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RESEARCH ARTICLE

Dispersion of NO_2 and SO_2 pollutants in the rolling industry with AERMOD model: a case study to assess human health risk

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Abstract

Steel and rolling industry are the most important industries polluting the environment. Therefore, aim of this study is to make an emission model for SO_2 and NO_2 pollutants released from the rolling industry of Sepid-Farab Kavir Steel (SKS) complex using the AERMOD model and health risk assessment. Sampling pollutants released from SKS complex was performed in January 2017 at 10 different sites. Distribution of these pollutants was investigated by AERMOD model, domain site of AERMOD was designed for area around the factory with a radius of 30 km, and also SO_2 and NO_2 modeling was performed for both natural gas and liquid fuel. Human health risk assessment was also studied. The results of this study demonstrated the emission of SO_2 and NO_2 from this complex is less than the maximum allowable, when used natural gas as the main fuel. The hourly concentration of SO_2 reached about 324 μg/m^3, which in higher than the standard value for 1 h. Considering the findings, the urban gas is considered as a clean source in terms of furnace air output and the concentration of emitted pollutants. Also, it has no side effects on workers' health.

Keywords AERMOD · Air pollution modeling · Steel complex · Risk assessment

Introduction

In spite of its important role in the development of country's economy, the steel industry is associated with high energy consumption and the production of high amounts of hazardous pollutants, which let to air pollution and concern all over the world [1–4]. NO_x and SO_2 are the most important pollutants from this industry. Investigations in 2013 showed that the emission rates of these two pollutants are 10.5% and 3.3% of total industrial emissions, respectively. Therefore, in terms of emissions, NO_x and SO_2 are in the third category of industrial pollutants[5, 6]. Sulfur dioxide (SO_2) and nitrogen oxides (NO_x) are mainly released from the combustion of fossil fuels in power plants and other industrial facilities [7, 8]. These pollutants cause serious and destructive effects on the environment via climate change, acid rain, and the formation of tropospheric ozone [9, 10]. In addition, exposure to these pollutants is associated with an increased risk of lung cancers [11, 12], and heart and respiratory diseases, so they are considered a serious risk on human health [13–16]. Studies show that more than 2 million premature deaths occurred each year due to air pollution-related diseases that more than half of which are related to the population of developing countries [17]. Therefore, in order to take precautionary measures, establish emission control laws, assess current air pollution sources, and their responsibility in future events it is necessary to predict the concentration of pollutants at different time and place scales [18]. Air pollution modeling is a useful and scientific method which helps researchers to understand the main features of air pollution and the concentration

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of environmental pollutants and their distribution through mathematical algorithms and pre-physicochemical processes [18–20]. Artificial neural network model is one of the most widely used modeling methods [21], HYSPLIT [22], AERMOD, CALINE$_3$, GAM [23],CALPUFF, AirQ [24] and etc. [25–27]. AERMOD is a relatively new model developed by the United States Environmental Protection Agency (EPA) and was introduced by the American Meteorological Association in 2004 [28]. This method belongs to the steady-state Gaussian column models and is able to evaluate and simulate the dispersion of pollutants such as PMs, SO_2, NO_x, VOC, hydrogen cyanide (HCN), sulfur hexafluoride (SF_6) as well as heavy metals such as chromium (VI). Capacity, total gaseous mercury (TGN), and odor-generating compounds are in the range of 50 km [29, 30. Various studies have conducted the usage of AERMOD in modeling the emission of pollutants from industries such as Iran [31–33], Colombia [34] and Thailand [35]. The results of the studies showed much similarities between the results of the model and the real data [36].

Therefore, citing the 20-years vision document of the country based on the development of the steel industry for sustainable development and given the potential negative effects of pollutants from these industries on human health, this study aims to modeling the emission of NO_2 and SO_2 from the rolling industry of SKS complex was performed using the AERMOD model and human health risk assessment.

Materials and methods

Studied area

Aran and Bidgol city is located in the northern of Isfahan province at 51 degrees and 29 min longitude and 34 degrees and 14 min latitude. This city lied on the southwestern edge of the central desert of Iran and has a dry and desert climate with an average annual rainfall of 132.6 mm. Considering wind rose, the eastern direction has the highest frequency and prevailing wind (Fig. 1). The SKS complex with 123 acres has been constructed in 6.7 km from the Aran-Bidgol city at 51 degrees and 30 min east and 34 degrees and 40 min north (Fig. 2) [37].

The operation phase of this complex is a hot rolling unit with capacity 350,000 tons steel rebar, which was operated in 2007. This area has weak and scattered vegetation of hawthorn and saffron species and steppe cover and is in the range from 865 to 895 m above sea level.

Weather information

Concentrations of pollutants in atmosphere are affected by various factors such as wind, temperature, vertical temperature profile, cloud, and humidity. Horizontal movements also influences on transporting pollutants in direction of the prevailing wind [38].

AERMOD meteorological information is entered into two forms of time series data (including wind direction and speed, cloud, temperature, precipitation, etc.) and real-time data. The first batch data is used for long-term applications (Long Term) and the second batch data for short-term applications (Short Term). In this study, 6-years data of Kashan Synoptic Station from 2010 to 2016 were used. Kashan Synoptic Station is located at 27–51 longitude, 33–59 latitude and at 982 m above sea level. The Climatic characteristics and meteorological data of the study area are shown in Table 1.

Data collection

Sampling

Firstly, the monitoring reports of the NOx and Sox, in the vicinity of the factory, which is seasonal in 4 years and had been done by the trusted laboratory of the environmental agency was reviewed. Additionally, sampling pollutants emitted from SKS complex was performed twice in January 2017 from 10 different sites for validation and evaluation of the results of the model's output (Fig. 3). The results obtained from AERMOD modeling were compared and evaluated with the field-measured values from ten receptors.

