentrations of these pollutants are influenced by the type of gas burned and the combustion efficiency of the flare. For the NGC, the analysis of sour gas shows it contains 2.95% hydrogen sulfide (H₂S) and 2.54% carbon dioxide (CO₂) (Abdulrahman and Zangana, 2020).

3. Methodology

3.1. Pasquill Atmospheric Stability

Atmospheric stability affects the vertical motion of air parcels and can be evaluated using different approaches depending on the data at hand. In this study, a modified version of the Pasquill method was used to determine atmospheric stability. This style employs hourly quantities of wind speed at a 10 m height, as well as information on solar radiation and cloud cover in the factory area (Table 4) (Mohan and Siddiqui, 1998). The stability modules are defined as follows: Classes A–C represent unstable environments, Class D represent neutral situations, and Classes E–F represent stable situations (see Table 4). Furthermore, Class G applies to low-wind conditions at night. These classifications were initially presented by Pasquill and Gifford and far along refined by Turner, leading to the extensively used stability indices 1–6, which correspond to the Pasquill-Gifford-Turner (PGT) system. (Kahl and Chapman, 2018).

Table 4. Modified Pasquill stability classes (Mohan and Siddiqui, 1998)

Wind speed (m/s)	Daytime incoming solar radiation (wm ⁻²)				Within 1 hours before sunset or after sunrise ²	Nighttime cloud amount (oktas)		
	Strong > 600	Moderate (300-600)	Slight (<300)	Overcast		0-3	4-7	8
≤ 2.0	A	A-B	B	C	D	F OR G ³	F	D
2.0 – 3.0	A-B	B	C	C	D	F	E	D
3.0 – 5.0	B	B-C	C	C	D	E	D	D
5.0 – 6.0	C	C-D	D	D	D	D	D	D
> 6.0	C	D	D	D	D	D	D	D

¹ (Ref. Davies and Singh, 1985). Excluding 1 h after sunrise and 1 h before sunset.

² Night was originally defined to include periods of 1 h before sunset and after sunrise. These 2 h are always categorised here as D.

³ Pasquill said that in light winds on clear nights, the vertical spread may be less than for category F, but excluded such cases because the surface plume is unlikely to have any definable travel. However, they are important from the point of view of the buildup of pollution and category G (nighttime, 0 or 1 okta of cloud, wind speed 0 or 0.5 ms⁻¹) has been added.

3.2. Gaussian Model

The Gaussian dispersion equation is a deep-rooted and broadly functional method for assessing atmospheric pollutant concentrations. It originated from the supposition that contaminant diffusion in the atmosphere agrees with a Gaussian (normal) distribution. This model can be used to act out the spread of plumes originating from both ground-level and elevated emission sources, as well as non-continuous releases (Varma et al., 2014). However, it is important to recognize that suspended PM released from flares exhibits dispersion characteristics that differ from those of gaseous pollutants. Due to gravitational settling, PM particles tend to deposit on the ground and, in most cases, do not re-enter the atmosphere (Gzar and Kseer, 2009).

$$PM = \frac{Q_p}{2\pi u \sigma_y \sigma_z} \exp \left[-\frac{1}{2} \left[\left(\frac{y}{\sigma_y} \right)^2 + \left(\frac{z - \left(H - \frac{v_d x}{u} \right)}{\sigma_z} \right)^2 \right] \right] \quad (5)$$

Where: PM: concentration of pollutant emitted from the flare in µg/m. Q_p : emission rate of particulate matter from the flare in µg/s. v_d : deposition or settling velocity of particulate matter in meter / second. z : vertical height above ground in meter. u : average horizontal wind speed in meters/second. σ_y : standard deviation of concentration distribution in the y direction (or horizontal dispersion coefficient) in meter. σ_z : standard deviation of concentration distribution in the z direction (or vertical dispersion coefficient) in meters. x : downwind distance x in meters (m). y : crosswind distance y in meters (m). H : effective stack height (The total height from the ground to the centerline of the plume after it has risen) in meter, where $H = h_s + \Delta h$. h_s : flare stack height in meters. Δh : called stack plume rise (The vertical distance that the plume rises above the physical height of the stack due to thermal buoyancy or momentum) in meter.

