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Research Article

Optimization Models for Reducing the Air Pollutants Emission in the Production of Insulation Bituminous

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Abstract
Delijan, the main production center production of bitumen insulation, is one of the most polluted cities in Iran. Therefore, the measurement and analysis of emissions and the optimization of energy consumption, and, thus the reduction of emissions of these pollutants are particularly important. This study aimed to measure the gaseous pollutants emitted from the chimneys of one of the bitumen insulation production units in the industrial city of Delijan and also to improve the performance of the exhaust gas cleaning systems. For this purpose, first, the flow parameters of the chimney are measured with the KIMO gas analyzer, model KIGAS300, and then the pollutants Carbon monoxide, Hydrocarbons, and Nitrogen oxides are optimized of two methods in the MATLAB software using the Genetic Algorithm method and python software using the multiple regression with Sklearn and Statsmodels approach. An objective function was formed that has a non-linear relationship between the preheater outlet air temperature, the percent excess air, and the production of CO, C_xH_y and NO_X pollutants. Statsmodels python regression were presented showing the effect of increasing or decreasing the preheater air temperature and the percent excess air (parameters for which the optimization is carried out) on the amount of pollutants production. According to the optimization results, the most suitable air temperature and percent excess air were selected to achieve the lowest pollutant emissions. Moreover, R^2 values are at the 0.89 level and above. Finally, the proposed method can solve optimization problems and support environmental management decisions in the insulation industry.
Keywords: Bituminous industry, Short-lived climate pollutants, Optimization, Genetic algorithm, Statsmodels python regression.

Introduction

The rapid development of the waterproofing industry in buildings has led to widespread environmental pollution in the form of energy consumption and the release of pollutants. Currently, there are many bitumen and bitumen insulation production plants operating in the city of Delijan, and the main air pollution in this city is related to exhaust gases from the chimneys of these plants

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due to the use of fuel oil, acid bitumen and inappropriate filtration systems in these units. The baking process of bitumen insulation produces unburnt hydrocarbons (due to incomplete combustion) and compounds of carbon monoxide, sulfur oxides, and nitrogen oxides due to the different raw materials and low bitumen insulation baking temperatures. NO_X ($NO + NO_2$) and CO are the most important precursors of ozone and the main plant increasing the concentration of this pollutant in the troposphere (Penkett et al., 1986; Seinfeld et al., 1986; Liu et al., 1987; Murao et al., 1990; Borhani et al., 2022a; Borhani et al., 2017; Cheraghi and Borhani, 2016a, b; Hoveidi et al., 2017; Maddah et al., 2022). CO and NO_X pollutants are short-lived climate pollutants (SLCPs) that are among the most important drivers of climate change (Forster et al., 2007; Scovronick et al., 2015; Borhani et al., 2021; Borhani et al., 2022b, c, d).

Daraie et al. (2011) investigated the monitoring of exhaust gases from the chimneys of cement production units and the problems of electrostatic precipitators in cement plants. Akram et al. (2019) in a study to investigate the amount of energy consumption and emissions of pollutants and finally optimize energy consumption using the Genetic Algorithm (GA) optimization method to reduce environmental emissions in the cake production industry in Guilan province. Mansouri and Khairi (2014) studied the pollutants emitted from asphalt plants, examined their emission rates, and proposed appropriate air purification systems. In 2019, carbon monoxide and nitrous oxide emissions from the chimneys of a bitumen insulation production plant were measured and then the distribution of these pollutants was modeled using the AERMOD model (Borhani et al., 2019). Borhani and Noorpoor (2020) investigated the concentrations of some gaseous pollutants emitted from the chimneys of some bitumen insulation production units in Delijan city and compared them with the existing standards. Their results indicate that the emission values of some gases are higher than the standard of pollutants emitted from the chimney of the bitumen insulation industry. Also, the highest concentration of carbon monoxide (about 678.00 ppm) was recorded in winter and the highest concentration of hydrocarbons (about 250.00 ppm) was recorded in summer (Borhani and Noorpoor, 2020).

Studies by Borhani and Noorpoor (2017) on the concentration of volatile organic compounds (VOCs) in bitumen insulation production units in Delijan indicate an increased risk of cancer due to occupational exposure of workers in production units. According to studies of pollutants released from the bitumen insulation plant, the more pollutants get out from the production cycle, the more heat will normally enter the environment. Finally, this accumulation of energy in the environment will determine the phenomenon of global warming (Vares et al., 2019). To solve this problem, reburning is usually used to complete the incineration and scrubber (Fig. 1a-d).

Therefore, simultaneous attention to reducing emissions, increasing production, and preventing the growing trend of global warming is the most important factor for the success of the production (Wang et al., 2011). Accordingly, the use of new methods to work out optimal patterns is one of the key factors for the proper design of energy consumption and the reduction of greenhouse effects (Pérez-Uresti et al., 2019). Moray et al. (2006) have explored energy efficiency opportunities in the stone and asphalt industry. by examining the existing system of crusher equipment and asphalt plant in the amount of energy consumption, they have achieved the weaknesses of each crusher and asphalt plant and then present their proposed solutions to optimize energy consumption and coordination of these two facilities.