Scope of this project was one square with a side of 30 km from the center of the factory and the distance between the receivers was given 50 m.

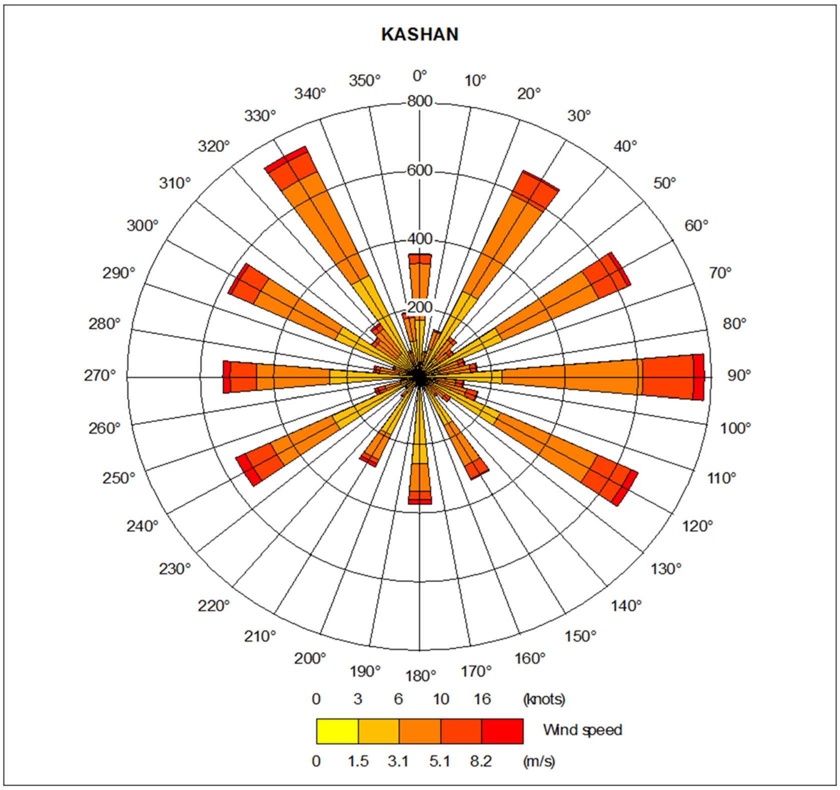
Sampling was done periodically by the trusted laboratory of the environmental agency in the following sections:

- Measurement of furnace flue gases with natural gas fuel
- Measuring the exhaust gases of diesel power generators with diesel fuel
- Measurement of rolling furnace output particles
- Measurement of gases and dusts in ambient air

How to calculate the emission rate of pollutants

There are two methods for estimating emissions from chimneys. First, that is to use the valid AP42 references and the relationships mentioned in them, and second, that is to use the available information on the concentration of pollutants in the chimney. In this study, these both methods were used and then modeling performed based on the highest diffusion rate. The SKS complex is mainly powered by natural gas and uses liquid fuel only in emergencies (on average 7 to 10 days a year). Therefore, depending on the type and amount of fuel consumed, the estimated emission values are different (Tables 2 and 3).

Fig. 1 Wind rose of Kashan Synoptic (1966–2010)



In this study, for SO_2, maximum values of 1 h was only used. For NO_2, it was considered the annual average in terms of natural gas, while it was the maximum values of 1 h for liquid fuel condition.

