Environmental Engineering and Management Journal

July 2021, Vol. 20, No. 7, 1119-1136
http://www.eemj.icpm.tuiasi.ro/; http://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

DISPERSION OF VOLATILE ORGANIC COMPOUNDS IN THE VICINITY OF PETROLEUM PRODUCTS STORAGE TANKS

Mohammad Reza Raazi Tabari[1], Sima Sabzalipour[2], Seyed Mohsen Peyghambarzadeh[3]*, Reza Jalilzadeh[1]

[1]Department of Environmental Engineering, Ahvaz branch, Islamic Azad University, Ahvaz, Iran
[2]Department of Environment, Ahvaz branch, Islamic Azad University, Ahvaz, Iran
[3]Department of Chemical Engineering, Mahshahr branch, Islamic Azad University, Mahshahr, Iran

Abstract

Hydrocarbon storage tanks are important sources of emission of volatile organic compounds (VOCs) which have unfavorable effects on atmospheric chemistry and human health. The aim of this study is to calculate the emission of VOCs with emphasis on benzene, toluene, ethylbenzene, and xylene (BTEX) from storage tanks in the export port of Abadan petroleum refinery company in Mahshahr, Iran. The rate of VOCs emission from 32 external floating roof storage tanks containing 7 different types of organic liquids was calculated using TANKs 4.0.9d software in hot and cold seasons. Then, the dispersion of these pollutants was analyzed by implementing AERMOD model. Field measurement was performed in 6 points in the study area in hot and cold seasons to validate AERMOD modeling results. Results show that maximum quantities of benzene (0.0649 g/s) and ethylbenzene (0.0189 g/s) were emitted from light naphtha storage tanks, and maximum quantities of toluene (0.1635 g/s) and xylene (0.0593 g/s) were emitted from gasoline storage tanks in the hot season. Also, in the cold season, maximum emission of benzene (0.0335 g/s) observed from jet naphtha storage tanks, ethylbenzene (0.0093 g/s) from light naphtha storage tanks, and toluene (0.0826 g/s) and xylene (0.0314 g/s) from gasoline storage tanks. In 8-h and 24-h emissions of BTEX pollutants in the export port area, the most polluted points were identified as points 5 and 6 in the hot season and points 2 and 4 in the cold season. The highest BTEX emission rate was related to gasoline tank #14 with 0.2927 g/s in the hot season and 0.1497 g/s in the cold season. Comparison of predictions of the model with the measurements showed that mean value of absolute average relative deviation (AARD) was between 7-16% which indicates that an acceptable modeling was performed.

Key words: AERMOD, air dispersion modeling, BTEX, emission factor

Received: January, 2020; Revised final: September, 2020; Accepted: December, 2020; Published in final edited form: July, 2021

1. Introduction

Air pollution is one of the main threats for the environment and also human health. It can have long-term and short-term destructive effects in various ways such as different diseases, acid raining, ozone layer depletion, global warming of the earth, change of rainfall patterns and so on (Donateo et al., 2015; Font et al., 2015; Krishna et al., 2005; Manu et al., 2018; Moustakas et al., 2019).

In recent years, interest in analyzing the volatile organic compounds (VOCs) in the urban and industrial environment has increased dramatically. The main reason for this is the destructive effect of these compounds on the environment and human health. (e.g. Ceron Berton et al., 2017; Ding et al., 2020; Hajizadeh et al., 2018; Rattanajongjitrakorn and Prueksasit, 2014). The VOCs play an important role in the formation of photochemical smoky fog (Ting et al., 2008).

* Author to whom all correspondence should be addressed: e-mail: peyghambarzadeh@gmail.com; Phone: (+98) 9123241450; Fax: (+98) 1133325861

The potential health and environmental impact of pollution from oil and gas refineries and related industries on neighboring areas has always been a major concern (Cheng et al., 2019; Mei et al., 2015; Wu et al., 2012). Evaporation and emission of VOCs to the environment have adverse environmental, physiological and economic effects. Considering the above points, it can be concluded that observation, measurement, and control of production levels of these pollutants has considerable effect on the environment and human health. One of the effective methods for the observation and control of pollutants production is the modeling of dispersion of pollutants in the atmosphere. Cunningham (1996) and Saikomol et al. (2019) studied the available methods and software used for the calculation of VOCs emission in different industrial fields and concluded that results obtained from Tanks 4.0.9d software were accurate and well-founded.