3.3. Dispersion Coefficients

Dispersion coefficients, including σ_y and σ_z , are determined based on the downwind distance between the emission source and the receptor, as well as prevailing atmospheric stability conditions. Briggs (1973) developed formulations for these coefficients for both urban and rural environments, including an interpolation approach consistent with Pasquill–Gifford stability classifications for distances ranging from 0.1 to 10 km. The U.S. Environmental Protection Agency recommends using these Briggs dispersion parameters for air quality modeling in both urban and rural settings. The relevant parameters are presented in Table 5 (Hamiza, 2021, and Briggs, 1973).

Table 5. Horizontal and vertical diffusion coefficient factors conferring to stability classes

Stability	σ_y	σ_z
A-B	$0.32x(1+0.0004x)^{-0.5}$	$0.24x(1+0.001x)^{-0.5}$
C	$0.22x(1+0.0004x)^{-0.5}$	0.2x
D	$0.16x(1+0.0004x)^{-0.5}$	$0.14x(1+0.003x)^{-0.5}$
E-F	$0.11x(1+0.0004x)^{-0.5}$	$0.08x(1+0.0015x)^{-0.5}$

3.4. Gravitational Settling Velocity

The dry deposition rate (v_d) of particulate matter, as defined in Calculation (5), is influenced by numerous factors, together with height above ground level, surface appearances, and the strength of atmospheric turbulence. The formulation of the settling velocity (v_g) is commonly based on resistance-based approaches that consider Brownian diffusion for ultrafine particles, inertial impaction for larger particles, and gravitational settling, which is the dominant mechanism for coarse particles. Deposition velocity is expressed as the inverse of the combined resistances—namely aerodynamic resistance (R_a) and laminar sublayer resistance (R_d)—along with the contribution of gravitational settling (v_g). In this framework, R_a represents aerodynamic resistance (s/m), while R_d denotes resistance to transfer across the atmospheric laminar sublayer (s/m), as shown in the following equation (Hassoon and Al-Dabbagh, 2023).

$$v_d = v_g + \left[\frac{1}{R_a + R_d + (R_a R_d v_g)} \right] \quad (6)$$

$$R_a = \frac{1}{\kappa u_*} \left[\ln \left(\frac{z}{z_0} \right) + 4.7 \frac{z}{L} \right] \quad (7)$$

$$R_d = \frac{1}{(Sc^{-2/3} + 10^{-3/St})u_*} \quad (8)$$

$$Sc = \frac{v_a}{D_b} \quad (9)$$

$$St = \left(\frac{v_g}{g} \right) \left(\frac{u_*^2}{v_a} \right) \quad (10)$$

where Sc : is Schmidt number that is defined as the ratio of momentum diffusivity (viscosity) and mass diffusivity (dimensionless), St : is stokes number (dimensionless), v_a : is kinematic viscosity of air ($\sim 0.15 \text{ cm}^2/\text{s}$), and D_b : is the Brownian diffusivity (cm^2/s) of the pollutant in air, (Beychok, 2005).

$$v_g = \frac{\rho_p g D^2}{18\mu} \quad (11)$$

Where: ρ_p : particle density (2 g/cm^3), μ : air dynamic viscosity ($1.8 \times 10^{-4} \text{ g/cm.s}$), g : gravitational acceleration (9.8 m/s^2), κ : (Von Karman constant) = 0.4. Other factors include: u_* , L , z_0 , are provided based on the case study.

4. Results and Discussion

4.1 Description of the Chemical Composition of the Tested Gas Samples

Hydrocarbons, or alkanes, are considered the primary components of associated gas, or natural gas. A typical fuel gas sample may contain CH_4 , C_2H_6 , C_3H_8 , $n\text{-C}_4\text{H}_{10}$, $i\text{-C}_4\text{H}_{10}$, $n\text{-C}_5\text{H}_{12}$, $i\text{-C}_5\text{H}_{12}$, C_6H_{14} , C_7H_{16} , H_2S , CO_2 , and N_2 , where n and i stand for normal (straight-chained) and iso (branched), respectively (Koyanbayev et al., 2022). The first step of processing starts by taking a gas sample from the flare line upstream using a regulated and filtered sampling system. The second step is injecting it into the gas chromatograph through a fixed-volume sample. The third step is separating components based on their physical properties, which are detected using detectors and sensors. In four steps, GC software calculates gas composition, heating value, and other properties, which are displayed on the GC screen (Fig. 3). Figure 4 shows an image of the GC in the laboratory. The results of this analysis are very important to control flare operation, ensure safe combustion, and meet environmental regulations.