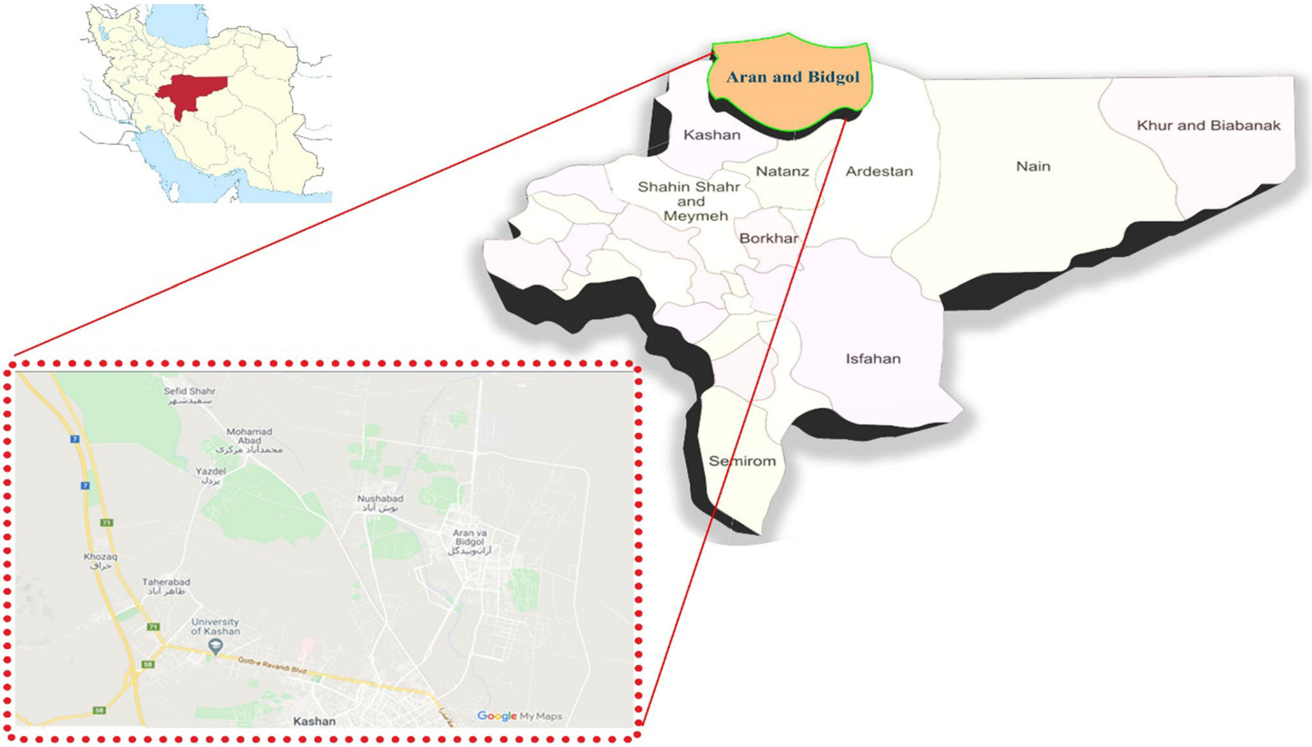


Fig. 2 Location of the steel complex site in relation to the political divisions of Isfahan province and Aran and Bidgol cities

Table 1 Climatic characteristics of the studied area

No	Meteorological parameters	Month	Level
1	Minimum temperature average	January	−1.3
2	Maximum temperature average	July	40.3
3	Maximum monthly rainfall	February	34.5 mm
4	Number of rainy days	12 months	41 days
5	Most sunny hours	August	349.1 h
6	Maximum wind speed	February	20 m/s
7	Wind direction (degree)	–	180 degrees
8	Maximum relative humidity	Dec-Feb	84%
9	Minimum relative humidity	August	10%
10	Annual average of cloudy days		41 (Day)
11	Air pressure from sea level		30.24–30.44 atm

AEPMOD model

AERMOD is applied in computation of pollutant dispersion in rural and urban, flat and complex terrain, leveled and elevated areas, and multiple sources (point, area, and volume) of emissions [39, 40]. AERMAP and AERMET are two preprocessor of AERMOD. AERMAP is used for topographic analysis of the area and AERMET used for analysis of meteorological data [41]. Meteorological data are received by AERMET and then converted to SAMSON format file, which is a recognizable format for this pre-processor. Land surface parameters for AERMET are based on land use type including surface roughness, albedo, and Bowen ratio.

In this study, surface roughness is 0.3, the albedo coefficient is 0.32 and the Bowen ratio is 4.7 (suitable for desert areas with very low vegetation). In this project, modeling the emission and the distribution of pollutants was performed for a 24 average hours. It should be noted that the SKS complex was surrounded by desert and there were no changes in the land use and area properties. Therefore, a circle area (with a radius of 30 km) is considered around of the chimneys. After collecting data to run the AERMAP model, the digital elevation model (90 m accuracy) was used for the receptor network with 2 m height above the ground. Meteorological data was also entered into AERMat. Finally, the model was implemented for a network with a receptor distance of 500 m, receiver with 2 m height (breathing height) and 30 km radius from the chimney. The data obtained from these two preprocessors, after completion and execution, were mainly processed in the AERMOD software version 8.9, and the final simulated output was obtained. After implementing the AERMOD model, its output was transferred to ArcGIS software environment, and according to the sampling environment, the distribution of pollutant concentrations was obtained.

Risk assessment

Considering the seasonal measurements of these two pollutants were performed by a reliable environmental laboratory, same time of modeling, health risk assessment was performed to predict the effects on health over time based on 8 h work per day and a total work time of 30 years for each person. Health risk assessment consisted of 4 stages: diagnosis, exposure assessment, toxicity assessment, and risk assessment [42]. The most key step for risk management among the mentioned stages is to identify risk because the correctly identifying of the risk result in correctly doing the next stages and finally a risk management with a higher guarantee [43, 44]. Health risk assessment in humans using potential health impact assessment methods in the exposed population is based on the rules of the US Environmental Protection Agency (US-EPA), which assesses health risk based on exposure to chemicals and the environment [45]. That also is developing a method that can be used to assess non-carcinogenic risk using the Hazard Quotient (HQ) for soil, air, and water contaminants [46]. Using Eqs. 1 and 2, the Average Daily Dose (ADD) can be calculated in inhaled and dermal exposure, respectively:

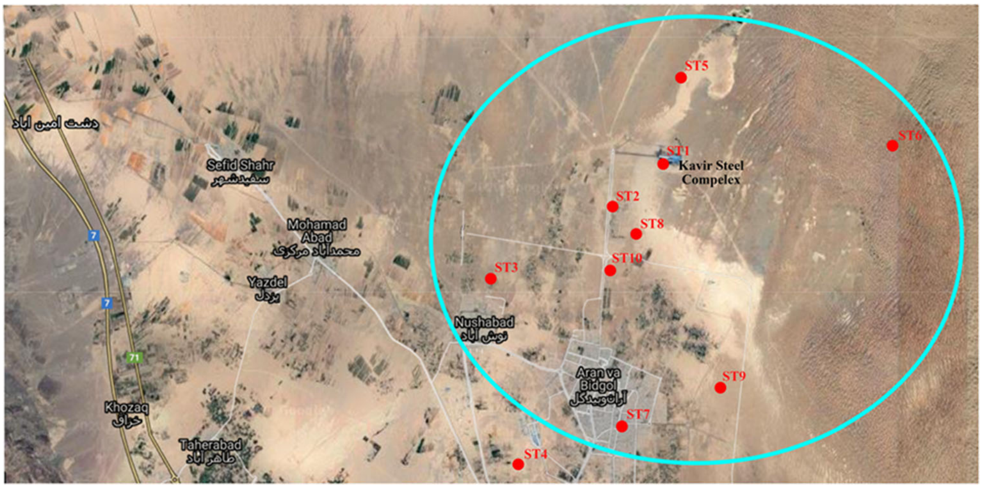


Fig. 3 Location of air sampling stations in the field of environmental studies

Table 2 Fuel consumption in existing phase furnaces and development

The name of the furnace	Dosage	
	Gas (cubic meters per day)	Diesel (liters per day)
Pumini furnace (operation phase)	40,000	30,000