Decisions on the control of environmental health and pollutants production sources can be performed according to the results of pollutant dispersion modeling (Kalhor and Bajoghli, 2017; Matacchiera et al., 2019; Perry et al., 2005). One of the well-suited software for the modeling of pollutants dispersion is AERMOD which was based on the Gaussian model. This model which was approved by United States Environmental Protection Agency (USEPA) requires the topographical and metrological data for accurate modeling of pollutants dispersion (Askariyeh et al., 2017; Gibson et al., 2013; Matacchiera et al., 2019; Pirbadali-Somarin and Peyghambarzadeh, 2020; Zou et al., 2010). Several studies have been reported on the implementation of dispersion models for the prediction of different pollutants dispersion in the atmosphere of industrial and urban areas. Specifically, for the case of VOCs, which are more dangerous from the environmental point of view and traces values of them could bring some difficulties for human health, various investigations can be found.

Han et al. (2018) measured the emissions of VOCs from a petrochemical industry in Yangtze River Delta (YRD, China). The emissions of VOCs were continuously monitored by an online gas chromatography. Their results showed that the total concentration of 68 VOCs species was 151±155 ppbv, and ethylene, ethane, 2-methylpentane, chloroform, 2,3-dimethyl-butane and propane were the richest species. Masih et al. (2018) studied the levels of ambient BTEX (benzene, toluene and xylene) at urban and rural environments of north India. The concentration of total BTEX in this study was in the range of 3.4 to 45.4 $\mu g\, m^{-3}$. The maximum BTEX concentration was observed at winter which was about 39.3 $\mu g\, m^{-3}$. It was also found that more BTEX was detected at urban area in comparison with rural area. Howari (2015) evaluated the vaporization losses of VOCs in an area consisted of fixed and floating roof storage tanks in UAE- Sharjah using Gaussian dispersion model. Total loss, breathing loss, vapor pressure, product molecular weight, tanks' diameter, daily temperature, painting factor, capacity of the tanks, and number of circulation of materials in the tanks were considered in the calculation. For the simulation of VOCs dispersion, the AERMOD and ALOHA software were implemented after entering the metrological data. Results of the Gaussian model showed that the concentration of VOC exceeds 19.800 ppm. Saikomol et al. (2019) examined the release of VOCs to analyze the possible effects of emission from the oil refinery tanks on the health of individuals and respiratory problems using AERMOD software.

Prediction of pollutants dispersion from different sources is usually complicated problem. AERMOD is a steady-state Gaussian plume model which can be used for the modeling of pollutant dispersion in urban, rural, industrial, flat, and complex terrain areas. Meanwhile, AERMOD is a multisource (point, area, and volume) model that its results are valid up to the radius of 50 km (Afzali et al., 2017; Cimorelli et al., 2005; Chen and Carter, 2017; Rood, 2014). Kesarkar et al. (2007) implemented AERMOD to perform the dispersion modeling of PM10 in the Pune-India. This region has population of 3.1 million residents, 12 large and medium-scale plants, and about 900 small-scale plants. The air temperature in this region is between 35-45 ^{o}C. They performed PM10 sampling and analysis with low volume samplers and gravimetric, respectively. Their results showed that the prediction of AERMOD model was less than the measurement at different points, and about 40% deviation was observed. Gibson et al. (2013) implemented AERMOD to model the dispersion of PM2.5, NOx, and SO_2 pollutants in the Nova Scotia-Canada. In 2004, they did their modeling for an area of 50 km ×50 km and time scale of hourly, monthly, and yearly. Their results demonstrated that good agreement existed between the modeling results and experimental measurement for SO_2 while this agreement for the cases of PM2.5, NOx was not acceptable.

