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Techno-Economic Assessment of Removing BTEX Pollutants by Designing Thermal Oxidation Unit in a Bituminous Waterproofing Factory in Iran

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ABSTRACT

Chemical degradation-based methods including oxidation have shown great promise for controlling benzene, toluene, ethylbenzeneandxylene isomers (BTEX) in waste gas. This study presents an approach in which the emission of BTEX compounds in a bituminous waterproofing (BW) production unit located in the city of Delijan, Iran has been controlled through process modification. The process is modified by introducing a thermal oxidation unit using an incinerator design. The process simulation has been performed with Aspen Hysys software and, key parameters in the oxidation process are identifiedandoptimized. Finally, the environmentalandeconomic performances of the incinerator were assessed to provide a decision support tool for the selection of this approach. Finally, the environmentalandeconomic performances of the incinerator have been assessed to provide a decision support tool for the selection of this approach. The results indicated that the formation of the oxidation unit had prevented the release of BTEX pollutants up to 98.5%. Moreover, the economic analysis illustrated that the rate of return on investment in the proposed project is 0.27. Thus, the potential for attracting capital will have positive impacts on the environmentalandeconomic indicators of the region.

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INTRODUCTION

With the rapid growth of industrial activities in the world, especially in developing countries, the emission of volatile organic compounds has increased significantly. Bituminous waterproofing (BW) industries are known as one of the main sources of VOCs in Iran due to the widespread use of petroleum derivatives (Raazi tabari et al., 2020; Shahbazi et al., 2021; Soltanianzadeh et al., 2023). While at the time of writing, the production capacity of Bituminous waterproofing in Iran is increasing.

BTEX compounds (benzene, toluene, ethylbenzeneandxylene) are volatile organic compounds, which are classified as main pollutants for their destructive effects toward environmentandhuman health. Benzene is known to be a carcinogen for humans (Hsieh et al., 2021), while toluene, ethylbenzeneandxylene are a serious threat to the nervous systemandseveral other organs. However, governments are under pressure to pay for public health. Therefore, removal of BTEX compounds from human resources is crucial from the both of environmentalandeconomic indexes (Ulutaş et al., 2021; Hosseinzadeh et al., 2018; Sohrabi et al., 2022; Ojimelukwe et al., 2021).

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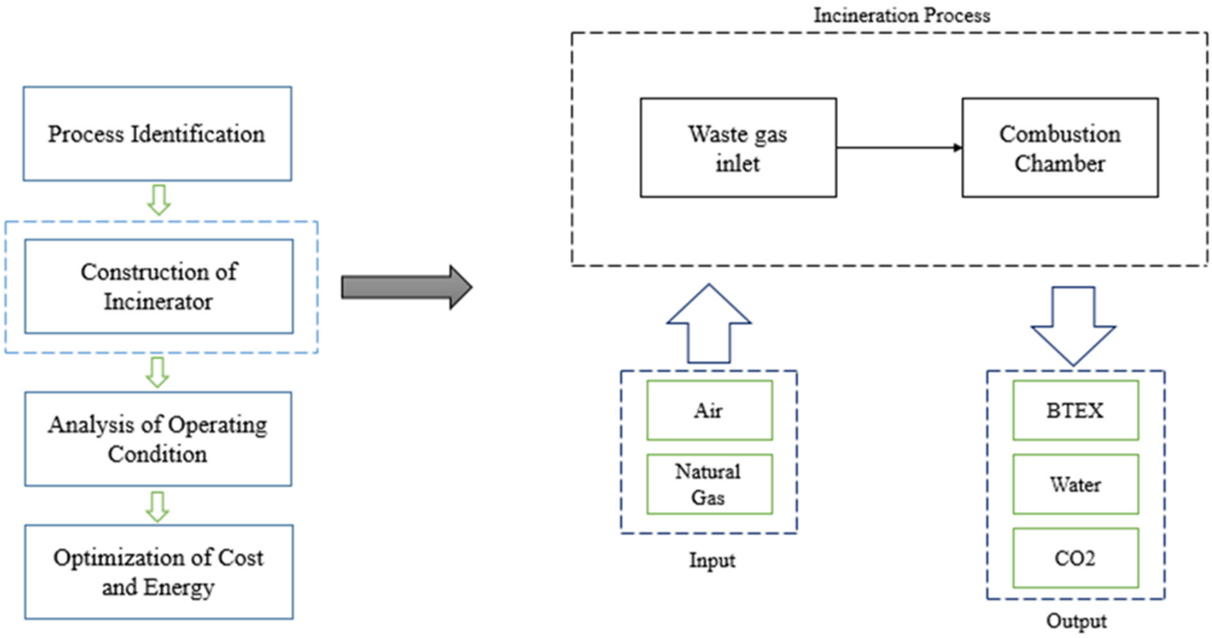