Any combustion process of fuel gas releases heat, along with gaseous and particulate pollutants (Torres et al., 2012). This study analyzes the volumetric ratios of associated gas routed to flaring

operations within the Baba Industrial Zone of the North Oil Company, which operates thirteen gas flares. Five gas samples were collected in August 2020 from various processing units: the Wet Crude Treatment Unit, Shoraw and Baba Degassing Stations, Old Terkiz Stripping Units, and the AB3 Compressing Station; see Table 1. The compositional analysis revealed important differences between the samples: Sample 4 (Wet Crude Oil Treatment Unit) was methane-rich (83.82 mol%), in contrast to a dry gas with low molecular weight (19.76) and definite gravity (0.6824).



Fig. 3. Gas Chromatography (GC) instrument in the laboratory to analyze natural gas

Sample 5 (Old Terkiz Units) showed the peak concentrations of ethane (18.72 mol%), propane (11.85 mol%), and butane, as well as heavier hydrocarbons (C^{4+} , and C^{6+}), representing a rich gas with the peak LPG probable (TONLPG = 15.11) and molecular weight 37.32.

Hydrogen sulfide (H_2S) concentrations ranged from 0.5% to 4.64%, with the maximum in sample 5, indicated the need for desulfurization. Carbon dioxide (CO_2) was correspondingly detected in small amounts typically less than 2%, which may somewhat intensify the sharpness of the gas stream and affect dispensation, but these levels remain practicable. All samples displayed zero nitrogen (N_2), confirming that they were obtained from sealed, air-free internal sites.

All gases from these components are compressed into a single channel and transported by the AB3 compressing station to the North Gas Company. An increased in carbon and sulfur content in hydrocarbons is predicted to lead to higher emissions of pollutants and harmful gases, along with increased aerosol particle concentrations (Production Department and Oil Processing Department, 2020). The study applied the Gaussian dispersion equation to model emissions, combining wind speed, direction, and solar radiation data from the gas sample test days. Meteorological data were obtained from the NASA Power platform website (<https://power.larc.nasa.gov/data-access-viewer/>). These parameters were important for approximating horizontal and vertical dispersion coefficients, atmospheric stability modules, and aerosol concentrations.

4.2. Estimation of $PM_{2.5}$ Emission Rate from Baba Flares

A crucial component of this investigation is evaluating the PM emission rate from gas-flaring operations in the Baba industrial zone. The project process tracks an organized approach that begins by examining the configuration of the flare gas, as outlined in Section 2.2. The next stage involves defining the emission factors (EF) that match these gas samples. Once these factors are recognized, the PM emission rate is designed using the bulk of gas burned in the flares, as created in Equation 4. Table 6 presents the computed emission factors and the resulting PM emission rates for five different gas samples. These samples were examined using GC before ignition, with most samples collected in August from numerous working units that underwrite to the Baba industrial flare structure. According

to the data in Table 7, the wet crude behavior station displays the highest PM discharge rate, around 0.1 grams per second.

This is qualified to the higher gas mass current rate of this unit, which spreads everywhere 1,765 m³/h, meaningfully surpasses that of the other units. In difference, the AB3 station displays the lowest emission rate, roughly 0.01 grams per second, equivalent to a lower gas flow rate of 59 cubic meters per hour, as shown in Table 6.