Delavar et al. (2019) conducted a study using a hybrid model consisting of an artificial neural network and an autoregressive nonlinear model, and finally provided answers using a high-precision genetic optimization algorithm to improve the weather in Tehran. Due to the nature of the process and the high temperature of the furnace, the production and emission of pollutants in bitumen insulation production are very high. Due to the importance of this issue, in this study, we have controlled the pollutants released into the air by developing an optimal system in one of the bitumen insulation production plants.

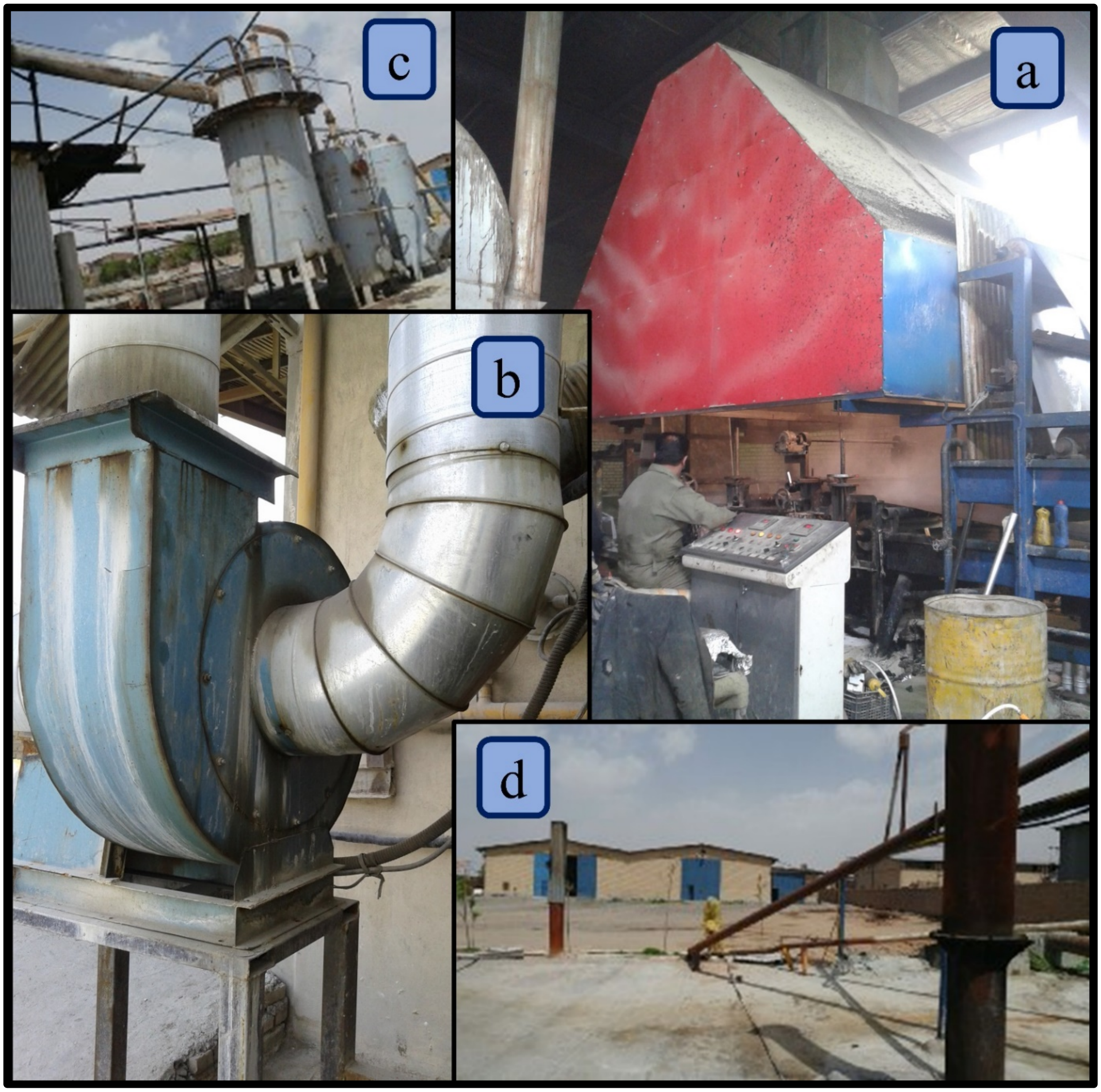


Figure 1. **(a)** Hood collects gases from the tissue exit from the pond, **(b)** Indoor gas suction fan, **(c)** Indoor gas transfer to three-stage scrubber towers, **(d)** Transfer of gases from scrubber (wet detergent) to re-combustion furnace.