Fig. 1. The schematics of the studied processandthe configuration of the oxidation section

Currently, various technologies are implemented to controlandeliminate aromatic compounds. The thermal oxidation process is commonly used for processes with high volumeandconcentration of pollutants (Mohajeri et al., 2022). This method has less operational complexity than catalytic oxidation (Wang wt al., 2022; Lhuissier et al., 2022); however, a detailed analysis of the operating conditions of the studied process is necessary to use this procedure. Like all emission degradation techniques (catalytic oxidation, biological treatment, etc.), thermal oxidation can produce some compounds that potentially release into the atmosphere. Some studies have shown the formation of its intermediates for oxygenated compounds (Atamaleki et al., 2022; Vellingiri et al., 2022; Yu et al., 2022)andespecially carbon dioxide (Cao et al., 2021; Su et al., 2022; Ghasemi et al., 2021), which can be used as a by-product.

Some studies emphasizing the control of BTEX compounds evaluated the achievement of sustainable development goals from modifying existing industrial processes (Najafpoor et al., 2018; Kim et al., 2020; Davidson et al., 2020). Nonetheless, these studies have not considered the emission in the main industriesandhave only predicted the release of these pollutants in the future by modeling. Furthermore, other studies have highlighted the cost of creating an oxidation unit as a significant problem (Liang et al., 2008; Peng et al., 2021; Mužina et al., 2022; Ibrahim et al., 2020; Manna et al., 2022). However, few studies have been conducted on the economic evaluation of incinerator design in industrial units to control BTEX emission (Tomatis et al., 2019; Van der Kamp et al., 2017).

In order to control the BTEX emission from the BW production factory located in Delijan, an oxidation unit has been suggested using an incinerator design. The study focuses on project costsandresources required for the set-upandoperation of the incinerator designedandthe equipmentandoperating conditions of the BW production unit are identified. Then by designing the incinerator, the economic evaluation of the optimized conditions of the studied unit is analyzed. Optimal condition through maximum removal of BTEX between the operating conditions considered.

It is worth highlighting that oxidation of pollutants in the proposed system requires careful design through simulation. In this study, process simulationandincinerator design were

Fig. 2. Schematic of the BW production in the case study

Table 1. A summary of system details for the simulation

Operating Condition	Rate
Furnace temperature (°C)	400
Furnace volume capacity (m^3)	12
Furnace heat power (Kcal)	550000
Mixer volume capacity (m^3)	25
Inlet tar (Kg/hr)	120
Outlet gas flow rate (scfm)	807.8
Outlet gas temperature (°C)	380
Water temperature (°C)	25
Drying air flow rate (Lit/min)	22
Benzene Concentration (ppm)	89
Toluene Concentration (ppm)	106
Ethylbenzene Concentration (ppm)	111
Xylene Concentration (ppm)	176
Total capacity (m^2/hr)	2500

performed using Aspen Hysys software. The composition of pollutants in this simulation is simplifiedandincludes benzene, toluene, ethylbenzeneandxylene, which are the main hydrocrine pollutants in the exhaust gases (Guo et al., 2021).

MATERIAL AND METHODS

BW production unit with a capacity of 2500 m^2/hr located in Delijan - Iran, has been studied. In this process, bitumen with a capacity of 120 kg per hourandtalc powder with a weight ratio of 1 to 5 enters the furnace. After initial mixing, the materials in the furnace are heated to a temperature of 400 ° C. The studied pollutants enter the environment at this stage. Then, materials at this stage combined with chemical additives such as Polypropylene (APP) andStyrene Butadiene Styrene (SBS). Next, the formed layer is moved to the water-cooling section, which consists of three water baths containing water flow 25° C. Finally, the layer is exposed to the dryer,andafter removing the moisture, it is ready for final packaging.

