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Assessing the environmental impact of offshore flares in the Persian Gulf: A comprehensive analysis of SO_2 emissions

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ABSTRACT

Flares are recognized as significant environmental risks that impact ecosystems. This research aims to analyze the impact of flares on ecosystem pollution and human health in the Persian Gulf. Specifically, it focused on modeling sulfur dioxide (SO_2) emissions from an offshore flare at the South Pars gas platform using AERMOD software for accurate analysis. For this purpose, the amount of SO_2 gas emissions in the first six months of 2022 was obtained based on field measurements. Subsequently, the distribution of these pollutants was investigated using the AERMOD distribution model in an area of 10 x10 km2 in both the X and Y directions, considering time averages of 1, 3, and 24 hours. To assess the accuracy of the model's outputs, these values were compared with the results of field measurements at six separate receptors. The findings revealed that the maximum concentration of SO_2 emissions during a 1-hour period was 1.73 $\mu g/m^3$, primarily localized in the vicinity of the flare. The AERMOD software confirmed the significant influence of wind direction on SO_2 emissions, with pollution dispersing up to 4.5 km from the emission center in the northwest to east direction within the first hour. Importantly, the investigation demonstrated that the pollutant emission levels from the flare remained well below the standards established by Iranian and American environmental organizations. Consequently, the activity of the studied flare poses no immediate danger to workers, residents, or ecosystems in the Persian Gulf. Statistical analysis illustrated a significant correlation between the model and field results (r = 0.943, Sig. = 99%), indicating the accuracy and robustness of the used model for estimation. In conclusion, the results provide a

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comprehensive framework for assessing air pollution stemming from flares to mitigate their deleterious effects on ecosystems.

1. Introduction

The term "flare" can be described as an instance of an uncontrolled combustion of ignited fire sparks. However, within the context of the chimney manufacturing industry, it predominantly pertains to a stack or vertical pipe employed to ensure the safety of devices and personnel by facilitating the ignition of waste gases. The utilization of flares contributes significantly to energy inefficiency, economic resource depletion, and greenhouse gas emissions. The aforementioned phenomenon serves as the primary catalyst for global warming and generates detrimental impacts on the well-being of individuals and other living organisms [1]. The proposed approach's high-accuracy prediction suggests that Iran's greenhouse gas emissions will surpass 1096 Mt/year by 2028 [2]. The Global Gas Flaring Reduction Partnership (GGFR) of the World Bank reports that Iran's gas flaring rose by 31% between 2019 and 2020, reaching its highest level since 2007 at 17.3 Billion Cubic Meters (bcm). Iran was the third-largest gas flaring country in 2020, following Russia and Iraq [3]. Iran has committed to reducing its gas flaring by 2025 as part of its Nationally Determined Contribution (NDC) under the Paris Agreement [4]. Furthermore, the Global Gas Flaring Reduction Partnership has proposed the imperative need for a comprehensive examination and assessment of the ecosystem within the South Pars vicinity in order to mitigate the release and recover the gases emitted through flaring [5, 6].

Flare systems can engender a multitude of consequences from both economic and environmental standpoints. The primary consequence is global warming, as these activities release large amounts of carbon dioxide into the environment, leading to greenhouse effects and potential reduction of pH levels, resulting in acidic rain [7, 8]. Secondly, flaring waste gases lead to environmental pollution and health impacts, with approximately 250 toxic materials released into the air during the burning process. Flares also emit soot particles, nitrogen oxides, sulfur oxides, volatile organic compounds, unignited hydrocarbons, and other harmful ignition products. These pollutants can cause respiratory system disorders, chronic bronchitis, and even premature death [9]. The third consequence is the loss of valuable resources and energy, with an estimated 150 bcm of natural gas flared annually, equivalent to 5% of global production. Financial resources are also allocated for the maintenance of flare systems. In Iran alone, a significant amount of accompanying gases is burned, with 67% being continually burned and 36% ignited temporarily or periodically [10, 11].