In this study, gaseous pollutants (i.e., CO_2, CO, NO_X, SO_2, C_xH_y) in one of the bitumen insulation production units of Delijan industrial town, were collected at different intervals during 2020 by the relevant devices. Multiple Regression in python with sklearn and statsmodels of CO, C_xH_y and NO_X concentrations based on preheated air temperature and percent excess air were presented. Also, the optimization of the mean concentration of CO, C_xH_y and NO_X pollutants in the bitumen insulation production unit was analyzed using the Genetic Algorithm (GA) program in MATLAB software. Finally, the optimal values of air temperature and percent excess air as well as the minimum values of pollutants were calculated.

Methodology

Study Area

Delijan is one of the cities of Markazi province in Iran. The city with an area of 2170 km^2 is located at $33^{\circ}99'N$ and $50^{\circ}68'E$ (Figure 2). The town of Delijan is situated at an altitude of 1530 meters above sea level. The mean annual rainfall is 178.40 mm, the maximum, mean and, minimum temperatures are 42.80, 16.10 and, -21.40 ℃ respectively, and the mean relative humidity is 39%. The maximum continuous wind speed is 122 km/h (MPMO, 2021).

Air pollution in Delijan town is generally due to the presence of polluting industrial centers. There are about 120 waterproofing manufacturing plants in Markazi province, of which more than 40 are located in the industrial city of Delijan and more than 20 in the industrial center of Bu Ali Delijan. In this industrial city, 70% of the insulation materials needed in the country are centrally produced. On the other hand, Delijan town is located in a semi-arid climate and is one of the least rainy towns in Markazi province. Due to its industrial and geographical location, Delijan is the fourth most polluted city in Markazi province (Borhani et al., 2016). In this study, the control systems of exhaust pollutants from the chimneys of a bitumen insulation production plant ($35^{\circ}68'92''N$ and $51^{\circ}38'90''E$) were investigated, as shown in Figure 2.

Figure 2. The locations of unit of Delijan Bituminous Company *Field measurement*

A KIMO gas analyzer, model KIGAS300, manufactured by KIMO France, with the capability to analyze SO_X, CO_2, CO, H_2S, NO, NO_2 and NO_X with an accuracy of ±10% of the measurement was used to measure the concentration of pollutants from the chimneys of the bitumen insulation factory in the industrial town of Delijan, Markazi province (Table 1).

Table 1. Pacifications of KIMO- KIGAZ 300 for measuring gases

Parameter	T_g	SO_2	NO_X	NO_2	NO	CO	O_2
Unit	°C	ppm	ppm	ppm	ppm	ppm	%
Measuring range	500	0-5000	0-5155	0-1000	0-5000	0-8000	0-21

The average emission concentrations were recorded at the chimneys in 2020. Chimney gas analyzer, chimney gas detector, KIMO KIGAZ 300 ability to calculate carbon dioxide (CO_2), combustion efficiency, percent excess air, heat loss and suction of the chimney, the ability to measure pressure, gas velocity through Pitot tube and flow meter calculation of exhaust gas, with gas system dilution to increase the range of carbon monoxide gas up to 40 times, it has a gas preparation unit for distillation of the exhaust gas and absorption capability to print through the infrared printer and connect to a computer to process stored information.

Other features of this device include the ability to analyze and test multiple gases, connection and support of several gas detection props, very professional accuracy and speed of operation, along with magnetic protective coating, self-calibration, has 3 pressure sensors and the replaceability of the flue gas probe pointed out, the type of fuel used in the plant under study is natural gas. To investigate the effect of ambient temperature is 39°C and the amount of excess oxygen is 3%. To investigate the effect of the percent excess air, the ambient temperature of 40 °C and furnace temperature of 220 °C were considered and optimization was performed. Combustion systems operate with different levels of excess air.

Oxygen and combustible materials such as carbon monoxide in combustion products can be measured to monitor excess air changes. In many heating systems, 2 to 3 percent oxygen with 10 to 50 ppm of combustible material indicates the ideal performance of the system and there is no need to modify the percent excess air.

Genetic Algorithm

In general, optimal selection and design in many scientific and technical issues produce the best possible product or answer in a particular situation. Evolutionary algorithms in general and Genetic Algorithms, in particular, are search methods that can be used to find the optimal answer (Goldberg, 1989). The Genetic Algorithm (GA) uses the idea of the evolution of living organisms (Holland, 1975; Michalewicz and Michalewicz, 1996). In this way, at first, a set of answers is guessed randomly and their closeness to the optimal answer is determined by calculating a fitness function for each of them. Then better and more graceful answers are used to create a new set of answers. The Genetic Algorithm (GA), on the one hand, seeks the optimal solution in all possible solution spaces due to its random nature, and as a result, is theoretically able to find the overall optimal, and on the other hand, because the search operation in each the step is done around the current quasi-optimal answers, this action is done purposefully and the search is not done blindly. In this research, a Genetic Algorithm (GA) has been used to find the coefficients of the parameters of the objective functions (Dasgupta and McGregor, 1993; Ghaffarizadeh, 2006; Shamshirband et al., 2015).

