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Evaluation and modeling of radiation and noise pollution in the north of the Persian Gulf (Case study: South Pars gas platforms)

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ABSTRACT

Gas flaring in the petrochemical industries is an important issue due to the significant economic value of the emitted gases and the detrimental effects on the environment and workers' health through gas combustion. Iran has the second largest gas reservoir in the world, with an extensive facility for gas exploitation in the Persian Gulf, indicating its significant role in the environmental conditions of the Persian Gulf. Therefore, this investigation, for the first time, endeavored to evaluate the design of offshore flares and model the amount of produced radiation and noise in the South Pars gas platforms using Flaresim software. The field data were obtained from Phase 7 of the South Pars platform. The results indicated that the amount of radiation from the flare flame in the surrounding area and the receptor points was less than the American Petroleum Institute (API) standard 521 regarding the stack length of 305 ft. The estimated values were 286 (0.9021 kW/m^2) and 283.9 btu/h/ft^2 (0.8955 kW/m^2) in the base-flare and helideck areas, respectively. Moreover, the noise level in the receptors was less than the standard of the Occupational Health Organization of Iran. The current investigation can provide a practical framework to assess the compatibility of flare systems with environmental standards towards achieving sustainable development.

1. Introduction

The Persian Gulf is a unique model of a geopolitical region, including diverse national regions that are coordinated and homogenized in terms of political, strategic, and economic issues. It is recognized as a major global energy supplier due to its tremendous oil and gas platforms, which leads to severe environmental problems [1]. According to the Iran Petroleum Ministry, Iran's proven natural gas reserves are about 1,201 trillion cubic feet (34.0 trillion cubic meters) or about 17.8% of the world's total reserves, of which 33% are as associated gas and 67% are in non-associated gas fields. It has the world's second-largest reserves after Russia [2]. Hence, Iran is

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known as an international gas giant, and at current rates, it has a reserves-to-production ratio of just under 130 years. South Pars gas field is the biggest explored gas reservoir in Iran so far, which possesses 60% of the total of Iran's gas production, located in the northern part of the Persian Gulf. Iran has brought online several phases of the offshore South Pars natural gas field since 2014 and continues to develop natural gas fields. These activities have presented enormous environmental risks to the Persian Gulf ecosystem. Therefore, it is necessary to evaluate and adopt management strategies to overcome these problems. Gas flaring is an alternative approach for releasing non-extractable energy during petroleum exploitation and burning [3]. According to the world bank report, billions of cubic meters of natural gas are flared annually from oil production sites [4]. Gas flaring induces adverse effects on human health and the environment due to greenhouse gases (GHG) accompanied by toxic components, including benzene, toluene, sulfur dioxide, and dioxins [5,6]. Notably, more than 350 million tons of CO_2 are emitted every year, intensifying global warming and climate change [7]. Acid rain, corrosion of buildings, depletion of the ozone layer, an increase in solar UV radiation, skin cancer, DNA damage, and lung disease are other severe harmful impacts of gas flaring [8,9]. Another considerable public concern associated with gas flaring is noise pollution, leading to stress, sleep disturbance, hearing loss, and hypertension [7,10]. Given this, to meet the strict environmental regulations, optimizing energy consumption and reducing pollutants are the focus of different industries, especially in the oil, gas, and refinery industries. Furthermore, various methods are applied for the initial design of flares or the modification of existing units [11-13]. Although different methods and equipment are proposed to control emitted gases, flares are appropriate tools for the safe disposal of combustion gases into the environment [14,15]. They safely burn excess hydrocarbon gases using pilot flames to provide the ignition source. Flare systems are employed in oil facilities such as upstream oil industries, refineries, and petrochemical industries, as well as in chemical units, to maintain the safety of personnel and equipment on-site [16]. The flare system generally burns incoming gases in three different modes of operation: (1) normal operating conditions of the units, (2) turbulence conditions that occur while the unit is running and stopped completely, which produce a higher volume of gases, and (3) emergencies because of a technical failure or power outage, resulting in inadvertent gas accumulation [17,18]. In the two former conditions, if the adjustment of the fuel-to-air ratio in the aforementioned operational conditions is inappropriate, it can create black and smoky flames, releasing a massive amount of hydrocarbon compounds into the atmosphere [19-21]. Given this, the significant impacts of radiation, air, and noise pollution should be monitored in the flare design. Although numerous investigations have been conducted on the flaring phenomenon regarding the effects of air pollution on human health [22-24], the negative impacts associated with flaring, including radiation and noise pollution, have been less analyzed. To cover these knowledge gaps, the current investigation was carried out as a fundament for forthcoming studies, and the precise appraisal of produced radiation and noise by gas flaring was considered. In this regard, the field data of South Pars platforms was collected, and modeling was performed.