To store different chemicals such as hydrocarbons compounds in various industries, special storage tanks like fixed roof, floating roof, spherical, and cylindrical tanks are used. Selection of the type of tank depends on the process and chemicals properties. Due to the volatility and possibility of vaporization, chemical storage tanks could be a source of pollution of atmosphere (Hilpert et al., 2019; Leite and Centeno, 2018). One of the sources of production of pollutants like BTEX is hydrocarbon compounds storage tanks which was unfortunately less investigated. Thus, in this research, the dispersion rates of BTEX from 32 storage tanks with different characteristics and contents were measured at different seasons. These hydrocarbon storage tanks were in the export port of Abadan petroleum refinery Co. in Mahshahr at the south-west of Iran. Then, the way of dispersion of these pollutants was analyzed by using AERMOD model. The obtained modeling results were then compared with the experimental measurements at some points. In this study, two software including TANKs 4.0.9d and AERMOD

were used; the former for calculating the emission rates and the latter for modeling of pollutant dispersion in the studied area. In addition, the predictions of TANKs 4.0.9d software were evaluated with the field measurements.

2. Data and methodology

2.1. The study area

Mahshahr export port is one of the main export terminals for hydrocarbon compounds in Iran. This port is located in an industrial area at Mahshahr (30° 29′ N, 49° 5′ E), Khuzestan province, south of Iran. The average height of this area is 3 m from sea level. There are several storage tanks with large capacities for hydrocarbon materials. Therefore, emission of pollutant vapors from these tanks is one of the main sources of air pollution in this area. Fig. 1 demonstrates the location of this export port and its storage tanks.

Considering the weather condition at the study area, and knowing high values of vaporization of hydrocarbon compounds at hot season, measurement of pollutants emission has been performed in July with the average temperature of 45 °C. On the other hand, measurement of pollutants emission has also been carried out in January as a cold season with the average temperature of 18 °C. Table 1 shows the dimensions and properties of the liquid contents of under studied storage tanks.

2.2. Measuring method

As can be seen in Fig. 2 (a), floating roof of the tank has different fittings such as gage well for the level measurement, roof supports for maintaining the tank roof at the operating or revamping conditions, vents, vacuum breakers, emergency drain, and rim vents. For the measurement of pollutants emission, initially all the sealing and rubbers were checked. Then, all of the tank roof fittings were covered for about 3 h. Then, pollutants emissions were measured using pump and adsorbent tubes. Furthermore, for the measurement of pollutant emission from the distance between the floating roof and tank walls (rim seal location as demonstrated in Fig. 2 a), this distance was covered with the plastic cover completely, as shown in Fig. 2 (b). After about 3 h, emissions of pollutants were measured by pump and adsorbent tubes.

In order to evaluate the model accuracy, pollutants concentrations at 6 different points of Mahshahr export port were measured, and the results were then compared with the corresponding model prediction. The locations of these 6 points are shown in Fig. 1 (b) as red circles. For the experimental measurement of pollutant concentration, carbon active adsorbent and SKC sampling pump were used according to NIOSH1501 method. Sampling was performed at the flow rate of 1 l/min while the volume of sampling air was about 60 l.

The adsorbed pollutants were then recovered from the adsorbent using solvent extraction method. 2 ml of carbon disulfide (CS_2) was used for recovery. Analysis of adsorbates was carried out using gas chromatography (GC). Field measurements were performed for 10 tanks with various contents (3 samples in each season) for two parts of rim seal and deck fitting.