Assessment of models

In this research, root-mean-square error (RMSE) and determination coefficient (R^2) (see Equations (1-2)) were applied to assess the accuracy of the proposed models (Beckerman et al., 2013; Elavarasan et al., 2018; Goap et al., 2018).

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \overline{y_i})}{\sum_{i=1}^{n}(y_i - \overline{y})} \tag{1}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \tag{2}$$

Where $\hat{y}_i$ and y_i are the observed and forecasted i values of $\overline{y_i}$, respectively, and $\bar{y}$ represents the mean y values of the observed and forecasted in the tested sample set. Moreover,n indicates the number of observations. R^2 was used to evaluate the strength of a linear relationship between pairs of variables. The RMSE deviation was used to evaluate the accuracy of the proposed regression equations estimation.

Result and discussion

Data analysis

The data obtained from the measurement of the mean value of the different volumetric concentrations of the exhaust gases, the average outdoor temperature, and the temperature of the flue gases are shown in Table 2.

Table 2. The average concentrations of gaseous pollutants and temperature in bitumen insulation production unit

Parameter	T_g (°C)	Ta (°C)	C_xH_y (ppm)	H_2S (ppm)	SO_2 (ppm)	NO_X (ppm)	NO_2 (ppm)	NO (ppm)	CO (ppm)	CO_2 (%)	O_2 (%)
	220.70	39.10	9.00	0.00	0.00	40.00	40.00	0.00	18.00	0.00	3.00

The results show that among the studied pollutant gases, nitrogen dioxide gas has the highest level of pollution and the measurement of hydrocarbons shows the lowest values. The factory chimney has the highest difference between the outside temperature and the flue gas temperature (181.6 °C). This temperature difference causes the exhaust gases to rise. Table 3 examines the effect of oven temperature and Table 4 the effect of percent excess air on amounts of gaseous pollutants emitted during the production of bitumen insulation.

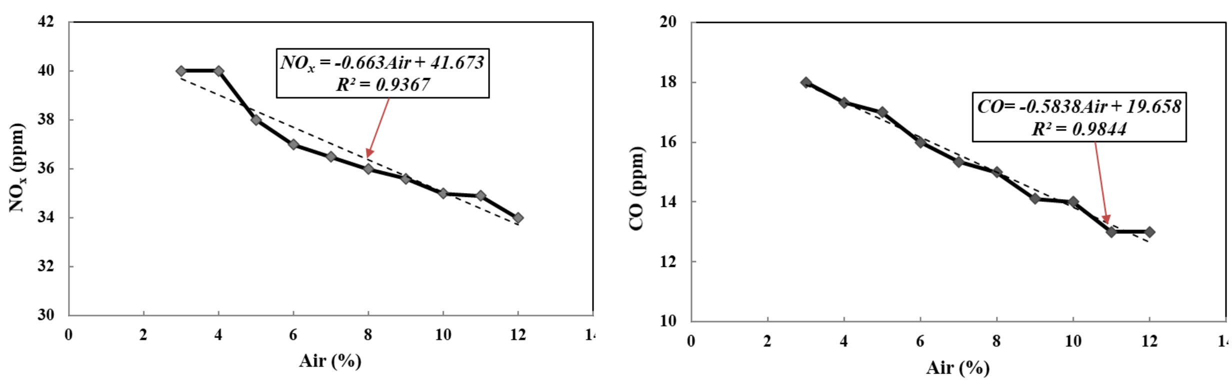
Table 3. Investigation of the effects of furnace temperature on the amount of gaseous pollutants

T (°C)	CxHy (ppm)	H_2S (ppm)	SO_2 (ppm)	NO_X (ppm)	NO_2 (ppm)	NO (ppm)	CO (ppm)	CO_2 (%)
220	9.00	0.00	0.00	40.00	40.00	0.00	18.00	0.00
240	9.00	0.00	0.00	40.00	40.00	0.00	18.00	0.00
260	9.00	0.00	0.00	41.00	41.00	0.00	19.00	0.00
280	9.50	0.00	0.00	42.00	42.00	2.00	17.00	0.00
300	8.50	0.00	0.00	43.00	43.00	3.00	16.23	0.00
320	8.00	0.00	0.00	43.00	43.00	3.00	16.00	0.00
340	8.21	0.00	0.00	44.00	44.00	5.00	16.00	0.00
360	7.50	0.00	0.00	48.00	47.00	6.00	15.75	0.00
380	7.00	0.00	0.00	55.00	53.00	9.00	15.55	0.00
400	7.50	0.00	0.00	58.00	57.00	15.00	15.60	0.00

Table 4. Investigation of the effects of percent excess air on the amount of gaseous pollutants