2. Material and methods

2.1. Data collection

The required process information and specifications of the inlet gases to the flare were extracted from the official documents of the offshore platforms of the Pars Oil and Gas Company, Bushehr, Iran (Table 1). The applied data in the current study was obtained from the real data of the Phase 7 gas platform, which is entitled SPD8. It includes information about the composition and chemical characteristics of the gases, their pressure and temperature, the height of the designed flare on the platform, and the distances of the desired receptors with the flare. Also, meteorological information, such as temperature, air humidity, wind direction, and wind speed, was obtained from the embedded meteorological equipment in the gas platform (Table 2).

2.2. Radiation and noise pollution modeling

The gas flare system was modeled, and the amount of radiation and noise pollution was estimated by Flaresim 5.2.1 software. This software is proposed by the US EPA for simulation and modeling of radiation, noise, and gas emission from flare systems; it is the most authentic software for this purpose. In fact, Flaresim software models the thermal radiation and noise footprints of flared fluids for offshore and onshore platforms, gas plants, refineries, and chemical plants, as well as predicting the temperature of exposed surfaces. Furthermore, gas dispersion calculations are available to model the flammability and toxicity of combustion products and unburnt flared fluids using a range of algorithms. According to the American Petroleum Institute Recommended Practices (API RP) 521, flare stack calculation includes thermal radiation, surface temperature, and noise models. Permissible design levels of radiation for personnel are shown in Table 3. Moreover, the solar thermal radiation intensity is 0.4~1.04 kW/m^2 and the thermal radiation intensity is 4.73 kW/m^2 in emergency conditions [25].

Table 1. Sour gas compounds of the flare based on the 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

Table 2. Characteristics of inlet gas, flare specifications of South Pars platform (Phase 7) and required meteorological data.

Molecular Weight	Lower Heating Value (LHV)	The ratio of special values cp/cv	Lower Explosive Limit (LEL)
34.1	34104 Btu/lb	1.1	2 %

Flare Tip Height	Flare diameter	Inlet gas flow	Steam Temperature	Bridge length
305 Feet	24 inches	90000 lb/hr	300 F	300 Feet

Solar Radiation	Wind Direction	Wind Speed	Humidity	Temperature
Ignored	90 (East)	20 m/s	76%	95 F

2.3. Surface temperature measurement

The temperature of the metal surfaces exposed to the thermal radiation at the equilibrium condition was calculated from a heat balance between the thermal radiation from the flame at a certain point and the heat losses from the same point (Eq. 1) [26].

$$\alpha K = (h_c + h_f) \times (T_m - T_\infty) \quad (1)$$

where K and α are the thermal radiation at the receptor (W/m^2) and metal surface absorptivity (α=0.7), respectively. h_c is the convective heat transfer coefficient, which is estimated from a series of empirical correlations as a function of air velocity. The heat balance equation (Eq. 2) assumes that heat losses occur only from the surface exposed to thermal radiation. Given this, the radiative heat transfer coefficient is calculated by the following equation:

$$h_f = \sigma E \frac{(T^4{}_m - T^4{}_\infty)}{(T_m - T_\infty)} \quad (2)$$

where E is the metal surface emissivity (E=0.7), σ is the Stephan Boltzmann constant equal to 5.67×10-8 W/m^2·K^4, and u_∞, T_m, and T_∞ are the wind velocity (m/s), the metal surface temperature (K), and the atmospheric temperature (K), respectively.