$$CDI = \frac{C \times IR \times EF \times ED}{BW \times AT} \quad (1)$$

Where C, IR, EF, ED, BW and AT represent concentration of the pollutants, respiratory rate of workers, the periodicity of NO_x and SO_x exposure, the total duration of exposure to the two contaminants in question, the weight of individuals, and the average life expectancy of individuals, respectively.

The values of different parameters to calculate CDI in different age groups are shown in Table 4. This study was only performed for adults because this group consists of workers.

Using Eq. 1, the CDI value is calculated, which can be used to obtain HQ according to Eq. 2. In terms of non-carcinogenic risk assessment, HQ is a statistical term that indicates the possibility of a harmful effect of a contaminant on a person's health.

$$HQ = \frac{CDI}{RfD} \quad (2)$$

In this study, the reference dose of RFC for NO_2 and SO_2 was considered as 0.053 and 0.04 mg/kg, respectively, in accordance with the declaration of the maximum allowable concentration by NAAQS. When the HQ value is <1 the contaminant tested at the reported concentrations cannot be expected to pose a potential health hazard and therefore not cause any health concerns. When HQ value >1, it means the contaminant have an additional potential for non-carcinogenic risk and may even be associated with side effects [49].

Results

Results of modelling by AERMOD software

Modeling distribution of SO_2 and NO_2 was made using the AERMOD model according to the operation phase of SKS complex using meteorological information of Kashan Synoptic Station, digital altitude model and information on the emission of pollutants. The results of this study showed the concentration of SO_2 and NO_2 emitted from the operation phase is low, considering the main fuel of this complex is natural gas. This complex is considered as a clean industry in terms of furnace air output and the concentration of pollutants is lower than the allowable limit (Table 5). Only if the gas supplying to the complex is cut off in the cold seasons, liquid fuel (diesel) use approximately 7 to 10 days a year, in which case it is possible to increase the concentration of SO_2 pollutants for 1 h.

Table 3 The amount of emission estimated based on distribution factors

Furnace	Fuel type	Emission Value (gr/s)			
		NO_2	CO	SO_2	PM_{10}
Pomini oven	Gas	0.72	0.61	–	0.05
	Liquid	2.27	0.61	6.7	0.05

According to the sampling, the highest concentrations of SO_2 pollutants are related to the southern parts of the study area because of existence centers and roads population. Also, the highest NO_2 concentration was measured in the southern parts of the study area and around the site at 79 mg/m^3. The analysis of the obtained results shows when using natural fuel, the average annual values and the maximum hourly concentration of NO_2 pollutants are 23 g/m^3 and 68 μg/m^3, respectively. However, the maximum concentration of NO_2 is about 109 μg/m^3 if it uses liquid fuel. Also, the maximum one-hour concentration of SO_2 pollutants is about 324 g/m^3 when consuming liquid fuel, while the concentration of this pollutant is very low when using natural gas fuel. Due to the fact that liquid fuel was used about 1 week a year and, in the study year (2017), and was planned to strengthen the factory gas station and not using liquid fuel in the future, this disproportion is condescending.

The Fig. 4 shows the interval changes associated with nitrogen oxides and sulfur oxides from liquid fuels. As can be seen, the first maximum concentration occurs at a distance of about 250 m, and the second maximum concentration occurs at a distance of about 3 km in the case of roughness adjacent to

Table 4 Value of parameters used in non-carcinogenic risk assessment of inhalation

Parameters	Unit	Symbol	NO_x	SO_x	
Inhalation rate	m^3/d	IR	20	20	[47]
Exposure frequency	Days/Year	EF	335	335	[48]
Exposure duration	Year	ED	30	30	[48]
Body weight	Kg	BW	70	70	[48]
Average time	Days	AT	10,050	10,050	[48]

Table 5 Results of air sampling (January 2017)

Point	Contaminant concentration (μg/m3)							
	NO_2				SO_2			
	Measured value		Standard value: Maximum 1 h	Standard value: yearly	Measured value		Standard value: Maximum 1 h	Standard value: yearly
	Stage 1	Stage 2			Stage 1	Stage 2		
Point 1	75	72	200	100	27	28	196	150
Point 2	43	44			0	0		
Point 3	60	68			27	27		
Point 4	39	38			0	0		
Point 5	39	38			0	0		
Point 6	37	38			0	0		
Point 7	79	76			108	106		
Point 8	35	36			0	0		
Point 9	25	28			0	0		
Point 10	56	60			81	82		

the plant (Fig. 4). These are located in the east of the steel complex and it is 200 to 250 m higher than the site area.