Table 6. The configuration and fraction distribution of hydrocarbon compounds in related gas samples from five types of flares in the Baba Industrial Zone were determined through gas chromatography (GC) investigation (Production Department and Oil Processing Department, 2020)

Source of Sample	Shoraw Degassing Station	Baba Degassing Station	AB3 Compressor Station	Wet Crude Treatment	Oil Process (Old Terkiz)
Sampling Point	Elevated Flare	Finger (12 tips) flare	Suction Scr. Blowdown	L.P., H.P. flare	Unit 12,13 flare line
Date of Testing	21/08/2020	21/08/2020	2/8/2020	21/08/2020	21/08/2020
Composition	Result of Investigation mole%				
N ₂ : (Nitrogen)	0	0	0	0	0
C1: Methane (CH ₄)	73.04	75.23	76.35	83.82	37.13
CO ₂ : Carbon dioxide	1.17	0.66	0.85	0.11	0.46
C ₂ : Ethane (C ₂ H ₆)	13	12.38	11.15	10.45	18.72
H ₂ S : (Hydrogen Sulfide):	1.19	1.72	2.39	0.5	4.64
C3: Propane (C ₃ H ₈)	4.39	3.62	4.63	2.85	11.85
i-C4 (Iso-Butane): C ₄ H ₁₀	1.21	1.16	1.05	0.21	4.34
n-C4 (n-Butane): C ₄ H ₁₀	2.1	2.01	1.78	0.37	8.42
i-C5 (Iso-pentane): C ₅ H ₁₂	0.98	0.93	0.68	0.35	4.22
n-C5 (n-Pentane): C ₅ H ₁₂	0.9	0.81	0.61	0.32	3.84
C ⁶⁺ (Hexane and Heavier Hydrocarbons): C ₆ H ₁₄ and beyond	2.02	1.48	0.51	1.02	6.38
Total	100	100	100	100	100
Mol. WT	23.5	22.65	21.85	19.76	37.32
Tonlpg/MMSCF	4.61	4.11	4.41	1.91	15.11
Density gm/cc	0.000993	0.000956	0.000923	0.000835	0.001576
SP. GR.	0.8115	0.782	0.7543	0.6824	1.2886

Table 7. Baba industrial flare PM Emission Factor and Amount by means of Five Tests Examples taken on August 1 and August 21, 2020

Regions	HHV (Mj/m ³)	EF _{PM} (g/m ³)	V (m ³ /hr)	Emission Rate (g/hr)
Old Process Department	72.1	0.377	659.2	2644
AB3 Compressing Station	43.1	0.282	58.9	19
Shoraw Degassing Station	46.6	0.307	588.6	363
Baba Degassing Station	45.1	0.298	588.6	281
Wet Crude Treatment Unit	40.7	0.252	1765.8	378
Total mass of BC				3685

4.3. Atmospheric Stability and Related Meteorological Parameters

Atmospheric stability categorisation is vital feature in considerate how pollutants, mainly gases unconstrained from hydrocarbon burning, dissolve in the atmosphere. In this research, we considered atmospheric stability classes via wind speed and solar radiation, subsequent to the criteria outlined in Table 4. During a nine-day monitoring period, a total of 192 stability classes were recognized. These quantities resemble the days surrounding a gas selection operation, in which samples were collected and investigated prior to flaring and atmospheric diffusion. Due to the occurrence of high solar radiation points during the study period, most of the recognized stability classes were considered as unstable, precisely within classes A-B, B, B-C, and C, which accounted for around 85 groups. In contrast, neutral conditions were observed in 65 categories, whereas stable circumstances, consistent to classes E and F, were well known in 42 categories (Fig. 4).

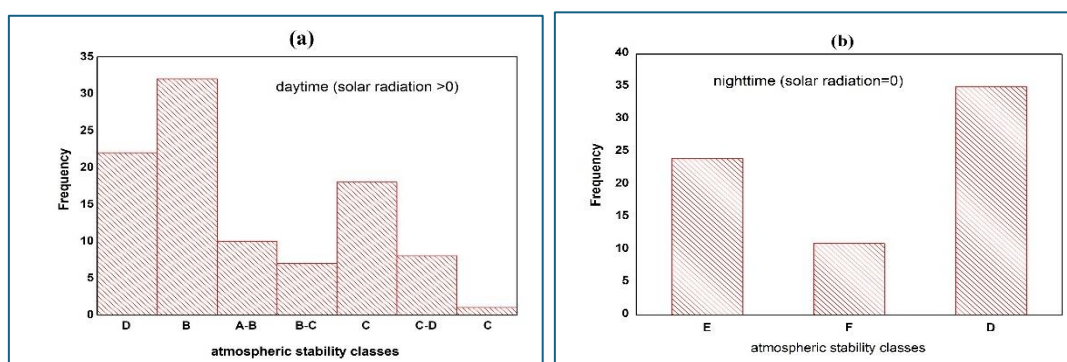


Fig. 4. Frequency of atmospheric categories in (a) Daytime and (b) Nighttime hours