Sulfur dioxide (SO_2) is among the primary hazardous gases emitted into the atmosphere from flare systems. The release of SO_2 through flaring can significantly affect human and ecosystem health. SO_2 is a highly reactive gas that, upon exposure, can have detrimental effects on the respiratory system of humans. Inhalation of SO_2 can cause respiratory distress, exacerbate asthma, and contribute to the development of respiratory diseases [11]. Additionally, SO_2 emissions from flares can combine with other pollutants in the atmosphere to form fine particulate matter, which can penetrate deep into the lungs and cause respiratory and cardiovascular problems. Besides its impact on human health, SO_2 emissions can also harm ecosystems. Acid rain, resulting from the reaction of SO_2 with atmospheric moisture, can lead to the acidification of soils and waters. This acidification can disrupt the balance of ecosystems, affecting plants, animals, and aquatic life. Furthermore, SO_2 emissions contribute to the formation of smog and the depletion of ozone in the atmosphere. SO_2 can affect ozone depletion through several pathways, such as the creation of sulfate aerosols, interaction with hydroxyl radicals, and modulation of atmospheric concentrations of hydroxyl radicals and tropospheric ozone [12, 13]. Therefore, minimizing and regulating the release of SO_2 associated with flaring is crucial to safeguard both human health and ecosystems [14].

The application of AERMOD in modeling the dispersion of air pollutants, such as SO_2 emissions from flare systems, offers several notable benefits. AERMOD is a widely used and scientifically validated air quality dispersion model that takes into account various factors, including meteorological conditions, topography, and emission characteristics. By utilizing AERMOD, researchers and environmental professionals can accurately estimate the concentration and spatial distribution of SO_2 emissions from flare systems, providing valuable insights into potential impacts on human health and the environment. Its ability to simulate near-field and far-field dispersion scenarios ensures a comprehensive understanding of the pollutant's behavior under different conditions [11]. AERMOD also facilitates the evaluation of potential mitigation strategies and the assessment of compliance with regulatory standards.

Furthermore, the model's user-friendly interface and extensive data inputs allow for efficient and reliable analysis, enabling decision-makers to make informed choices regarding emission control measures and the siting of flare systems. Overall, the application of AERMOD in modeling SO_2 dispersion from flare systems offers a robust and valuable tool for assessing and managing air quality, facilitating the protection of human health and the environment [15]. Mirrezaei and Orkomi [6] employed the AERMOD model in conjunction with the Advanced Research WRF (ARW) to project the levels of BTEX, revealing a yearly range of 0.18 to 2.67 μg/m^3 for benzene and 0.21 to 2.95 μg/m^3 for xylenes. In another study on gas flaring in Nigeria [16], a strong correlation between flared gases and temperature was found, with observed SO_2 concentrations ranging from 19.73 to 51.54 μg/m3 at distances of 50-1700 m from the flare source. Amaechi-Onyerimma, et al. [17] evaluated the environmental impact of gas flaring near a flow station, noting a CO_2 concentration of 563.5 μg/m^3 linked to respiratory issues, skin ailments, and ear defects. Hesami Arani, et al. [18] discussed SO_2 and NO_2 emissions from a rolling industry, highlighting compliance with emission standards at the Sepid-Farab Kavir Steel Complex when utilizing natural gas as the primary fuel source. Angas, et al. [19] utilized the AERMOD model to simulate SO_2 emissions from the Tehran oil refinery, demonstrating its effectiveness in predicting SO_2 concentrations from specific emission points. The study's results indicated that both 1-hour and 24-hour average SO_2 levels remained below regulatory limits, underscoring the model's accuracy in forecasting SO_2 concentrations. Despite generally acceptable readings, ongoing monitoring and control of emissions are imperative to mitigate potential urban air pollution concerns.

In this context, the current study utilized AERMOD software to replicate the spatial distribution, dispersion, and concentration of sulfur oxides (SOx) emitted from an offshore flare system situated on the SPD8 platform within Phase 7 of the South Pars gas field. Empirical data were utilized to model the dispersion of SO_2 and subsequently conduct a comparative analysis against established regulatory standards.