The results of this study showed the maximum hourly concentration of Sox is estimated at a maximum of 40 μg/m^3 when using liquid fuel in residential areas, which is lower than the allowable limit (196 μg/m^3). Also, the results of the study of cumulative effects according to the sampling performed in the region and the prepared layers indicate that for nitrogen oxide pollutants, the maximum background concentration assumed in the region is about 79 μg/m^3. Addition of the value estimated by the model under liquid fuel conditions reaches a maximum of 188 μg/m^3 (cumulative concentration), which is less than the standard maximum hourly and annual values (100 μg/m^3, 200 μg/m^3). This result obviously can be inferred for the conditions used of gaseous fuel because in those conditions the values of cumulative concentration are less than in the case of using liquid fuel. For sulfur oxide pollutants, the background concentration in the range, where the maximum concentration from the modeling prediction occurs is about 25 μg/m^3. That is assuming the addition of the estimated value by the model in liquid fuel conditions, the maximum reaches 350 μg/m^3 (cumulative concentration), which violates the maximum values of 1 h (196 μg/m^3) Fig. 5.

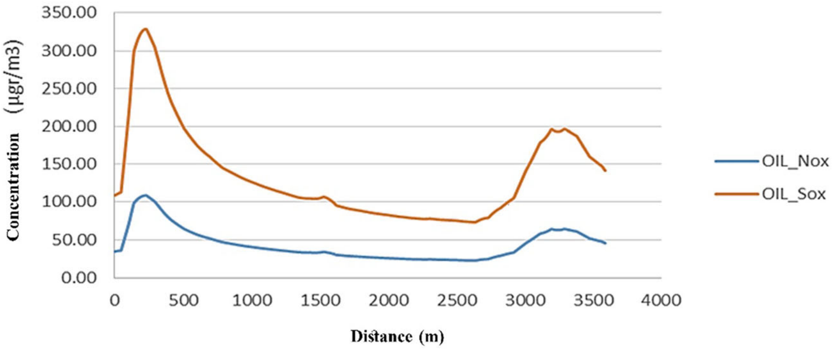
Risk assessment

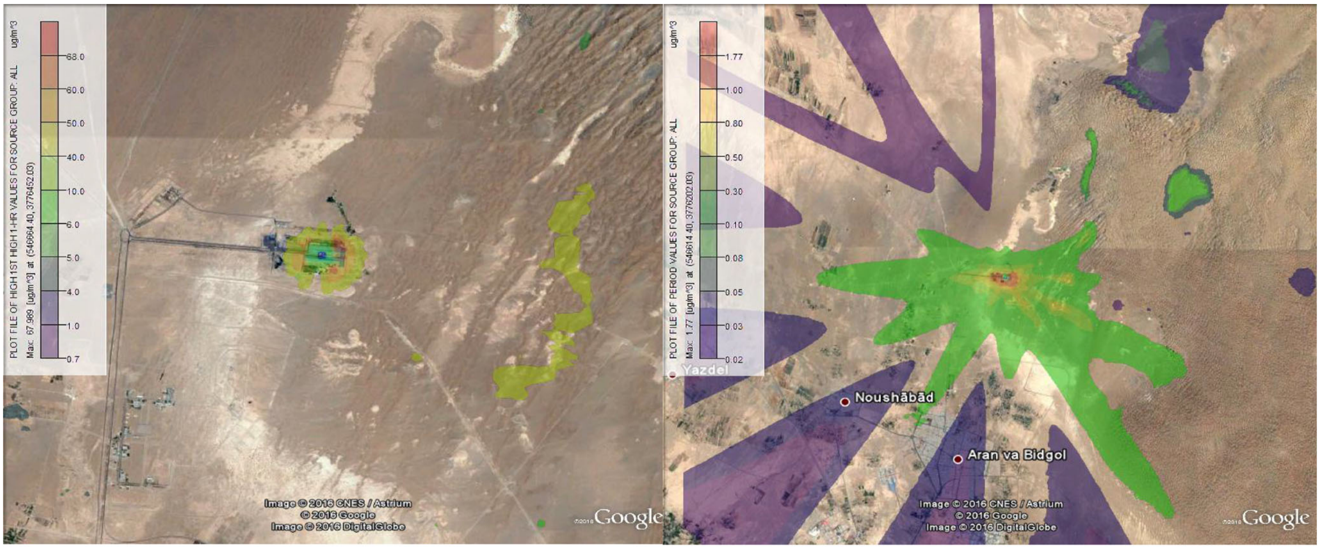
Results of NO_2 risk assessment with 90% certainty showed that in the 95th percentile the value of HQ is equal to 0.021 with mean = 0.012 and in the 5th percentile of HQ is equal to 0.006 (Fig. 6). Also, the risk assessment for Sox shows that in the 95th percentile HQ is equal to 0.042 with an average of 0.016 (Fig. 7). There are no risk for the workers because the HQ values in the 95th percentile of both pollutants are very low and less than 1 [49].