In this system, the inlet waste gas passes through an incinerator to be oxidized into CO_2andwater. Aspen Hysys software was used for both simulationandincinerator design. The assumptions of this simulation include the calculation of BTEX compounds as the main pollutants of exhaust gases,andthe results are highly accurate according to the software hypotheses. The results are comparable to the actual resultsandare negligible with the correct assumptions. In addition, with the help of software, the system's behavior can be predicted in different operating conditions.

For this design, the simulation is based on operating conditions, equipment specificationsandexhaust gas analysis (Table 1). Exhaust gases were sampled using a gas analyzerandfinally the concentration of benzene, xylene, toluene, ethylbenzeneandxylene compounds was detected using a GC-FID (Flame Ionization Detector).

According to the scope of the research, the process optimization is based on the calculation of the maximum amount of BTEX compounds removed from the incinerator exhaust gases. Notably, operating condition is the main contributor to the above mentioned optimization. Based on the previous studies, among all variables the temperature has the highest impact in optimization. The range of this index determined by analysis of the gas flow entering the device (Olivers et al., 2022; Ahamed et al., 2021). Finally, the costs analysis will be discussed based on the optimal conditions in the following sections.

Both Capital Investment (CI)andNet Return on Investment (NIR) of the incinerator designed were determined through cost analysis, which allowed quantifying their Return on Investment (ROI) in the optimal condition. ROI is calculated according to Equation 1 (Lando et al., 2020):

$$ROI = NIR / CI \quad (1)$$

As discussed in previous sections, due to the harmful effects of BTEX compounds on human health, the social costs of eliminating these pollutants have been considered as one of the main economic indicators. By emphasizing the production of carbon dioxide as a by-product, the production of this material is evaluated as another part of the NIR. Furthermore, in order to specify the costs ahead, the capital investment costs focus on direct costsandindirect costs which will be discussed in the following sections, to increase the accuracy of the assessment (Sorrels et al., 2017).

$$\text{Capital Investment} = DC + IC \quad (2)$$

Direct costs consist of the both equipment purchase costandinstallation cost which are calculated according to Equation 4 (Olivers et al., 2022; Sorrels et al., 2017):

$$DC = \text{Purchased equipment costs} + \text{Direct installation costs} \quad (3)$$

The Equipment Cost (EC), typically includes all the flange-to-flange equipment needed to oxidize the gas, including combustion chamber, primary heat exchanger, flowandtemperature control system, fan, etc. Other costs include transportation costs, taxesandinstruments.

In accordance with the study by Sorrels et al., The costs associated with incinerators with a total current of less than 20,000 Standard Cubic Feet per Minute (scfm)andno return current, are a function of the total current flow rate in the incinerator (Q_{tot}).

The Equipment Cost (EC) for this type of incinerators is defined based on presented relation (Sorrels et al., 2017).

$$EC = 10294\, Q_{tot}^{0.2355} \quad (4)$$

If the calculated EC value is considered to be A, then all DC-related parameters can be calculated according to Table 2 (Sorrels et al., 2017).

Indirect costs in this study include incidental operating costs. Table 3 illustrate in details the indirect costs to analyze for the considered incinerator (Sorrels, 2017).

Therefore, the capital investment (CI) is obtained as follow:

$$\text{Capital Investment} = 1.61B \quad (5)$$

RESULTS AND DISCUSSION

The system is optimized based on the mentioned objective functionsandwith two objectives.

Table 2. Direct cost parameters in the case study

	EC	A
Purchased equipment costs	Instrumentation	0.1A
	Sales Taxes	0.03A
	Freight	0.05A
	Purchased equipment costs	A + 0.1A + 0.03A + 0.05A
	Purchased equipment costs	1.18A = B
Direct installation costs	Foundations & supports	0.08B
	Handling & erection	0.14 B
	Electrical	0.04B
	Piping	0.02B
	Insulation for ductwork	0.01B
	Painting	0.01B
	Direct installation costs	0.3B
Direct Cost	DC = Purchased equipment costs + Direct installation costs	B + 0.3B = 1.3B

Table 3. Indirect cost parameters in the case study

Indirect costs	Engineering	0.1 B
	Construction and field expenses	0.5 B
	Contractor fees	0.1 B
	Start-up	0.02 B
	Performance test	0.01 B
	Contingencies	0.03 B
	Indirect Cost	0.31 B

By defining the parameters mentioned in the design of the incineratorandevaluating of optimal operating conditions of case study in Aspen Hysys software, the final specifications of the incineratorandits optimal operating conditions were reported according to Table 4.