Figure 4 displays the distribution of stability classes over nine days in August, distinguishing between daytime and nighttime environments. At night, when solar radiation is reduced to zero, the dispersion performance leans towards modification toward more stable or neutral conditions. Particularly, on August 21st, gas samples were analyzed by gas chromatography. On this particular day, atmospheric conditions were mainly unstable due to low wind speeds coupled with strong solar radiation that reached up to 900 W/m² (refer to Fig. 5, which demonstrates the conditions on August 21st).

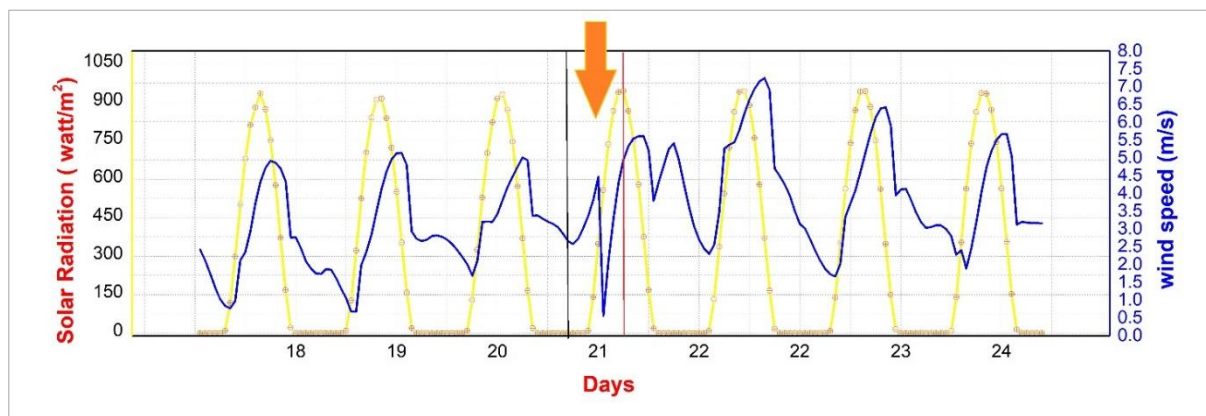


Fig. 5. Monitoring of solar radiation and wind speed over nine days of gas flaring, prominence the August 21st pre-flare gas sample examines for compositional appearances

4.4. Characteristics of Wind Speed and Direction

On August 21, 2020, hourly wind data in Kirkuk showed an average wind speed of 4.0 m/s, with experimental values extending from 0.6 to 5.6 m/s (Fig. 6). Remarkably, there were no calm situations recorded during this period. The most frequently detected wind speed, accounting for 21% of all

comments, was between 5 and 6 m/s. The dominant wind direction on that day was from the west (270°), as shown in Fig. 6. This dominant wind pattern proposes a probable path for pollutant transportation from west to east, indicating that discharges from western sources could influence the research area. Consideration of wind speed and direction are important for evaluating pollutant dispersion and supporting the classification of atmospheric stability. These parameters are dangerous for calculating pollutant concentrations. However, it is important to recognize that wind speed and stability conditions can change over time.