Sensitivity analysis

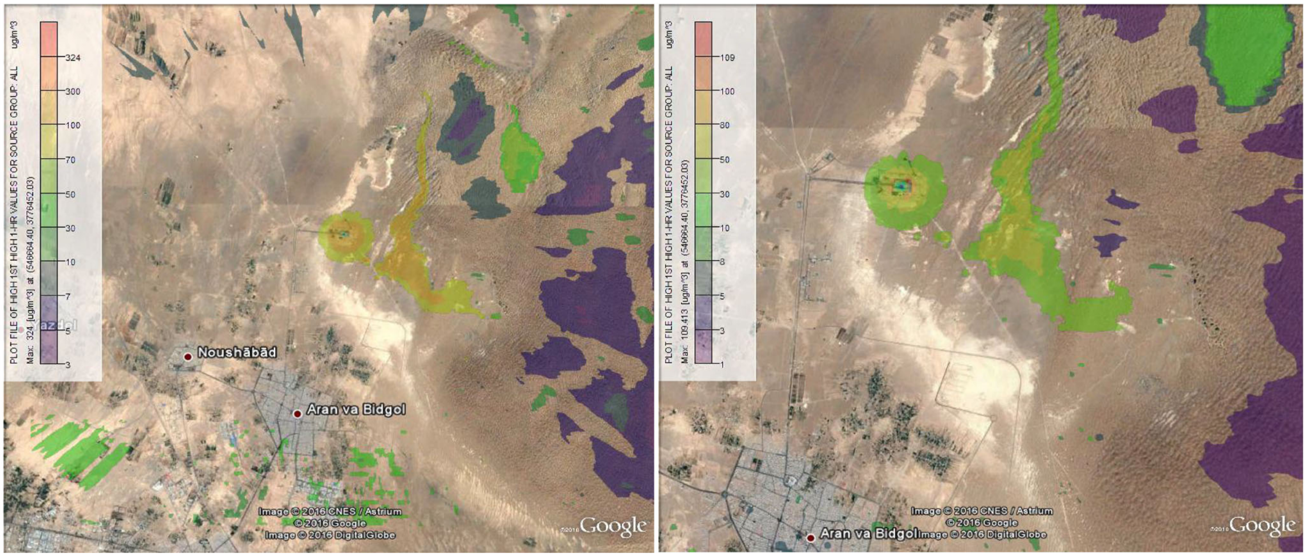
The results of sensitivity analysis in the form of tornado plot are shown in Fig. 8. The results showed that in the estimated risk for NO_2, the most positive effect was for concentration of NO_2 by 86%, and the most negative and reducing effects of risk NO_2 concentration in air for workers was BW value in

Fig. 4 Concentration changes with distance from the site for concentrations up to 1 h





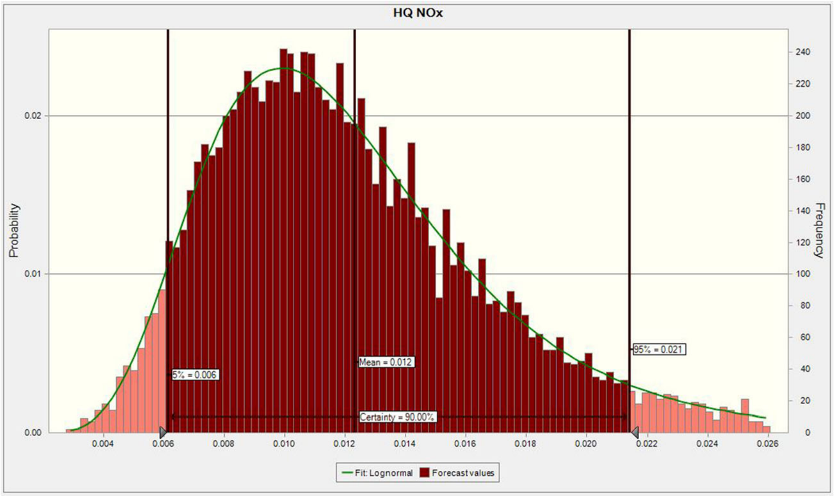
Dispersion of hourly NO$_2$ concentration (gas fuel) Dispersion of annual NO$_2$ concentration (gas fuel)



Hourly dispersion of SO$_2$ concentration (liquid fuel) Dispersion of hourly NO$_2$ concentration (liquid fuel)