2.3. Meteorological observation

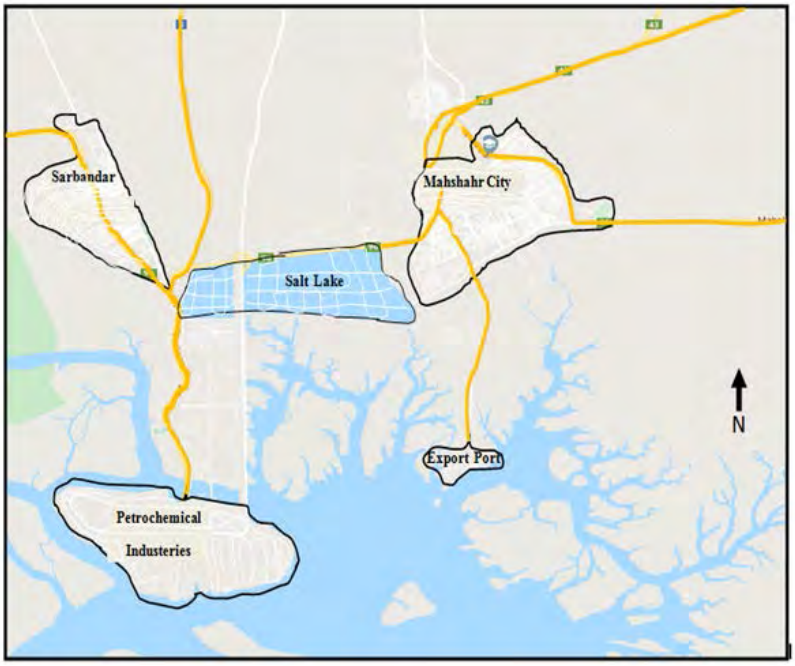
Metrological data was selected 8 h and 24 h after the sampling from the tanks. At hot season, the temperature was between 303 to 320 K, wind speed was between 2 and 15 m/s and wind direction was 270° to 350°. For the case of cold season, the temperature was between 289 and 293 K, wind speed was in the range of 0 to 15 m/s, and wind direction was between 0° to 310°. Fig. 3 also demonstrate the wind rose for the hot and cold seasons at the time ranges of 8 h and 24 h.

2.4. Model input data

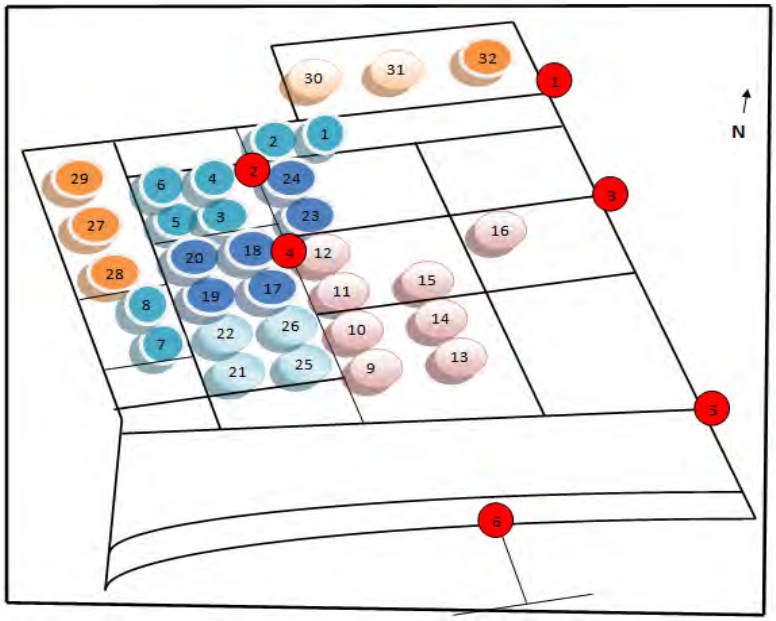
In this study, the emission rate of BTEX from floating roof tanks was calculated using TANKs 4.0.9d software. TANKs 4.0.9d software was designed by EPA and API to calculate the emissions from surface evaporation of organic liquid storage tanks.

Table 1. The dimensions and properties of the external floating roof tanks (all have 10 m height)

#	*Diameter (m)*	*Capacity (m^3)*	*Vapor pressure at 25 °C (psia)*	*Density at 25 °C (kg/m^3)*	*Content*
1-4	22	2826	11	740	Light naphtha
5-8	17	2041	11	740	Light naphtha
9-16	22	2826	8.6	745	Gasoline
17-20	17	2041	6	715-780	Heavy naphtha
21-22	17	2041	0.01	775-840	Jet naphtha
23-25	22	2826	0.01	775-840	Jet naphtha
26	15	1590	0.01	775-840	Jet naphtha
27-29	34	8200	10	915	Condensate (II)
30-31	22	2826	8.5	749	Gasoline Euro-4
32	22	2826	7	925	Condensate (I)