Table 3. Recommended design thermal radiation for personnel.

Permissible design level (kW/m^2)	Conditions
1.58	Maximum radiant heat intensity at any location where personnel with appropriate clothing can be continuously exposed.
4.73	Maximum radiant heat intensity in areas where emergency actions lasting 2 to 3 min can be required by personnel without shielding but with appropriate clothing.
6.31	Maximum radiant heat intensity in areas where emergency actions lasting up to 30s can be required by personnel without shielding but with appropriate clothing
9.46	Maximum radiant heat intensity at any location where urgent emergency action the personnel is required reach to. When personnel enter or work in an area with the potential radiant heat intensity is greater than 6.31 kW/m^2, then radiation shielding and/or special protective apparel (e.g., a fire approach suit) should be considered. SAFETY PRECAUTION-It is important to recognize that personnel with appropriate cloth cannot tolerate thermal radiation at6.31 kW/m^2 for more than a few seconds.

2.4. Thermal radiation intensity

To determine the flame radiation for the desired point, the flame with a single radiant epicenter was considered, and the experimental equation by Hajek and Ludwig [27] was employed as follows.

$$D=\sqrt{\frac{\tau FQ}{4\pi K}} \quad (3)$$

where *D* is a minimum distance from the epicenter of the flame to the object being considered and τ is the fraction of radiation heat transmitted through the atmosphere.

2.5. Noise pollution

Flare noise is mainly composed of combustion noise and nozzle noise [28]. Different frequencies constitute the noise, and each frequency noise contributes to the average value depending on whether the noise source is a flare combustion or sonic flare nozzle. The noise spectrum is usually caused by 63 Hz~8000 Hz, indicated by a sound power level and sound pressure level:

$$PWL = 10\log\left[\frac{W}{W_0}\right] \quad (4)$$

$$SPL = 10\log\left[\frac{P}{P_0}\right]^2 \quad (5)$$

where *PWL* and *SPL* are sound power level (dB) and sound pressure level (dB), respectively, W_0 is the reference value (W_0=10^{-12}), and P_0 is the reference value (P0=2×10^{-6} Pa). When the flare device is positioned in the surrounding empty environment, the sound pressure level and sound power levels of noise are as follows:

$$SPL = PWL - 20\log D - 0.49 - SPL_A \quad (6)$$

where *D* is the minimum distance from the flare midpoint to the receptor (m) and SPL_A is the attenuation of the sound pressure level of noise in the atmosphere (dB). The attenuation is a function of the noise frequency, with higher frequencies being more readily attenuated than lower ones. Moreover, *PWL* and *SPL* are associated with the noise of the vent pipe nozzle and the combustion noise, respectively. The API 615 sound control of mechanical equipment for refinery service and 29 CFR 1910 Occupational Safety & Health Standard (Table 4) were used to evaluate the noise pollution [29].

Table 4. The permissible worker noise level.

Permissible Exposure	Level, dB
12 hours per day	88
8 hours per day	90
Less than 8 hours per day	94
45 minutes per day*	100
Control room, office, and lab.	60
Service area	65
Public area	55
Communication room, bedroom, clinic, etc.	45

**Only in special conditions, 45 minutes per day criteria shall be applied.*

3. Results and discussion

Modeling and designing of the gas flaring in the South Pars platform (phase 7) were performed using meteorological data and the characteristics of gas components, which were attained from the distributed control system (DCS). It should be pointed out that the wind direction was towards the check point, and the wind speed was calculated as 20 m/s (Table 2). Generally, by increasing the wind speed, the potential of gas dispersion would be enhanced, resulting in low environmental impacts on the platforms. In the study area, due to the low wind speed, the effect of radiation at each point on the platform seems to be high. Therefore, a detailed analysis was necessary to reveal more information [29].