Fig. 5 Output images of AERMOD model

Fig. 6 Histograms of the uncertainty analysis of NO$_2$



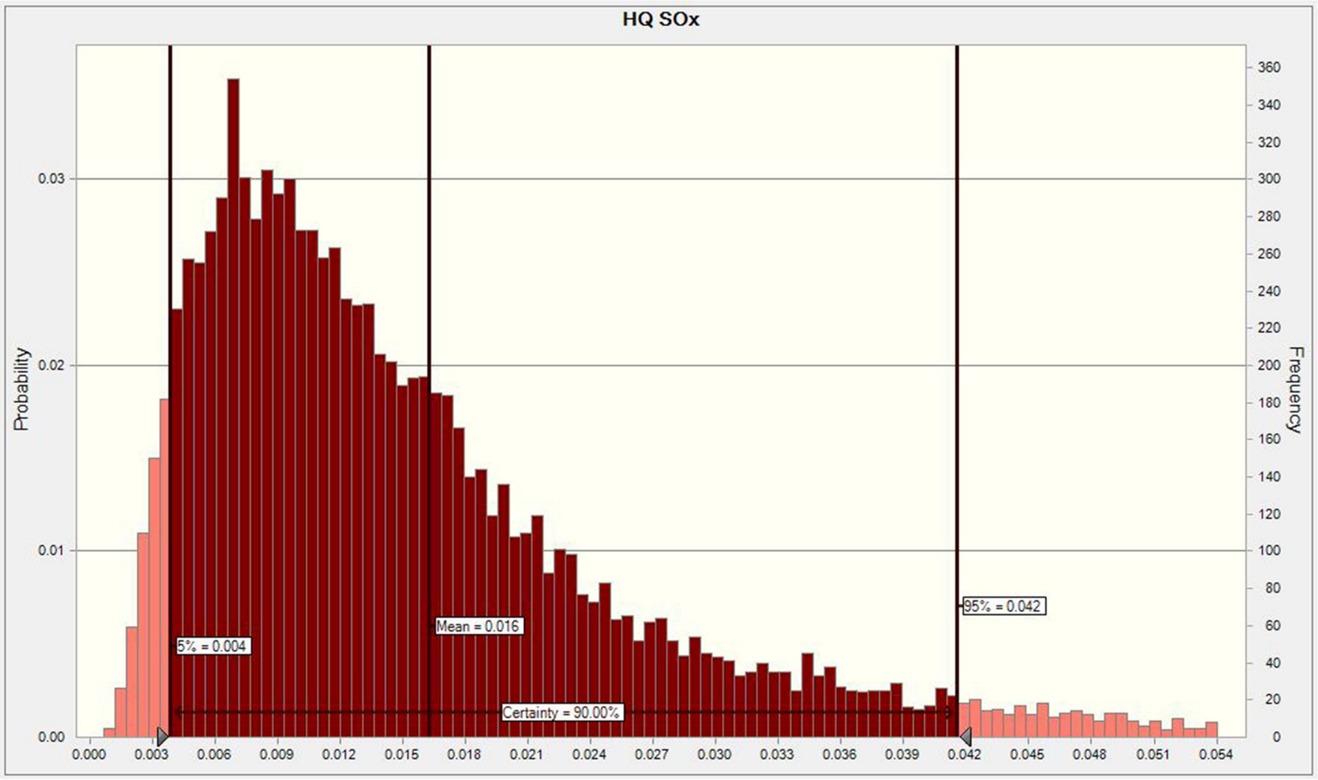


Fig. 7 Histograms of the uncertainty analysis of SO_2

amount of 6.9%. The ED, ET and EF parameters have a positive effect of 1.9, 1.7 and 1.1%, respectively, and the AT parameter has a reducing effect of 2.3% on the estimated risk of NO_2 in the respiratory air of workers (Fig. 8). The results also showed that in the estimated risk for SO_2, the concentration of SO_2 at 95.5% was the most positive effect, and the most negative and reducing effect for the risk of SO_2 in the inhaled air by workers was for BW value at 1.9%. The ED, ET and EF parameters have a positive effect of 0.7, 0.6 and 0.6%, respectively, and the AT parameter has a reducing effect of 0.8% on the estimated risk of SO_2 in the respiratory air of workers (Fig. 9).

Discussion

Air pollution is one of the greatest consequences of civilization, which has become inevitable throughout the world due to increasing energy consumption along with population growth and rapid development and industrialization [50, 51]. Controlling ambient air pollutants is critical to assess exposure levels as well as to assess the health risks and threats posed by human exposure to pollutants. For this purpose, acquiring sufficient and deep knowledge about the distribution of air pollutants in the environment is necessary [52]. Nowadays, the effects of air pollution have led to the monitoring and control of air quality in all societies at the forefront of national issue [53, 54]. Thus, national air quality standards are established by the United States Clean Air Act to protect humans and environments against damaging caused by air pollutants [55]. So the needs for tools and methods to control and manage pollutants for similar making and forecasting air quality is felt more than ever [56, 57]. This study was conducted to compare the emission of NO_2 and SO_2 pollutants due to combustion of two types of gas and liquid fuels (diesel) from the hot rolling industry of SKS complex using the AERMOD model. Mokhtar et al., evaluated the health risk effect of SO_2 in a coal power plant using the AERMOD model [58]. This model has also been used to predict the release of hydrogen sulfide (H_2S) from a wastewater treatment plant (STP) in Oman [59]. Results of the Boadh et al. [60] study, with the aim of evaluating the dispersion of nitrous oxide using the AERMOD model in a tropical industrial region indicate that this model has a good efficiency in showing the dispersion of air pollution in the Ranchi region [60]. The results of these studies indicate the high performance of the AERMOD model, which agrees with our study. Results of this study showed that the concentration of pollutants emitted in case of using gaseous fuel is very low, and is lower than the maximum allowable value. However, these concentrations increase with liquid fuel consumption.

Studies have shown that gasoline and diesel fuels contain large amounts of sulfur, which when oxidized can produce large amounts of sox. If the amount of sulfur in natural gas

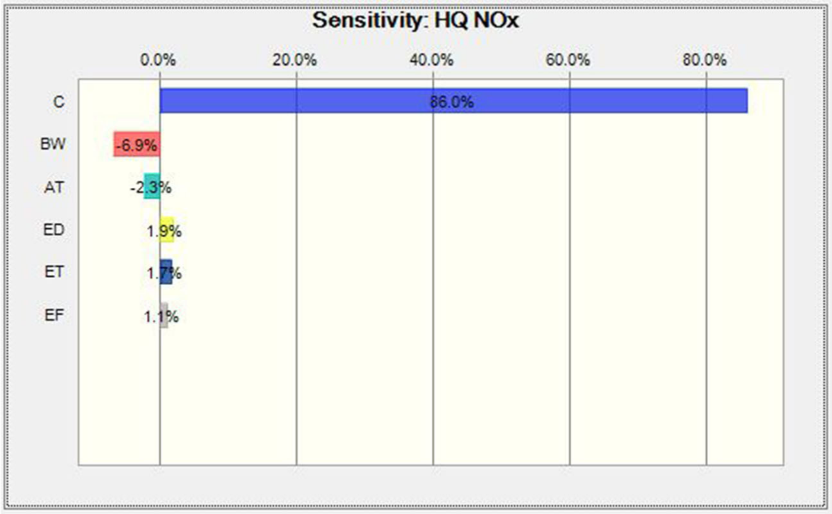


Fig. 8 Sensitivity analysis of Adults exposed to NO_2

is almost zero(PATI) [61], this reason can justify the release of excess concentration of Sox for 1 h when consuming liquid fuel. Numerous studies also show that NO_x is one of the most important pollutants emitted by diesel engines [62], which increases the NO_2 concentration produced by this complex. Ibrahiem [63] in a study entitled “Assessing the cost of air pollution in the use of fossil fuels in some Egyptian industries”, was compared the emissions of SO_x, NO_x, PM_{10}, and $PM_{2.5}$ from fuel fossil fuels of diesel, natural gas, and coal in three industries; steel, aluminum, and cement. The results of this study showed that diesel fuel has the highest NO_x emissions, and natural gas has the lowest pollution compared to diesel and coal [63]. Another study conducted in 2016 by Kumar et al. in India, concluded that the best way to control pollution sources is to use Natural gas fuel is due to low SO_x production, which the results of these two studies are consistent with the results of our study [64].