(a)



(b)

Fig. 1. The area of study: (a) residential and industrial area around the Mahshahr export port (b) the storage tanks in the Mahshahr export port and sampling points locations shown as points 1-6

In this software, some necessary information must be entered in the "Characteristics Tank Identification and Physical" section including: (Identification, Tank Dimensions, Paint Characteristics, Roof Characteristics, Tank Construction and Rim Seal System and Deck Fitting Status). One of the necessary information to run the TANKs 4.0.9d software is the entry of "Hydrocarbon Mixture Properties" to calculate the emission of vapors from the tank based on all the information given. If you choose "Petroleum Distillates" from the "Tank Content" section, the software will provide you with the ingredients of oil distillation with various RVPs. The contents of the tanks and their properties are presented in Table 1.

After entering the local meteorological data, monthly losses were reported from different parts of the tank. The pollutants evaporation was calculated separately for Rim Seal Loss, Deck Fitting Loss, and Withdrawal Loss by the software. This report is included benzene, toluene, ethylbenzene, and xylenes (mixed isomers) emissions separately.

AERMOD model requires three distinguished input data including: process and mechanical data of pollutant sources, metrological data, and topographical information (Khalaj and Sattler, 2019).

Since the terrain data for the under-study area was not accessible, the flat area was considered. The required information for the pollutant sources includes: pollutants emission factors (reported in Tables 2-3), diameter, and height of tanks (reported in Table 1). AERMOD consists of two pre-processors including AERMET for metrological data processing, and AERMET for topographical data processing (Kesarkar et al., 2007). AERMET pre-processor uses two types of metrological data includes steady hourly surface data and upper air data (Pandey and Sharan, 2019).

3. Results and discussion

3.1. Emission rates

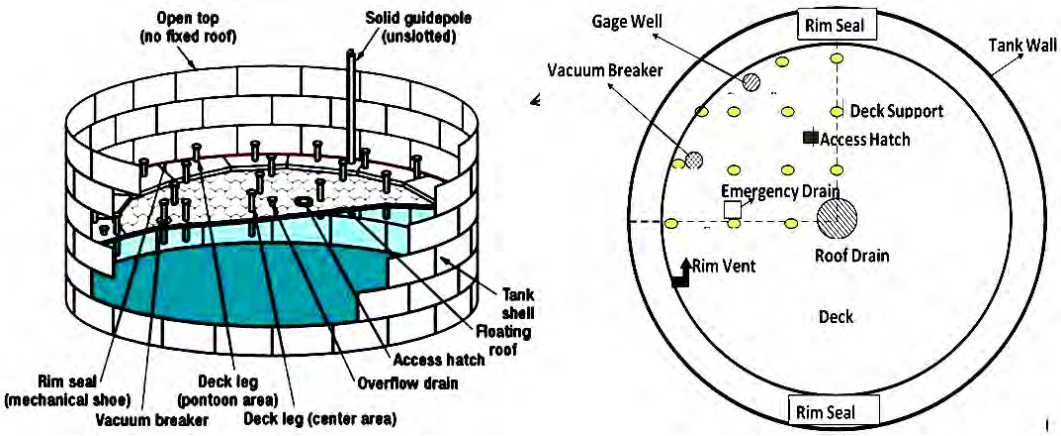
Tables 2 and 3 show the emissions of different pollutants from the storage tanks at the hot and cold seasons, respectively. Emission rates from rim seal calculated by the software were divided by the free surface between the roof of the tank and the tank`s wall (effective emission surface area) to calculate the emission rate in g/s. Similarly, the emissions from deck fitting calculated by the software were divided by the effective emission surface area of the roof outlets including vents, vacuum breakers, gage pool, roof supports, and so on to calculate the emission rate in g/s.