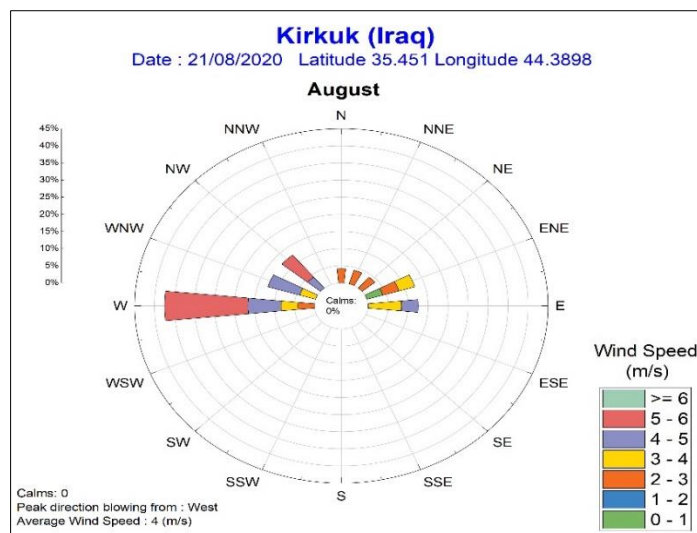


Fig. 6. Hourly wind speed and direction (wind rose) on 21 August

4.5. Evaluation of Aerosol Concentration Around Flare Stacks

The main objective of this study is to evaluate the concentrations of aerosols resulting from the combustion of surplus gas during flaring actions at the NOC in Kirkuk City. An essential step in this calculation is defining the volume and weight percentages of the flare gas apparatuses, which are vital for calculating both the production coefficient and the rates of particulate matter. Alternative critical parameter in this examination is the settling velocity of aerosol particles, chiefly individuals with a diameter of $2.5\mu\text{m}$. This velocity is vital for dispersion modeling using the Gaussian plume equation. As shown in Fig. 7, the settling velocities of aerosol particles, expressed in cm/s, were initially minimal under atmospheric stability class E, representing calm and stable conditions. In contrast, under unstable conditions (class A), the deposition velocity meaningfully increased due to improved turbulence and diffusion procedures. These dissimilarities are influenced by multiple factors, which are labeled in the series of deposition velocities in Equations 6 to 11.

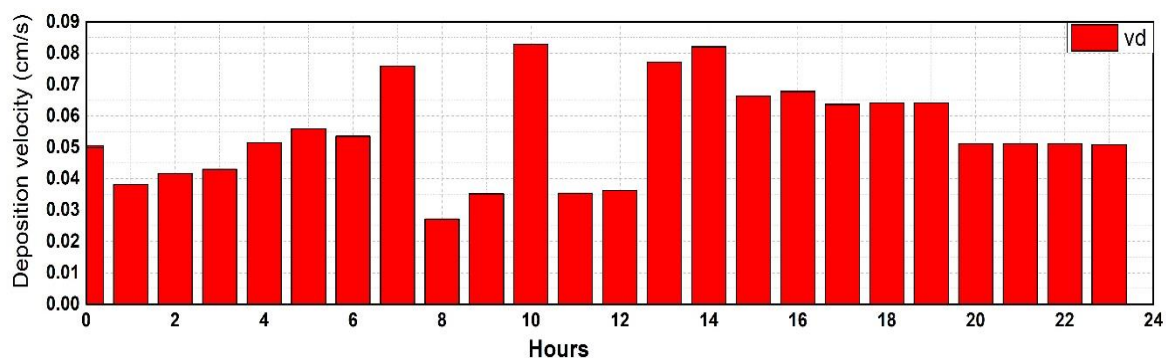


Fig. 7. Deposition velocity of aerosol particle size ($2.5\mu\text{m}$) in cm/s on August 21, 2020

The Gaussian dispersion model integrates several meteorological parameters, together with the Monin-Obukhov length (L), friction velocity (u_*), and the horizontal and vertical diffusion coefficients (σ_y and σ_z). These parameters were obtained from Table 5, with supplementary meteorological data obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) database. Using the Gaussian model, the study considered the delivery of aerosol concentrations constructed on a total emission rate of 3,685 g/h (equivalent to 1.02 g/m³). This rate embodies the collective emissions from all flare stacks over a 24-hour period on August 21, 2020 the same day gas configuration investigation was achieved. Aerosol concentrations were assessed at various downwind distances from the flare stacks: 1000, 3000, 5000, and 8000 m, as shown in Fig. 8. The highest aerosol concentrations were recorded under neutral stability conditions (class D) at 1000 meters, particularly at 4:00 AM. Furthermore, maximum particulate matter (PM) attentions were observed toward the end of the day at 6:00 PM (Fig. 8).