According to the sampling, the highest concentrations of SO_2 and NO_2 pollutants are related to the southern parts of the study area due to the presence of population centers and roads. The results of a study in (2012) indicated the production of these pollutants from urban vehicles [65], which is in line with the results of our study. In another study conducted in 2011 by Banerjee in Pantnagar, India, the share of NO_2 produced by urban vehicles was estimated at 9 to 39% [66].

The graphs obtained from the changes in the concentrations of the studied pollutants showed their maximum concentrations in dealing with the roughness around the plant. These roughness are mainly located in the eastern part of the complex site, which due to the prevailing wind direction in the region, the accumulation of pollutants in this area has been the highest. It accorded because the heights prevent the passage of horizontal air currents and as a result lead to heterogeneous distribution of pollutants [67]. Results of this study indicate that the highest distribution of SO_2 and NO_2 pollutants is in the vicinity of the mountains in the northwest of the study area. Other researcher also achieved similar results in their study entitled “Performance of AERMOD and CALPUFF

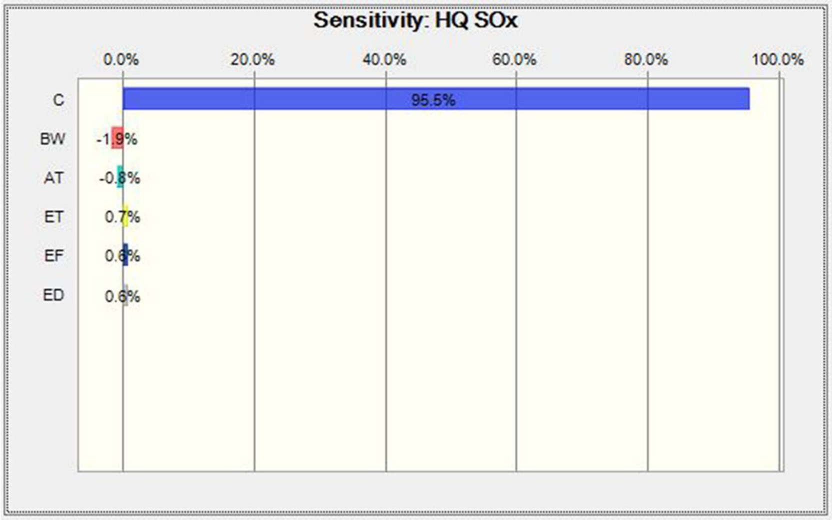


Fig. 9 Sensitivity analysis of Adults exposed to SO_2

models on SO_2 and NO_2 emissions for future health risk assessment in Tema Metropolis" [68]. Study by Silverman et al. in an industrial complex in the eastern United States also found that human health risk assessments for pollutants emitted from the complex were below the threshold [69].

In comparing the AERMOD model and monitoring data, it was found that differences in predicted results of AERMOD model and actual data. As in some stations, well performance was not observed in predicting SO2 concentrations for this model. Nevertheless, AERMOD has demonstrated the ability to provide a suitable model for dispersion from point sources and estimating hourly concentrations of NOx and SO_2. especially for concentrations of ambient ground-level on the vicinity of the industrial regions. Which can be used as a suitable scientific and analytical tool for control and policy strategies in reducing and preventing air pollution.

Conclusion

According to the issues presented in this study, it can be concluded that although SO_2 and NO_2 are among the main pollutants in the rolling industry resulted from the operation of equipment such as furnaces, stands, and mobile machines such as trailers, as well as other activities such as welding, cutting, and turning. Based on the results of sampling performed in the operation phase and modeling the distribution of air pollutants, when the gas is used as fuel in the preheating furnace, the concentration of SO_2 and NO_2 in the whole affected area is less than standards of the Environmental Protection Organization and in terms of Health risk assessment. Also, the concentration of the two studied pollutants does not have any dangerous side effects for workers' health. Only usage of liquid fuel can increase the concentration of SO_x contaminants for 1 h and violate the standard of the EPA in some areas. Although this happens in a short period of the year, the temperature of the furnace burners and the ratio of air to fuel must be carefully controlled in the complex in order to minimize the amount of air pollution from the flue gases. Additionally, the development of green fields in the interior as well as the peripheral areas of the complex can significantly reduce this effect.

Author contributions Study conception and methodology: Mohsen Hesami Arani and Nematollah Jaafarzadeh. Data analysis: Mohsen Hesami Arani, Mohammad Rezvani Ghalhari. Investigation: Mohsen Hesami Arani and Mahdiyeh Mohammadzadeh. Writing – original draft: Mohsen Hesami Arani, Mahdiyeh Mohammadzadeh and Mehrdad Moslemzadeh. Writing – review & editing: Mohsen Hesami Arani, Mahdiyeh Mohammadzadeh, Mehrdad Moslemzadeh and Samaneh Bagheri Arani. Corresponding Author: Mahdiyeh Mohammadzadeh. All authors read and approved the final manuscript.

Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval This paper is the result of a research project supported by the steel industry and lacks an ethical code.

Consent to participate Not applicable (The manuscript does not report on or involve the use of any animal or human data or tissue).

Consent to publication Steel Company has allowed to publish the information obtained from this research.

Competing interests The authors declare that they have no competing interests.

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