2. Materials and methods

2. 1. Study area and data collection

The SPD8 gas platform examined in this study is situated at coordinates 52°1 longitude and 26°43 latitude, as depicted in Figure 1. The inlet gas characteristics of the South Pars platform flare (stage 7) were obtained from real data sourced from the SPD8 gas platform at South Pars gas platform 7 (Table 1). The compositions of sour flare gases were also extracted from the official documents of the Pars Oil and Gas Company's marine platforms (Table 2)

2.2. Modeling of pollution caused by the emission of SO_2 gas

The utilization of the AERMOD model is predicated upon incorporating three types of information: 1. Data pertaining to flare characteristics and pollution emissions, 2. Meteorological information specific to the study area, and 3. The digital elevation model of the study area. Fluid details of the gas flare from the Pars South platform 7 for modeling are documented in Table 3. Moreover, the minimum meteorological information required by AERMET for meteorological data analysis includes wind speed, dry temperature, humidity, and cloud cover recorded hourly. This study utilized the meteorological data from the Pars Deep Sea Research Company for the first six months of 2022. The corresponding data are shown in Table 4.

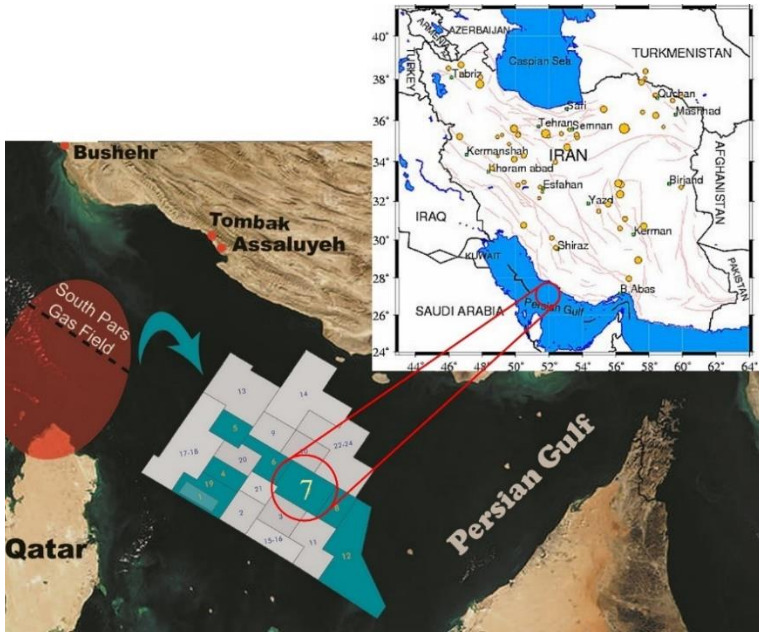

Fig. 1. Location of the SPD8 platform in Phase 7 of the South Pars gas platform.

Table 1. Characteristics of inlet gas, flare specifications of South Pars platform (Phase 7), and required meteorological data.

Lower Explosive Limit (LEL)	Molecular Weight	Lower Heating Value (LHV)	The ratio of special values cp/cv	Lower Explosive Limit (LEL)
2%	34.1	34104 Btu/lb	1.1	2%
Flare Tip Height	Flare diameter	Inlet gas flow	Steam Temperature	Bridge length
92.96 m	609.6 mm	90000 lb/hr	148.9 ºC	300 Feet
Solar Radiation	Wind Direction	Wind Speed	Humidity	Temperature
Ignored	90 (East)	20 m/s	76%	35 ºC

Table 2. Sour gas compounds in the flare based on molar percentage.

Component	Mole (%)
Hydrogen sulfide (H_2S)	5.38
Carbon dioxide (CO_2)	4.48
Nitrogen (N_2)	0.11
Methane (CH_4)	63.35
Ethane (C_2H_6)	13.90
Propane(C_3H_8)	6.03
Iso-Butane (i-C_4H_{10})	1.36
Normal-Butane (n-C_4H_{10})	2.44
Iso-Pentane (i-C_5H_{12})	1.03
Normal-Pentane (n-C_5H_{12})	0.73
Hexane (C_6H_{14})	1.19
Water (H_2O)	0.00
Total	100