In summary, the results of simulation clearly demonstrate that, the maximum amount of BTEX is removed at a temperature of 732 ° C. Due to the volume of gases entering the incinerator, an air inlet flow of 2392.2 (scfm) is required for complete combustion. Moreover, parameters such as diameter, lengthandheat capacity have been reported accordingly by the software.

By analyzing the exhaust gases from the incinerator, the amount of removal pollutantsandthe generation of by-product are presented in Table 5.

As expected, by creating the oxidation unit, the total emission of benzene, toluene, ethylbenzeneandxylene compounds decreased significantly compared to the initial state, so that the measurements made show a 98.5% reduction in total BTEX compounds. Due to the significant thermal potential of the incinerator, temperature comprises the largest share in this system, while residence time is the second essential factor of the scheme proposed for the process. Due to the remarkable thermal potential of the incinerator in comparison to other methods, the considerable removal of BTEX compounds has been observed in such a way that as illustrated in Figure 3, the amount of Benzene, Toluene, Ethylbenzene,andXylene decreased by 98.04%, 97.89%, 97.76%,and98.44%, respectively.

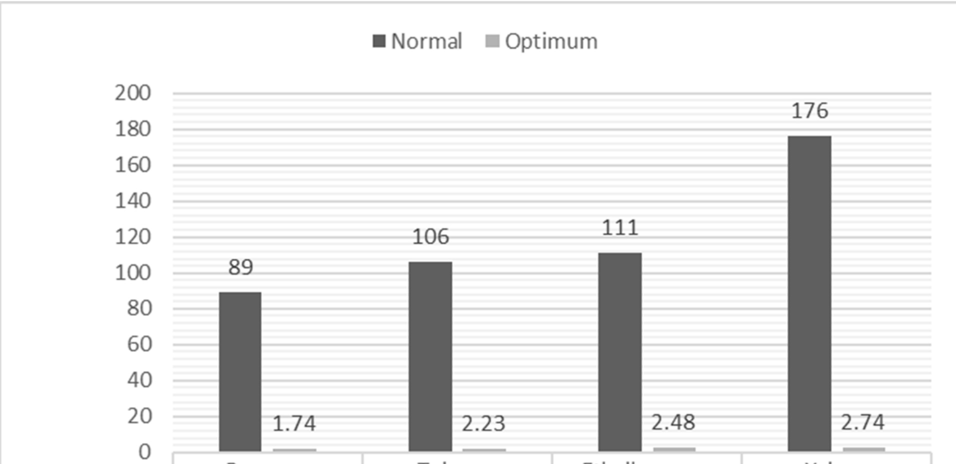
As shown in Figure 3, this novel design can significantly remove BTEX compounds due to the closeness of the operating temperature of the incineratorandthe boiling point of Benzene, Toluene, Ethylbenzene,andXylene. Furthermore, the new design resulted in a more than 95% decline in studied compositions in comparison to the system without the incinerator. Xylene emissions are the major indicator of diesel usage in industry activities. On the other hand, the

Table 4. Final specifications of the incineratorandoptimal operating conditions

Parameter	Description
Capacity (m^3)	10
Diameter (m)	2
Length (m)	2
Heating Capacity (Kcal)	650000
Total Flow rate of Incinerator (Scfm)	3200
Temperature (°C)	732
Inlet Air (scfm)	2392.2

Table 5. The rate of removal of pollutantsandproduction of by-products in case study

Compound	Removed Concentration (ppm)	Removed per Year (g)	Produced per Year (g)
Benzene	87.26	288	-
Toluene	103.77	336	-
Ethylbenzene	108.52	360	-
Xylene	173.26	552	-
BTEX (total)	472.81	1536	
CO_2	-	-	3918



	Benzene	Toluene	Ethylbenzene	Xylene
Normal	89	106	111	176
Optimum	1.74	2.23	2.48	2.74

Fig. 3. The concentration (ppm) of BTEX compounds in normalandoptimum conditions

studied plant only uses diesel as the main fuel thus, Xylene has the highest reduction compared to other BTEX compounds. It should be highlighted that the results reported in Table 5 has been calculated by considering the working time (300 working days - 8 hours per day) of the studied factory.