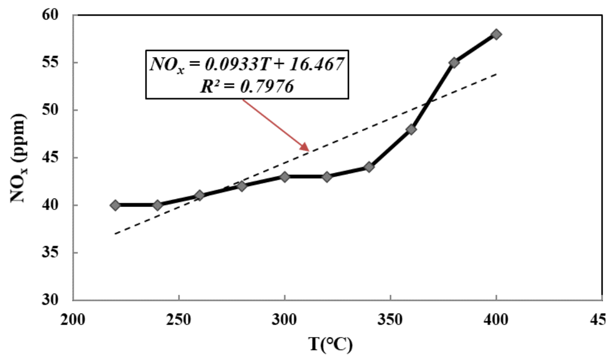
Air (%)	CxHy (ppm)	H_2S (ppm)	SO_2 (ppm)	NO_X (ppm)	NO_2 (ppm)	NO (ppm)	CO (ppm)	CO_2 (%)
3	9.00	0.00	0.00	40.00	40.00	0.00	18.00	0.00
4	9.00	0.00	0.00	40.00	40.00	0.00	17.33	0.00
5	8.90	0.00	0.00	38.00	38.00	0.00	17.00	0.00
6	8.70	0.00	0.00	37.00	37.00	0.00	16.00	0.00
7	8.40	0.00	0.00	36.50	36.50	0.00	15.35	0.00
8	8.25	0.00	0.00	36.00	36.00	0.00	15.00	0.00
9	8.10	0.00	0.00	35.60	35.60	0.00	14.11	0.00
10	8.00	0.00	0.00	35.00	35.00	0.00	14.00	0.00
11	7.85	0.00	0.00	34.90	34.90	0.00	13.00	0.00
12	7.80	0.00	0.00	34.00	34.00	0.00	13.00	0.00

The pattern of change of emitted gaseous pollutants due to the production process of bitumen insulation (i.e., CO and NO_X) is inversely proportional to the percent excess air (Air%) (Figures 3a and 3b). NO_X gas pollutant changes with furnace temperature have a positive slope and CO gas pollutant changes with furnace temperature have a negative slope (Figures 4a and 4b).

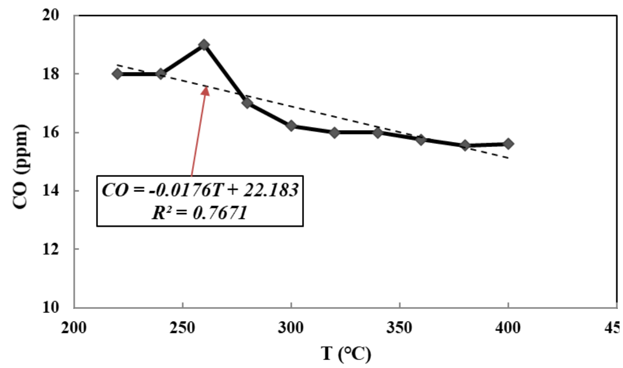


(a) (b)

Figure 3. Investigation of the effects of percent excess air on the amount of gaseous pollutants using MATLAB software, (a) nitrogen oxides, (b) carbon monoxide



(a)



(b)

Figure 4. Investigation of the effects of furnace temperature on the amount of gaseous pollutants using MATLAB software, (a) nitrogen oxides, (b) carbon monoxide

Exergy Based Optimal Control

Since the main purpose of this research is to optimize the performance of combustion furnaces to reduce amounts of pollutants produced by combustion operations, it is necessary to determine the parameters on which the optimization is performed. The parameters to be optimized are the percent excess air, pre-heater outlet air temperature. Taking into account the effects of these two factors, the optimization is done in such a way that the emission of pollutants is close to its minimum. The pollutants in question are CO and NO_X.

To perform the optimization operation, it is necessary to form a target function that has a linear or non-linear relationship with the outlet air temperature of the preheater and the percent excess air on the amount of CO and NO_X pollutants produced. The following relations have been prepared using information fitting methods.

In this way, the results obtained from the objective function can be written as needed in any of the following ways (see Equations (3-4)):

1) Reduction of CO

$$\begin{aligned} y_1 = {} & 0.1252\, cos(2\, x_1) - 0.5904\, x_2 \\ & - 0.2703\ \ cos(exp(x_2 - 0.04972)) - 0.04218 x_1 \\ & - 0.1252\, sin(x_2)^2 \\ & + 0.4276\, cos(\, {x_1}^2) + 1.212 (cos\, x_2)^2 - 0.7171 exp\ (sin\ ({x_1}^2)) \\ & + 1.788\, sin\ (\, 0.02992 x_1) + 0.1236\, cos\ (\, x_2) + 1.397\, sin\ (\, x_1) \\ & + \frac{8.01 (x_2)^2}{10^5} \\ & + 1.523\, cos\ (\, cos\ (\, x_2))\, cos(x_1) + 0.3084\, sin\ (\, {x_2}^2))\ \ cos(x_1) \\ & + \frac{8.01 (x_1)^2}{10^5} + 23.57 \end{aligned} \tag{3}$$

Where, x_1, x_2 and y_1 are optimal operating temperature (°C), percent excess air (%) and carbon monoxide (ppm), respectively.