The pre-processor for this study requires three surface characteristics from the study area as input: surface roughness, Bowen's ratio, and albedo coefficient. To determine these values, it is necessary to divide the study area into suitable sectors based on the surrounding land use and vegetation in a clockwise manner. In the context of this study, the focus is on investigating the SO_2 gas released from the SPD8 gas platform, which is one of the offshore gas platforms located in the Persian Gulf region. Since the gas platform is surrounded by water and there are no specific land uses in the vicinity within the investigated radius, it is not possible to define a particular land use for the surrounding area. In this case, the surface parameters used in this study are defined in Table 5. Among the other requirements of the AERMOD model, the input file contains information about pollutant emission sources, location receivers, specifications of meteorological files, and how to retrieve output from the model. In this research, grid receivers are defined in Cartesian coordinates within a 10x10 km2 area, with a grid spacing of 50 m in both the x and y directions, centered on the flare.

Table 3. Characteristics related to the gas flare of Pars South platform 7.

Fluid details	
Fluid	Methane
Operating pressure	1 bar
Operating temperature	30 °C
Operating density	20.24 Mol Wt
Viscosity	0.0124 cPoise
Maximum flowrate	12 kg/h
Differential pressure	500 mm WG
Pipe internal diameter	24.308 mm
Pipe flow velocity	4.43 m/s

Finally, by providing the necessary information for the AERMOD model, the dispersion of SO_2 caused by the flare of the SPD8 gas platform was modeled up to a range of 10 km. This modeling was conducted for the maximum concentrations over 1, 3, and 24-hour periods during the first six months of 2022. It should be noted that the modeling was performed for receivers located on the surface of the earth at a height of 1.5 m above the ground (breathing height).

3. Results and discussion

3.1. Wind rose direction and wind classifications

In Figure 2, the wind rose for the study area is depicted, utilizing meteorological data obtained from the SPD8 gas platform. The figure illustrates that the predominant wind direction at this location was from the northwest to the southeast, with an average speed of 14.6 m/s.

Table 4. Average meteorological data of the first six months of 2022 used in the AERMET model.

Month	Temperature	Humidity Saturation	Cloud Cover	Wind Direction	Wind Speed	Cloudiness
1	22.40	65.47	10.83	172.83	27.15	1.08
2	22.14	60.97	19.41	159.39	17.79	1.94
3	23.05	61.66	11.23	257.28	11.11	1.12
4	28.88	65.61	7.77	255.59	15.71	0.78
5	27.78	63.75	9.87	305.30	15.15	0.99
6	32.27	67.66	3.88	287.85	12.87	0.39
Average	26.10	64.21	10.40	240.68	14.60	1.04

Table 5. Surface parameters around SPD8 gas platform.

Season	Land use	Surface roughness (m)	Bowen's ratio	Albedo coefficient
First half of 2022	Water	0.0001	0.45	0.14

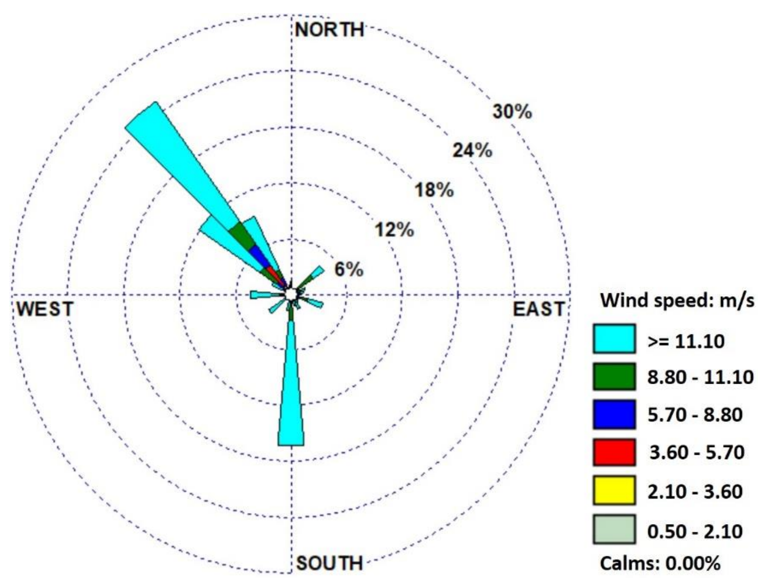

Fig. 2. The wind rose direction based on the meteorological data of the studied gas platform in the first six months of 2022.