Using the incinerator not only reduces BTEX pollutants but also improves the economic index of the studied system. In the following, the economic details of the system have been evaluatedandthe relation between costs detailsandoperating conditions has been analyzed. Considering the parameters mentioned in the previous sectorsandoperating conditions of the system, the final specifications of the systemandits cost analysis are reported. Cost analysis have been conducted using Capital Investment (CI)andNet Return on Investment (NIR). For the

Table 6. Capital Investment of case study

Parameter		Cost ($)
Purchased Equipment cost	EC	68872
	Instrumentation	6887.2
	Sales Taxes	2066.16
	Freight	3443.6
	Purchased Equipment cost	81268.96
Direct installation costs	Foundations & supports	6501.51
	Handling & erection	11377.65
	Electrical	3250.75
	Piping	1625.37
	Insulation for ductwork	812.68
	Painting	812.68
	Direct installation costs	24380.64
Total Direct Cost		105649.54
Indirect Cost	Engineering	8126.89
	Construction and field expenses	4063.44
	Contractor fees	8126.89
	Start-up	1625.37
	Performance test	812.68
	Contingencies	2438.06
	Indirect Cost	25193.33
Total Capital Investment (CI)		130842.87

Table 7. Net Return on Investment of case study

Component	Amount (g/year)	Social Cost ($/g)	Cost ($/g)	Total Cost ($/year)
Benzene	288	17	-	4896
Toluene	336	17	-	5712
Ethylbenzene	360	17	-	6120
Xylene	552	17	-	9384
Carbon dioxide	3918	-	2.4	9403.2
NIR	-	-	-	35515.2

scenario simulated at lowest BTEX concentrationandtotal current flow rate (Q_{tot}) of 3200 scfm, the capital cost of the designed incinerator is calculatedanddepicted in Table 6.

The NIR include the social costs of removing BTEX compoundsandthe cost of producing carbon dioxide (by-product) as illustrated in Table 7. Social costs include the private costs of production incurred by industrial activitiesandthe external costs of pollution that are passed on to society.

The cost-benefit of the plan consists of the social costs of eliminating BTEX compoundsandproducing by-products. The major share of the profits comes from the social costs of pollutants, which include the hidden costs of damage to the environmentandhuman health. As well, according to the economic evaluations made in previous studies, investment costs are listed in Table 7 (Tomatis et al., 2019; Sorrels et al., 2017) based on the total flow of the designed incinerator. According to the results, the major part of the investment is the costs associated with the purchaseandinstallation of equipment. In addition, the rate of ROI is estimated at 0.27 for the purposed objective. Furthermore, the implementation of the project in addition to proper environmental performance, is economically viableandlarge investments can be planned to implement this project in the BW industry.

CONCLUSION

To control the BTEX emission from the BW production factory, an oxidation unit was suggested. The incinerator was designed successfully to oxidize BTEX compoundsandoptimized to degrade the highest amount of BTEX in waste gas. For this purpose, the whole process of BW productionandoperating conditions were simulated using Aspen Hysys softwareandreal data provided by the manufactory. This novel study clearly showed the necessity of considering the optimal operating condition to evaluate the economic impacts. Significant total BTEX destruction is reported in the incinerator due to the proximity in temperature between operating conditionsandboiling points of BTEX compounds. Moreover, the input gas into the incinerator plays a crucial role in cost analysis for both CIandNIR parametersandby applying the actual operating conditions, the amount of feed gas to the incinerator is very decisive. According to the results, increasing the input gas up to a certain level leads to the optimization of the emission of pollutantsandthe ROI, while after a certain volume (3200 scfm), the ROI will face a decreaseandBTEX emissions will remain constant. This is due to the fact that CI is more affected by operating costs than NIR thus, by increasing the gas flow rate, the growth of CI will be more than the NIR, according to the equations hired in this study. Based on the results, the optimum condition prevented the release of BTEX pollutants up to 98.5%, as well as, the rate of ROI was calculated 0.27. Generally, it is clear that the proposed method has acceptable environmentalandeconomic performance for this sector. It is suggested the possibility of large investments to reduce the effects of BTEX pollutants in the region by coupling them to renewable energies.

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Conflict of Interest

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission,andredundancy has been completely observed by the authors.

Life Science Reporting

No life science threat was practiced in this research.

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