2) Reduction of NO_X

$$y_2 = (-0.26x^2 - 0.148\,sin\,(\,exp\,(x_1))\,(x_2 + 1) - 6.126)\,x_1 + 59.87x_2 + 1.373(sin(x_1) - 0.087514x_1)^2 + 504.1(cos\,(\,x_1))^2 + 190.9\,sin\,(\,exp\,(x_1)) - 158.5\,sin\,(\,cos\,(\,x_1)^2)) + 5.734(cos\,(\,x_1)^2))^2 + 56.35\,sin\,(\,x_1\,x_2) + 272.6exp(sin\,x_1)^2 - 56.35\,cos(x_1) + 59.87\,sin\,(\,x_1) + 48.68\,sin\,(\,x_2) - 50.65\,cos(2x_1)\,sin\,(\,x_1 + x_2) + 0.5258x_2\,cos\,(\,x_2) + 232.1 \quad (4)$$

Where x_1, x_2 and y_2 are optimal operating temperature (℃), percent excess air (%) and nitrogen oxides (ppm), respectively. As can be seen, the obtained relations are nonlinear functions of temperature and percent excess air. The optimization problem model was prepared using the above equations and using the Genetic Algorithm (GA) method, which is for optimizing nonlinear functions, and by performing optimization operations, optimal conditions have been obtained to minimize pollutant compounds. To obtain the optimal point of the system, the Genetic Algorithm (GA) method with the maximum generation, 430, population size is, 301, and tournament sizes 8, is hypothetically used (Man et al., 1996; Hong et al., 1996; Eiben et al., 2007).

Multiplication, subtraction, addition, division, and exponential functions have also been used for this purpose. All the above steps were performed by a computer program. This software is written in MATLAB programming language. The initial concentration of carbon monoxide optimized by the data envelopment analysis method was 17.9436 ppm and the concentration measured by the KIMO gas analyzer, KIGAS300 model, was 18 ppm (Table 2 and Figure 5a). At an optimum temperature of 362℃ and a percent excess air of 11%, the optimum amount of carbon monoxide is 5.9018 ppm (Table 5).

Table 5. Optimal points obtained from single-objective exergetic optimization of carbon monoxide

Parameter	Unit	Value
T	C°	362.00
Air	%	11.00
CO	ppm	5.9018

The initial concentration of nitrogen dioxide obtained optimized by the data envelopment analysis method was 40. 1908 ppm and the concentration measured by KIMO gas analyzer, model KIGAS300, was 40 ppm (Table 2 and Figure 6a). At an optimum temperature of 283.7 ° C and a percent excess air of 6.7%, the optimum amount of nitrogen dioxide is 0.0011 ppm (Table 6).

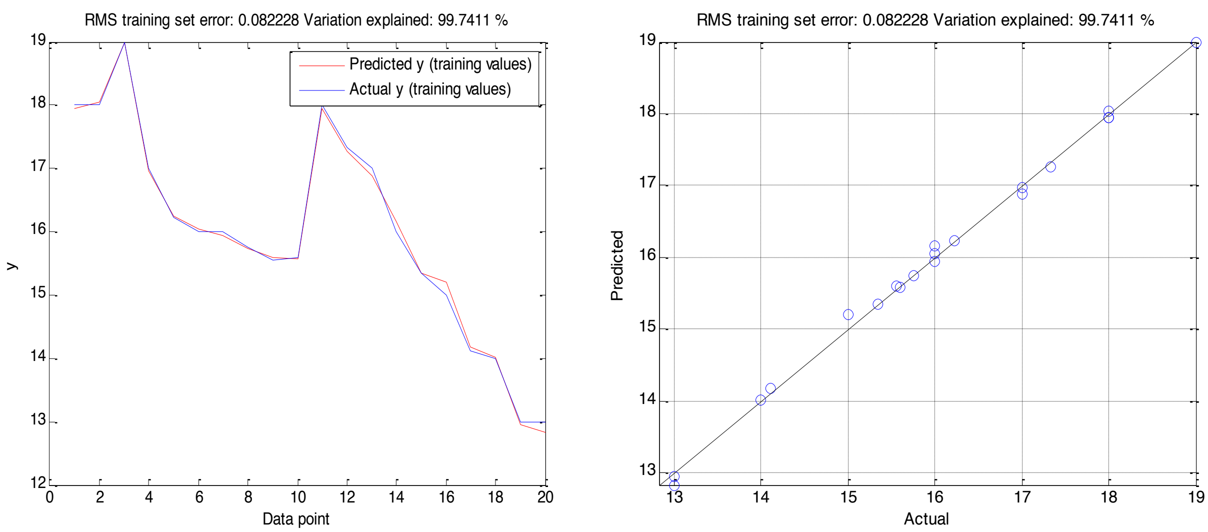
Table 6. Optimal points obtained from single-objective exergetic optimization of nitrogen oxides

Parameter	Unit	Value
T	C°	283.70
Air	%	6.70
NO_x	ppm	0.0011

After optimizing the model parameters of the Genetic Algorithm (GA), the model was validated using RMSE, R^2, and % error criteria. The RMSE was fitted using Fitness, one of the operators of the Genetic Algorithm. This fit was based on the initially measured values of pollutants and the optimized values of pollutants (Figures 5b and 6b).