Furthermore, Figure 3 displays the frequency distribution of wind layers at the SPD8 gas platform during the initial six months of 2022. The percentages obtained from the data indicated that the average wind speed exceeded 11 m/s on the majority of days during this period (>63%). This finding is significant as it suggests that wind conditions could play a crucial role in the dispersion of gases, including SO_2. When considering the direct influence of wind speed on dispersion modeling, the combustion efficiency was determined to be 94%, correlating with wind speed velocity and the net heating value [20].

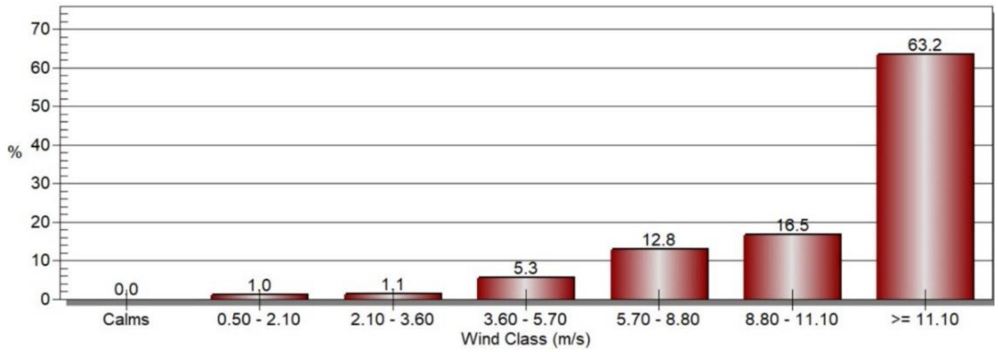

Fig. 3. The frequency distribution of wind layers on the SPD8 gas platform in the first six months of 2022.

3.2. Analysis of SO_2 emission

In this study, the AERMOD model was utilized to simulate the emission of SO_2 caused by the flare of the SPD8 gas platform up to a distance of 10 km. The modeling was conducted to determine the maximum concentrations of SO_2 for durations of 1, 3, and 24 hours during the first six months of 2022. The specific hours for these maximum concentrations were selected based on the standards set by the Environmental Protection Organization of Iran and the United States, allowing for a comparative analysis of the results using a standard table. Figure 4 illustrates the modeling results for the concentration of SO_2 in the vicinity of the South Pars gas platform (SPD8).