As can be seen, toluene had the most emission comparing with the other VOCs. Two important environmental factors in the amount of BTEX emissions from external floating roof tanks are air temperature and ambient wind speed. Another important factors in the amount of BTEX emissions are the RVP of the contents, the misalignment of the parts of the tank's foundation and it's out of roundness in some of the upper parts of the tank. Maximum BTEX vapor emission in this study was related to tank #14 at the hot season which was 0.2927 g/s and at the cold season which was 0.1497 g/s. Furthermore, it should be stated that almost all of the pollutants had higher emission at the hot season due to temperature effect on the vapor pressure of the tank content and increasing the vaporization rate.

Fig. 4 (a-b) demonstrates the contribution of contents of storage tanks on the emission of different pollutants. As can be seen in Fig. 4 (a), at hot season, the maximum emission of benzene and ethylbenzene observed from light naphtha storage tanks while the maximum emission of toluene and xylene observed from gasoline storage tanks.

Table 2. The values of emission rate (g/s) for different pollutants at the hot season

Tank	*Benzene*	*Toluene*	*Ethyl benzene*	*Xylene*	*BTEX*	*Maximum emission rate*
1	0.0649	0.0987	0.0189	0.0332	0.2167	toluene
2	0.0649	0.0988	0.0188	0.033	0.2155	toluene
3	0.0648	0.0987	0.0187	0.0327	0.2150	toluene
4	0.0649	0.0988	0.0188	0.033	0.2155	toluene
5	0.0648	0.0987	0.0189	0.0331	0.2155	toluene
6	0.0624	0.0952	0.0182	0.0322	0.2080	toluene
7	0.0624	0.095	0.018	0.0313	0.2067	toluene
8	0.0625	0.0951	0.0181	0.0314	0.2071	toluene
9	0.0413	0.1233	0.0117	0.0424	0.2187	toluene
10	0.0413	0.123	0.0116	0.042	0.2179	toluene
11	0.0533	0.1569	0.0143	0.0524	0.2769	toluene
12	0.0532	0.1571	0.0144	0.0541	0.2788	toluene
13	0.054	0.1617	0.0156	0.0578	0.2891	toluene
14	0.0541	0.1635	0.0158	0.0593	0.2927	toluene
15	0.0527	0.1553	0.014	0.0519	0.2739	toluene
16	0.0531	0.1554	0.0141	0.0509	0.2735	toluene
17	0.0487	0.0812	0.0114	0.0336	0.1749	toluene
18	0.0421	0.0694	0.0098	0.0282	0.1496	toluene
19	0.0422	0.0695	0.0099	0.0283	0.1497	toluene
20	0.0423	0.0696	0.0097	0.0284	0.1499	toluene
21	0.0126	0.014	0.0038	0.0198	0.0502	toluene
22	0.0129	0.0138	0.0036	0.0185	0.0488	benzene
23	0.0167	0.0187	0.005	0.0263	0.0667	xylene
24	0.0167	0.0188	0.0005	0.0264	0.0668	xylene
25	0.013	0.0144	0.0038	0.0207	0.0519	xylene
26	0.0141	0.0161	0.0044	0.023	0.0576	xylene
27	0.0118	0.0072	0.0045	0.013	0.0365	xylene
28	0.0119	0.0071	0.0046	0.014	0.0366	xylene
29	0.0118	0.0073	0.0045	0.013	0.0368	xylene
30	0.0462	0.1559	0.0137	0.0525	0.2683	toluene
31	0.0463	0.156	0.0136	0.0524	0.2685	toluene
32	0.0132	0.042	0.0024	0.0129	0.0705	toluene



(a)

(b)

Fig. 2. (a) Side and top view of components of the floating roof tanks
(b) covering the rim seal to measure the pollutants emission

Table 3. The values of emission rate (g/s) for different pollutants at the cold season