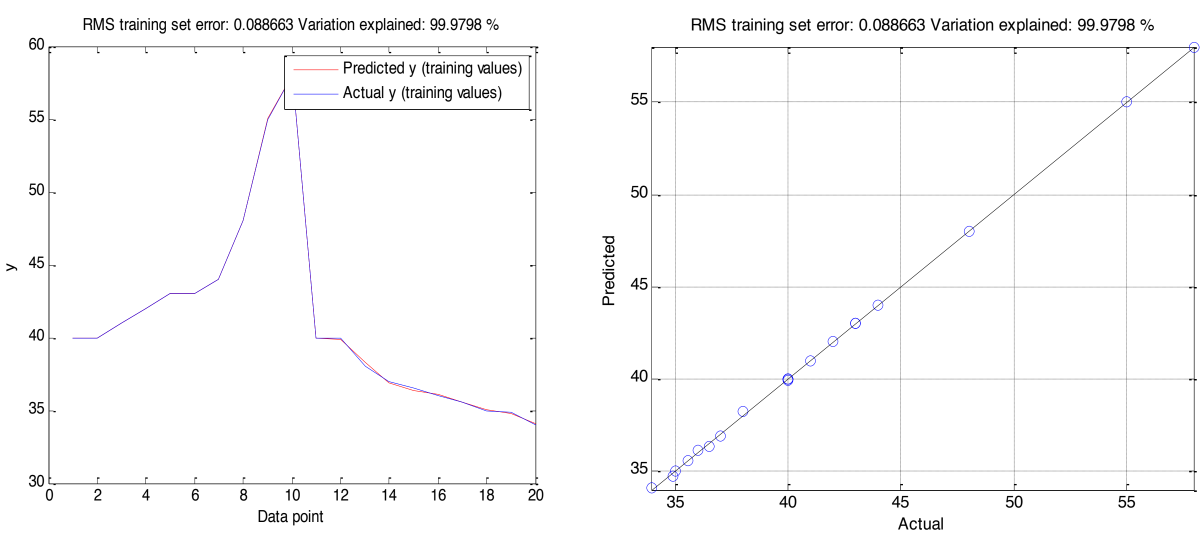
As already mentioned, there are equations up to the fourth degree for some pollutants. R^2 values are at the 0.90 level and above. For graphs that have more than two intercepts, the average of their x-values was used. The optimal joint value for the two variables temperature and air is equal to 0.1388, which after reversing the normal standard transformation gives a temperature value of 317.97 ° C and a percentage value of excess air of 7.89% (Figure 7 and Table 7).

Therefore, validation results showed that the Genetic Algorithm performed well in terms of RMSE, R^2, and % error criteria.



(a) (b)

Figure 5. Actual and optimized amount of carbon monoxide pollutant by GA method (a) %Error value (b) Fitness value



(a) (b)

Figure 6. Actual and optimized amount of nitrogen oxides pollutant by GA method (a) %Error value (b) Fitness value