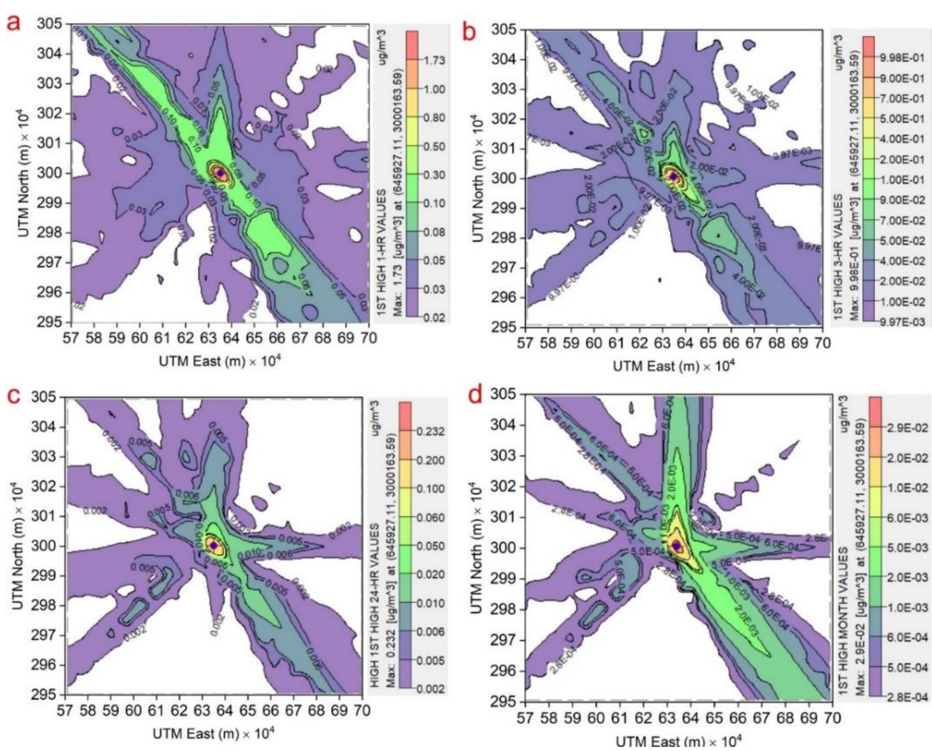

Fig. 4. Modeling results of sulfur dioxide gas concentration in the first six months of 2022 in the environment around SPD8 gas platform: (a) 1-hour maximum concentration, (b) 3-hour maximum concentration, (c) 24-hour maximum concentration, and (d) monthly maximum concentration.

In this particular case, it can be inferred that the prevailing wind direction in the region, which originates from the northwest and extends towards the southeast, resulted in the predominant dispersion of SO_2 pollutants in that specific direction. This emphasizes the significant role played by wind rose as a crucial factor in the propagation and dissemination of these pollutants [6]. Furthermore, upon careful examination of the output results obtained from the model, it becomes evident that the highest concentration of sulfur dioxide emissions was recorded during a one-hour time frame, reaching a value of 1.73 µg/m3. This concentration was measured at geographical coordinates represented by longitude 645927.11 and latitude 3000163.59, indicating its proximity to the flare location. These findings align with previous studies conducted by Bigharaz, et al. [10] and Eslamidoost, et al. [21], where it was observed that the maximum extent of pollutant dispersion occurred within the initial hour following the release, followed by a subsequent reduction in the rate of pollutant release over time. Within the scope of this study, it was observed that the maximum concentrations recorded over durations of 3 hours, 24 hours, and monthly intervals were all lower when compared to the 1-hour concentration; they also fell below the average concentrations stipulated by the Environmental Protection Organization of Iran and the United States. Specifically, the highest concentration documented during the 1-hour assessment (1.73 µg/m3) was observed at 5:00 a.m. on March 24, 2022. The peak concentration within the 3-hour average (0.998 µg/m3) was registered at 9:00 a.m. on March 17, 2022, while the maximum concentration within the 24-hour average (0.232 µg/m3) was observed at midnight on March 17, 2022.

Moreover, based on the outcomes derived from the modeling process, as illustrated in Figure 5, it can be ascertained that within a 1-hour time frame and in the direction towards the wind rose region, the pollutant dispersion extended up to a maximum distance of 4.5 km from the flare base, beyond which the pollutant concentration reached negligible levels. Within a 3-hour time frame, the dispersion expanded up to 5 km in the wind rose direction. Subsequently, no significant alterations in the pollutant's spread towards the wind rose region were observed within the 24 hours following the pollutant release. These observations corroborate the notion that the majority of SO_2 gas dispersion occurred predominantly within the initial hour after its release [22].