3.1. Radiation analysis

The radiation modeling was carried out by the application of the SPD8 data. The results are presented in Tables 5 and 6 for 305 ft and 200 ft flare lengths, respectively. As shown in the tables, the received radiation was reduced by increasing the distance from the platform. The highest received radiation was obtained at the point of -55.56 and 55.56, which were 281.9 and 263 btu/h/ft^2 for the flare length 305 ft and 564.5 and 493.5 btu/h/ft^2 for the flare length 200 ft, respectively. In addition, Figure 1a shows that the estimated data was less than the minimum amount of sterile area due to the high length of the designed flare (305 ft). So, the Flaresim software could not draw the relevant plot. Therefore, the radiation was monitored at a length of 200 ft to make the results easy to understand. In the 200 ft height (Figure 1b), a border was drawn but fell in a safe section of the zone (up to 440 btu/h/ft^2). Xuejiang, et al. [29] declared that the distribution of radiation intensity in an assessment point with v=2.5 m/s, ambient temperature =35.4 °C, solar Radiation= 0.700 kW/m^2, and tip length=12 m was equal to 0.790 kW/m^2. The obtained result was lower than that of the current investigation (0.8955 kW/m^2) because of the difference in flare engineering characteristics. Zhi, et al. [30] designed high-pressure and low-pressure flare systems via the Flaresim software for a large-scale offshore platform. They attained the radiation limit of 6.31 kW/m^2 by the application of a sonic tip. They recommended the 45° inclined stack form horizontal based on safety concerns. However, not only flare height but also wind speed [30], flare type and tailoring, and the pressure of output gases and their content [31] are influential parameters in the negative impacts on the surrounding ecosystems and staff's health. It is noteworthy to mention that in the sonic flare type, like the one used in the current investigation, the resultant flame was shorter, less prone to wind deflection, and emitted a low level of radiation compared with the conventional pipe flare [30]. The obtained results showed that the amount of radiation in the study area and receptors were less than the standard of API 521 [26], regarding the height of 305 ft of the flare type, which was 286 btu/h/ft^2 (0.9021 kW/m^2) in the base-flare and 283.9 btu/h/ft^2 (0.8955 kW/m^2) in the helideck. Based on the prevailing conditions, the flare's radiation did not have any acute impact on the workers' health, but preventive actions could be advised for long time exposure to guarantee safety in the workplace.

Table 5. Radiation assessment at a flare length of 305 ft.

btu/h/ft^2	-500.0	-388.9	-277.8	-166.7	-55.56	55.56	166.7	277.8	388.9	500.0
500.0	59.73	70.65	81.46	90.01	93.86	91.67	84.22	73.80	62.74	52.53
388.9	71.95	88.41	106.0	121.0	128.0	124.0	110.7	93.39	76.37	61.76
277.8	84.99	109.0	137.0	163.0	176.1	168.5	144.9	116.6	91.22	71.12
166.7	96.67	128.9	170.1	212.2	234.9	221.6	182.5	139.8	104.8	79.12
55.56	103.8	141.9	193.5	249.8	281.9	263.0	209.8	155.2	113.2	83.83
-55.56	103.8	141.9	193.5	249.8	281.9	263.0	209.8	155.2	113.2	83.83
-166.7	96.67	128.9	170.1	212.2	234.9	221.6	182.5	139.8	104.8	79.12
-277.8	84.99	109.0	137.0	163.0	176.1	168.5	144.9	116.6	91.22	71.12
-388.9	71.95	88.41	106.0	121.0	128.0	124.0	110.7	93.39	76.37	61.76
-500.0	59.73	70.65	81.46	90.01	93.86	91.67	84.22	73.80	62.74	52.53

Table 6. Radiation assessment at a flare length of 200 ft.