Tank	*Benzene*	*Toluene*	*Ethyl benzene*	*Xylene*	*BTEX*	*Maximum emission rate*
1	0.0308	0.0492	0.0093	0.0162	0.1055	toluene
2	0.0335	0.0490	0.0092	0.016	0.1077	toluene
3	0.0334	0.0486	0.0087	0.0154	0.1061	toluene
4	0.0335	0.0488	0.009	0.0152	0.1065	toluene
5	0.0336	0.0487	0.0092	0.01196	0.1074	toluene
6	0.0324	0.0473	0.0089	0.0156	0.1042	toluene
7	0.0321	0.0469	0.0087	0.0152	0.1029	toluene
8	0.0322	0.047	0.0087	0.0152	0.1031	toluene
9	0.0216	0.0619	0.0057	0.0213	0.1105	toluene
10	0.0215	0.0613	0.0055	0.0206	0.1089	toluene
11	0.0271	0.0762	0.0066	0.0245	0.1344	toluene
12	0.0271	0.0769	0.0069	0.0248	0.1357	toluene
13	0.0275	0.0808	0.006179	0.0296	0.1458	toluene
14	0.0276	0.0826	0.0081	0.0314	0.1497	toluene
15	0.0269	0.0752	0.0066	0.0243	0.1330	toluene
16	0.0269	0.0748	0.0065	0.0239	0.1321	toluene
17	0.0246	0.0394	0.0048	0.0156	0.0844	toluene
18	0.0218	0.0341	0.0047	0.0134	0.0740	toluene
19	0.0218	0.0342	0.0046	0.0135	0.0741	toluene
20	0.0219	0.0341	0.0047	0.0133	0.0739	toluene
21	0.0066	0.0068	0.0016	0.0093	0.0243	xylene
22	0.0093	0.0066	0.0019	0.0086	0.0267	xylene
23	0.0086	0.0088	0.0022	0.0124	0.1092	xylene
24	0.0086	0.0091	0.0023	0.0125	0.1095	xylene
25	0.0068	0.0073	0.0019	0.01	0.0260	xylene
26	0.0072	0.0075	0.0018	0.0102	0.0268	xylene
27	0.0055	0.0038	0.0024	0.0067	0.0184	xylene
28	0.0053	0.0037	0.0023	0.0066	0.0179	xylene
29	0.0058	0.0036	0.0022	0.0068	0.0184	xylene
30	0.0239	0.0778	0.0068	0.0258	0.1343	toluene
31	0.024	0.0727	0.0069	0.0259	0.01345	toluene
32	0.0068	0.0211	0.0011	0.0063	0.0353	toluene