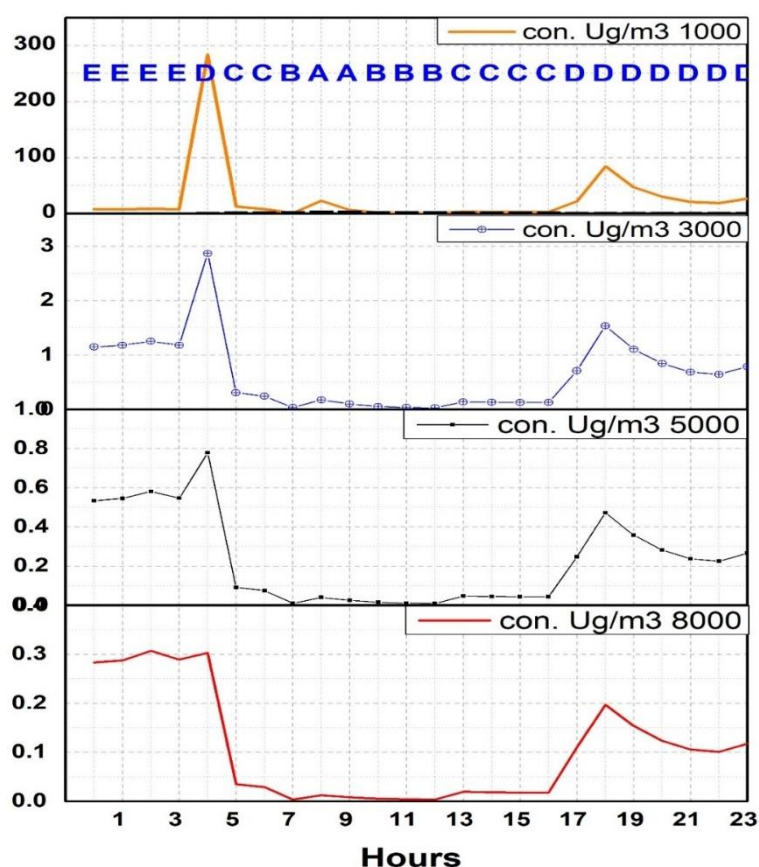


Fig. 8. Hourly variation of 2.5 µm aerosol particle concentrations on August 21, 2020, calculated at distances 1000, 3000, 5000, and 8000 m from the flare stacks

5. Conclusions

Iraq is an oil-producing country that relies entirely on crude oil exports, with numerous oil fields scattered throughout the country. The oil extraction process involves several stages, some of which involve the burning of unwanted petroleum and hydrocarbon derivatives as a byproduct of the production process. This study focuses on the byproducts of the production process in the oil fields of the Baba Industrial Area, operated by the North Oil Company. Quantities of associated gas from the extraction fields are sent to gas flares for burning due to the lack of systems capable of accommodating and utilizing it because leaving the gas in the existing systems leads to explosions. The gas flaring process generates particulate matter containing black carbon, also known as soot. This study assessed

the quantities of particulate matter produced using laboratory gas chromatography (GC) analysis of the gas components emitted by the flares. Analysis of five associated gas samples revealed high levels of methane (CH₄) in most samples (69.1% of the gas components), while hydrogen sulfide accounted for about 2.1%. Methane is considered a clean gas in terms of its combustion byproducts, because it contains only one carbon atom and four hydrogen atoms. Consequently, the flare combustion results did not indicate significant concentrations of particulate matter (soot). Calculations for particulate matter concentrations relied on a Gaussian model of atmospheric diffusion. The Gaussian equation revealed other potentially important factors in determining the overall condition, such as the stability classes at the time of sample analysis. Stable classes like E, F, and G increase in concentration due to higher sedimentation rates resulting from atmospheric stagnation, which in turn lead to high particulate matter values. Furthermore, the prevailing wind will direct floating particles towards specific areas, leading to poor air quality because flare combustion continues day and night. This study represents an important step in utilizing sample analysis data, atmospheric diffusion models, and atmospheric parameters to diagnose and monitor air quality in oil facilities and in surrounding areas.

Declaration of Competing Interest

The authors declare that they have no competing financial interests or personal relationships that could influence the work reported in this study.

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