btu/h/ft^2	-500.0	-388.9	-277.8	-166.7	-55.56	55.56	166.7	277.8	388.9	500.0
500.0	66.82	80.79	95.23	107.1	112.6	109.5	99.02	84.93	70.61	57.94
388.9	82.49	104.9	130.6	154.1	165.7	159.0	137.8	112.0	88.35	69.36
277.8	100.1	135.1	181.0	229.4	256.2	240.5	195.2	147.1	108.8	81.40
166.7	116.7	167.2	243.6	340.4	402.9	365.4	270.1	185.9	128.8	92.05
55.56	127.2	189.7	294.7	449.0	564.5	493.5	334.2	214.2	141.7	98.50
-55.56	127.2	189.7	294.7	449.0	564.5	493.5	334.2	214.2	141.7	98.50
-166.7	116.7	167.2	243.6	340.4	402.9	365.4	270.1	185.9	128.8	92.05
-277.8	100.1	135.1	181.0	229.4	256.2	240.5	195.2	147.1	108.8	81.40
-388.9	82.49	104.9	130.6	154.1	165.7	159.0	137.8	112.0	88.35	69.36
-500.0	66.82	80.79	95.23	107.1	112.6	109.5	99.02	84.93	70.61	57.94

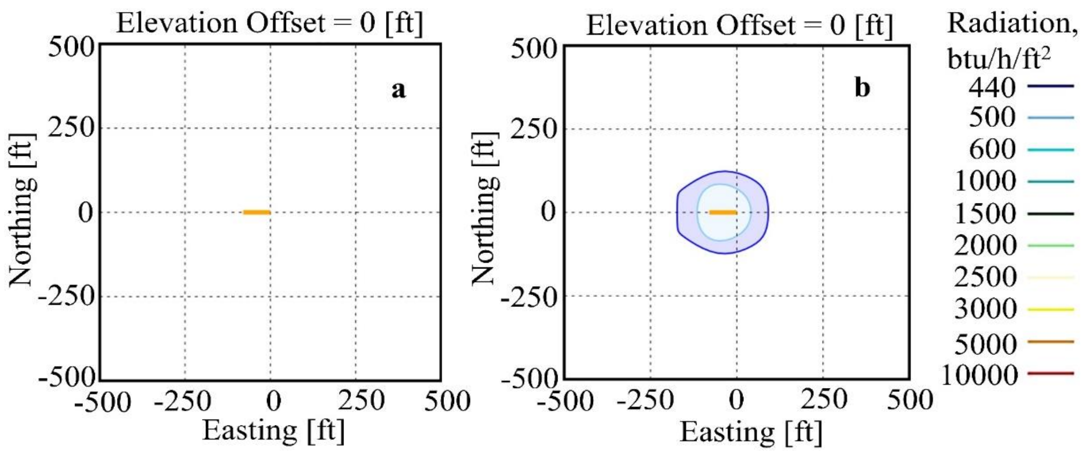

Fig. 1. Radiation from the gas flaring at a height of 305 ft (a) and 200 ft (b).

3.2. Noise analysis

The modeling of noise pollution was also conducted for this platform, and the results are described in the following. It should be pointed out that the flare with the height of 200 ft was analyzed because the obtained value associated with the flare with the height of 305 ft was significantly lower than the API standard. The results are shown in Tables 7 and 8 and Figures. 2 and 3. As shown in Table 7, the change in the values for noise pollution was in close agreement with the radiation values, and similar trends were observed. It means that the received noise decreased by increasing the distance from the platform. The maximum noise pollution was detected at the point of ±55.56 as 95.73 dB. In addition, Figure 2 showed that the estimated data was less than the minimum amount of sterile area (~80 dB) due to the appropriate high length of the designed flare (200 ft). So, the Flaresim software only showed the direction of flame from the south to the north based on the wind rose in the study area. Therefore, receiving noise pollution in the south part of the flare platform was significantly lower than in the opposite direction. The sterile area in Figure 2 shows that the noise level at 10 points was in agreement with international standards (<85 dB) [7]. However, based on the AP1615 and Iranian occupational health standards, the amount of noise in the receptors was less than 85 dB, which is categorized as a non-hazardous level. The amount of received noise at each point of the sterile area is presented in Table 8 and Fig. 3. The values of noise pollution in the frequency range from 31.25-16,000 Hz are disclosed in Table 8. As obviously perceivable, only at the points of 2000 and 4000 Hz did the noise pollution slightly exceed the API standard. This matter can easily be seen in Figure 3.