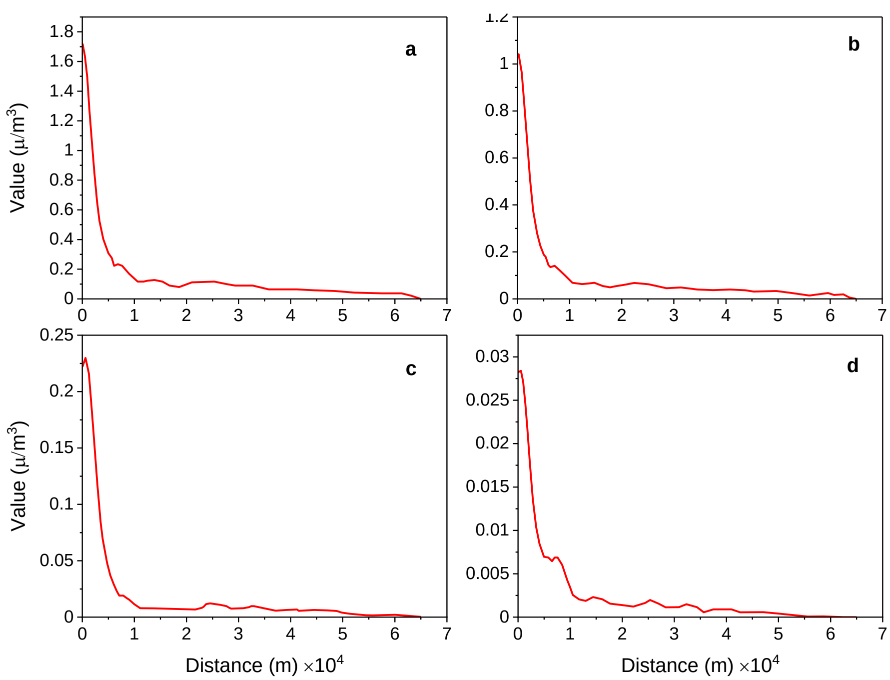

Fig. 5. Dispersion radius of SO_2 pollutant from the flare in the direction of wind rose region: (a) 1-hour timeframe, (b) 3-hour timeframe, (c) 24-hour time frame, and (d) monthly maximum concentration.

3.3. Validation of the model

In order to validate the model, six random sampling points were selected in the vicinity of the SPD8 flare, and the concentration of SO_2 pollutants was measured using an Aeroqual device manufactured in Germany, which has a detection limit of 0.01 μg/m3. The concentrations obtained from the field measurements were compared with the modeling results. It should be noted that the measured results of the control points were in parts per million (PPM), which were converted to μg/m3 using the molecular weight of the desired pollutant. Then, SPPS version 16 software was utilized to assess the correlation coefficient between the field results and the model. The results of Spearman's correlation analysis, based on the predicted values from the model and the measured values, indicated a correlation coefficient of 0.943 at a confidence level of 99%. This demonstrated the high capability of the AERMOD software in predicting the quantity and method of SO_2 gas emission [15, 23]. The aforementioned results are presented in Figure 6 and Table 6. Table 7 presents the concentration standards for SO_2.

Table 6. Comparison of predicted and measured values of SO_2 gas in SPD8 platform.

Control station number	Location[1]		Predicted value[2]	Measured value[2]
	X (m)	Y (m)		
1	646609.79	2999261.34	1.32	1.11
2	649045.04	2996976.35	0.64	0.68
3	643443.7	2998605.84	0.41	0.43
4	648162.41	3001270.72	0.63	0.59
5	642401.34	3004410.9	0.43	0.39
6	650020.56	3000976.13	0.27	0.30

[1]Height above the ground, 1.5 meters, [2,] μg/m^3

Table 7. SO_2 concentration based on the standard of the Environmental Protection Organization

SO_x standard.	Unit	1 h	3 h	24 h	Ref.
Iran's Department of Environment	μg/m^3	----	----	365	[24]
	μg/m^3	----	1300	260	[24]
OSHA*	μg/m^3	----	----	7000	[25]
US EPA	μg/m^3	75**	***500	----	[26, 27]

Occupational Safety and Health Administration (*), The Clean Air Act establishes two categories of national ambient air quality standards. The first category, known as the primary standards (**), aims to safeguard public health by providing protection for "sensitive" populations, such as individuals with asthma, children, and the elderly. The second category, known as the secondary standards (***), aims to protect public welfare by addressing concerns such as reduced visibility and the potential harm to animals, crops, vegetation, and buildings.