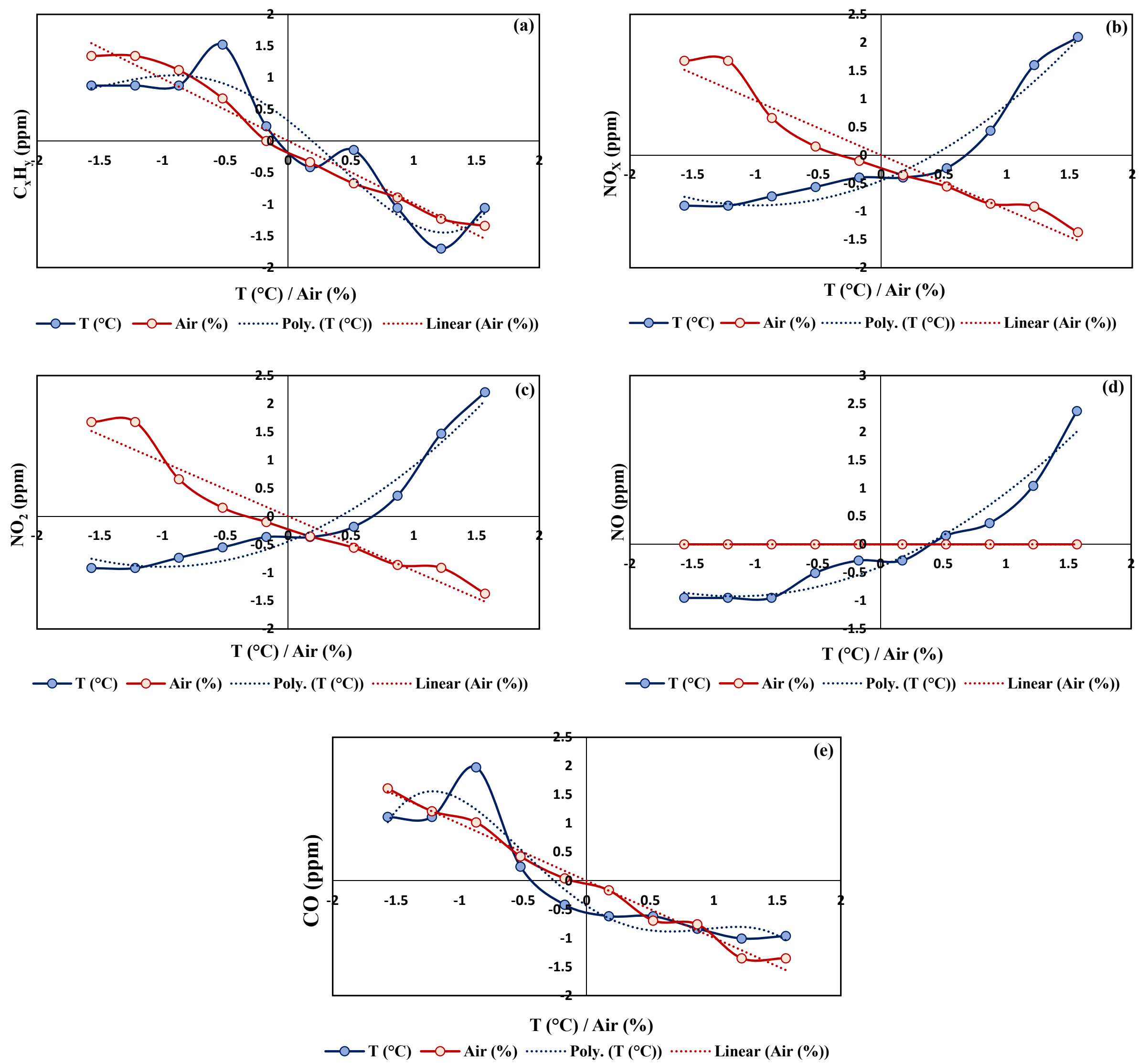


Figure 7. Investigation of the effects of percent excess air and temperature on the amount of gaseous pollutants using statsmodels python regression, a) C_xH_y, b) NO_x, c) NO_2, d) NO, e) CO

Conclusions

This study aimed to optimize the two pollutants CO and NO_X in a bitumen insulation production plant in Delijan town, Markazi province, using data analysis techniques (Statsmodels python regression) and a Genetic Algorithm (GA). The results of the comparison of the optimization of pollutant emissions by the data envelopment analysis and the Genetic Algorithm (GA) showed that when using the emission pattern expressed by the Genetic Algorithm (GA) compared to the data envelopment analysis, the pollutant emissions due to bitumen insulation production decrease significantly, indicating the superiority of the Genetic Algorithm (GA). Reducing carbon monoxide and nitrogen oxide emissions based on optimization will not only reduce air pollution and tackle climate change but also increase production efficiency, improve profitability, reduce direct and indirect costs and pave the way for sustainable competition with other similar bitumen and bitumen insulation industries.

Table 7. Optimal equations and points sobtained from statsmodels python regression for each pollutant

Explanatory Variable	Response Variable	Fitted Equation	R^2	Intersection points	Equivalent values placed in Eq (Y value)	Final value of the explanatory variable (Inverse transformation)
C_xH_y	T	$y = 0.1871x^4 + 0.3769x^3 - 0.6514x^2 - 1.553x + 0.3192$	0.8986	$x_1 = 0.419$ $x_2 = 1.339$ $x_3 = -1.039$	0.092171	8.392477
	Air	$y = -0.986x + 1E-15$	0.9723	$x_{AVE} = 0.239$	-0.13686	8.338872
NOx	T	$y = 0.4529x^2 + 0.8931x - 0.4529$	0.9567	$x = 0.230$	-0.32021	43.47766
	Air	$y = -0.9678x - 2E-15$	0.9367		-0.13433	36.43567
NO_2	T	$y = 0.448x^2 + 0.8959x - 0.448$	0.9583	$x = 0.227$	-0.31502	43.28612
	Air	$y = -0.9678x - 2E-15$	0.9367		-0.13433	36.43567
NO	T	$y = 0.3943x^2 + 0.9132x - 0.3943$	0.9545	$x = 0.372$	-0.25995	3.125606
	Air	$y = 0$	1		0	0
CO	T	$y = -0.3848x^4 + 0.3222x^3 + 1.1189x^2 - 1.448x - 0.4357$	0.8974	$x_1 = -1.412$ $x_2 = -0.493$ $x_3 = 0.864$	-0.61441	16.00193
	Air	$y = -0.9922x - 2E-15$	0.9844	$x_{AVE} = 0.347$	-0.13772	15.04624

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