Table 7. Analysis of noise pollution at a flare length of 200 ft.

dB	-500.0	-388.9	-277.8	-166.7	-55.56	55.56	166.7	277.8	388.9	500.0
500.0	87.63	88.47	89.21	89.78	90.10	90.10	89.78	89.21	88.47	87.63
388.9	88.47	89.49	90.44	91.20	91.63	91.63	91.20	90.44	89.49	88.47
277.8	89.21	90.44	91.63	92.64	93.24	93.24	92.64	91.63	90.44	89.21
166.7	89.78	91.20	92.64	93.94	94.75	94.75	93.94	92.64	91.20	89.78
55.56	90.10	91.63	93.24	94.75	95.73	95.73	94.75	93.24	91.63	90.10
-55.56	90.10	91.63	93.24	94.75	95.73	95.73	94.75	93.24	91.63	90.10
-166.7	89.78	91.20	92.64	93.94	94.75	94.75	93.94	92.64	91.20	89.78
-277.8	89.21	90.44	91.63	92.64	93.24	93.24	92.64	91.63	90.44	89.21
-388.9	88.47	89.49	90.44	91.20	91.63	91.63	91.20	90.44	89.49	88.47
-500.0	87.63	88.47	89.21	89.78	90.10	90.10	89.78	89.21	88.47	87.63

Table 8. Noise pollution in the base-flare and helideck.

	Base-flare		Helideck	
Frequency (Hz)	Standard (dB)	Noise value (dB)	Standard (dB)	Noise value (dB)
31.25	62.48	23.08	62.46	23.06
62.50	68.09	41.89	68.05	41.85
125.0	75.97	59.87	75.93	59.83
250.0	84.37	75.77	84.33	75.73
500.0	92.86	89.66	92.82	89.62
1000	90.06	90.06	90.02	90.02
2000	86.74	87.94	86.70	**87.90**
4000	82.74	83.74	82.69	**83.69**
8000	77.39	76.29	77.33	76.23
16000	67.74	61.14	67.68	61.08

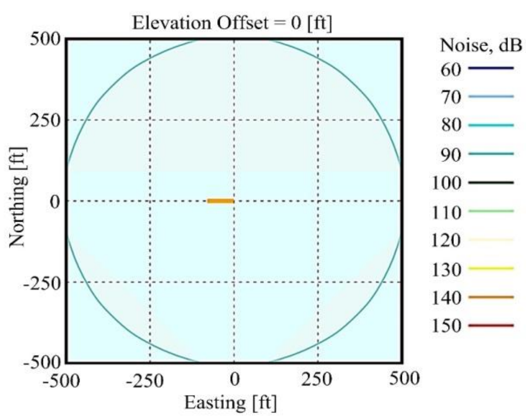

Fig. 2. The visualization of noise detection in the sterile area (±500 ft).

However, the average sound levels in the base flare and helideck receptors were 86.1 dB and 85.97 dB, respectively. According to the "Safety Rules for Offshore Fixed Platforms," the noise value for open spaces should not exceed 115 dB(A). Xuejiang, et al. [29] achieved the value of 131.9 dB for their vent pipe outlet's noise, exceeding 115 dB. It was dramatically higher than the present investigation. Although the obtained values in the current study were within the permissible standards and less than 88 dB (Table 4), the use of ear protection equipment is recommended for employees [32]. Therefore, in places where the noise value exceeds the permissible values, the installation of a sound barrier can be beneficial in controlling the noise [29].