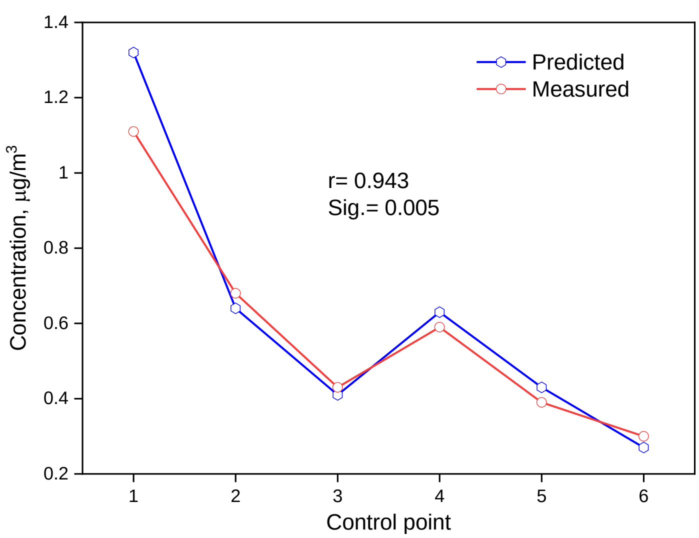

Fig. 6. Comparing the correlation coefficient of predicted and measured values of SO_2 gas in SPD8 platform.

3.4. *Comparison* of the obtained results with similar studies

The comparison of SO_2 emissions from gas flares with various characteristics is indicated in Table 8. The SO_2 emissions in this study were 1.03 to 5625.5 times lower than the lowest and highest values that were reported in previous studies. The notable variations observed could be attributed to the rise in average wind speed, leading to a decrease in the emission of SO_2 from acid gas flares. It is important to highlight that wind speed plays a significant role in combustion efficiency by diminishing the duration of pollutants held in the combustion zone [28, 29]. Additionally, the decrease in wind speed and the amount of SO_2 gas transferred to the flares, particularly during cold seasons, resulted in higher levels of SO_2 concentration [15]. The height of the flare also directly influences SO_2 emissions in unstable conditions and controls them at close distances (250 m). However, SO_2 concentrations can rapidly increase at further distances and under unstable atmospheric conditions [30].

Table 8. Comparison of SO_2 emission from gas flares.

Industry	Location	Source Height, m	Concentration, μg/m^3	References
Gas and Petrochemical	Iran	25	9732.11	[31]
Gas refinery	Iran	-	215	[15]
Thermal power	Iran	205	0.019	[32]
Oil and Gas Processing	Iran	-	1.78	[33]
Oil and Gas Processing	Iran	36.35	8509.42	[22]
Oil and gas	Nigeria	6.1	116.51	[34]
Oil and gas	Nigeria	7.53	6.41	[34]
Oil and gas	Nigeria	-	232	[35]
Oil and gas	Iran	93	1.73	This study

4. Conclusions

The Persian Gulf plays a key role in the global energy supply. This feature has led to the intense development of oil-related industries in this region, creating risks for these unique ecosystems in recent decades. Flares are one of the most important threats to these ecosystems, significantly affecting them by creating air pollution. Considering the subject's importance and the lack of available information regarding the role of flares in ecosystem pollution and their effects on human health, this study investigated the modeling of SO_2 gas emissions from the offshore flare located in the South Pars gas platform (SPD8) using AERMOD software. The obtained values were compared with the standards of the Environmental Protection Organization of Iran and the United States. Additionally, the results of the modeling of SO_2 pollutant gas within a 10 km radius of the flare during the first six months of 2022 using the SPD8 gas platform monitoring system revealed that the maximum concentration of SO_2 pollutant emissions in a 1-hour period was 1.73 μg/m3, occurring in the vicinity of the flare. The AERMOD modeling also confirmed the significant role of wind rose in the emission of SO_2 polluting gas. The pollution spread up to 4.5 km from the emission center in the northwest to east direction during the first hour of SO_2 emission; after that, the pollutant concentration reached zero. Notably, the amount of pollutant emission from the flare during the investigated period was very small compared to the standards set by the Iranian and American environmental organizations. From the perspective of SO_2 pollution, the activity of the mentioned flare posed no danger to the workers, residents, and ecosystems of the Persian Gulf. The validation of the model through comparison with field results also indicated the high usefulness of the obtained model (r = 0.943, Sig. = 99%). The results of this study provide a framework for reducing air pollution from flares in the South Pars region and mitigating their destructive effects on ecosystems.

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