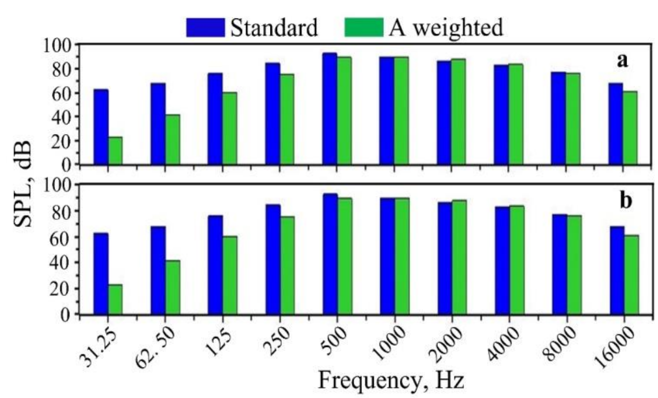

Fig. 3. Noise pollution in the base-flare (a) and helideck (b).

3.3. Comparison of the obtained results with similar studies

The results of the current study were compared with the relevant literature concerning radiation and noise pollution. As can be perceived from Table

9, the obtained results in the present study for the noise and radiation were compatible with the standards, but some protective measures are required to guarantee the safety of the employees in the study area. In some cases, the addressed data was higher than the current one, which was the majority due to the difference in the applied flaring system, type of tips used, and the volume of output burned gas. Moreover, the tip length was impressive in the radiation and noise values, which decreased when the tip length was enhanced. However, equipment installation and maintenance become difficult with the longer tip length, which upgrades the investment costs.

Table 9. Comparison of radiation and noise pollution produced by the gas flaring system.

Num.	Purpose of the article	Recipient position	Noise dB	Radiation kW/m^2	References
1	Evaluation and modeling of radiation and noise pollution in the north of Persian Gulf (Case study: South Pars gas platforms)	Helideck	85.9	0.8955	This study
2	Thermal Radiation and Noise Safety Assessment of an Offshore Platform Vent Pipe	Helideck	85.7	0.790	[29]
3	Thermal Radiation and Noise Safety Assessment of an Offshore Platform Flare Stack as Sudden Emergency Relief Takes Place	Helideck	67.1	0.1082	[26]
4	Thermal radiation assessment of flaring gas in floating LNG bunkering terminal	Helideck	---	0.896	[33]
5	Study and application of production relief and blowdown on the large-scale offshore oil and gas fields	Platform	---	6.31	[29]

4. Conclusions

The Persian Gulf has a key role in the global energy supply. This characteristic has led to the intense development of oil-related industries and caused some dangers for this unique ecosystem during the last decades. Flares are one of the greatest threats to this ecosystem, dramatically affecting it through radiation, noise, and air pollution. Some studies reported the role of flares on air pollution, but its contribution to radiation emission and noise remains unknown. For the first time, this study assessed the effect of radiation and noise released from the flare system on the Persian Gulf ecosystem. Towards this goal, the modeling and evaluation of radiation and noise pollution in the SPD8 platform located in phase 7 of the Persian Gulf were performed using Flaresim software. The radiation assessment in two different flares length illustrated that the receptors with distances up to ±500 ft to the base flares received less energy than the API standard, which was 286 btu/h/ft^2 (0.9021 kW/m^2) in the base-flare and 283.9 btu/h/ft^2 (0.8955 kW/m^2) in the helideck. Furthermore, the amount of noise in the receptors was less than 85dB, indicating no dangerous potential for the residents and employees. Summing up, the design of the flares in the SPD8 platform was safe from radiation and noise pollution, but the synergistic effect dealing with the numerous available flares in this area should be carefully evaluated to gain deep insight regarding their negative impacts on the Persian Gulf ecosystem. This research demonstrates fundamental results as a framework for further investigations to move towards sustainable development.

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