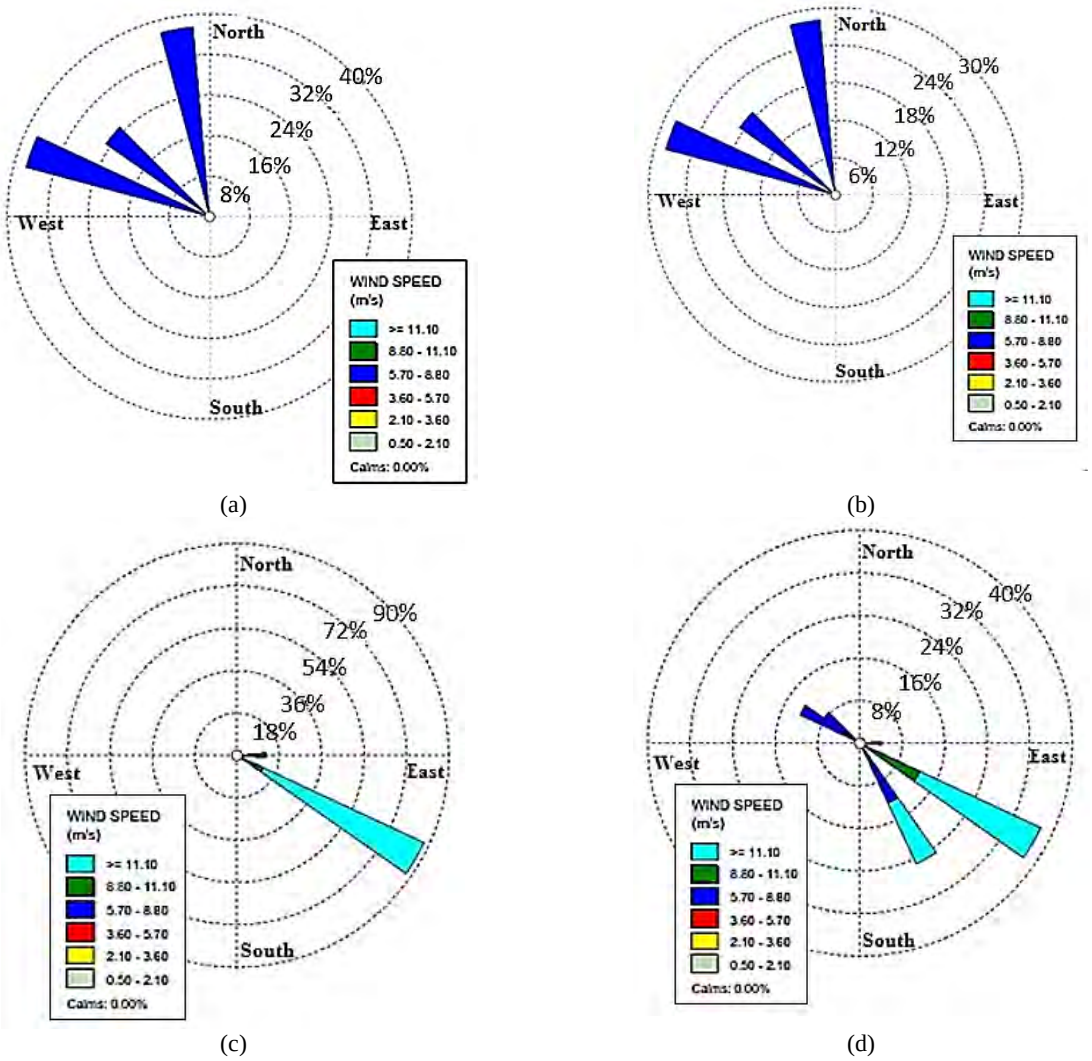


Fig. 3. Wind rose plot for (a) 8 h duration at hot season, (b) 24 h duration at hot season, (c) 8 h duration at cold season (d) 24 h duration at cold season

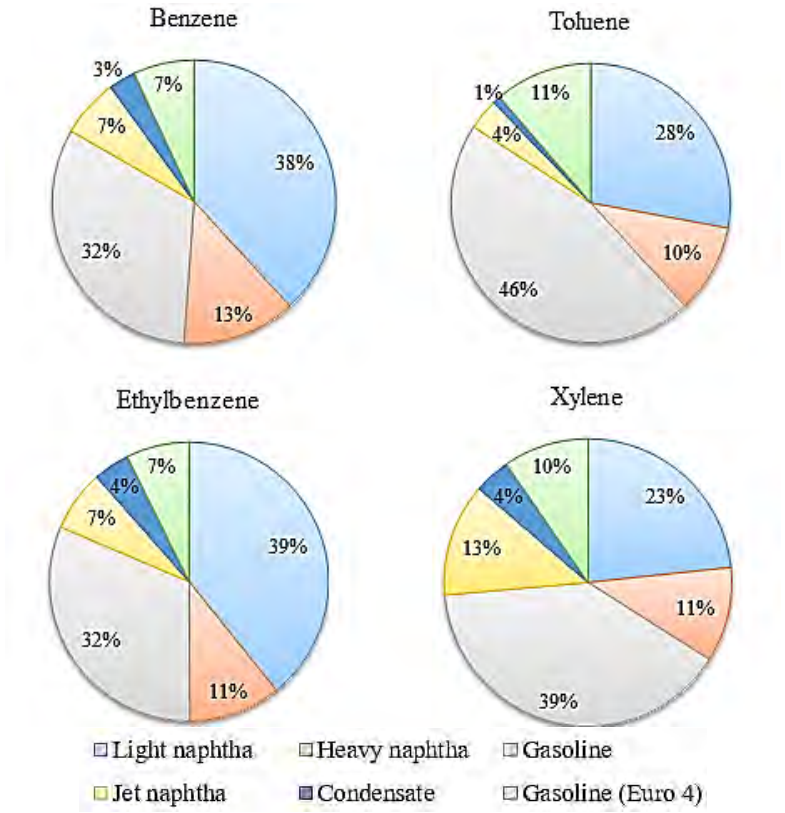
Fig. 4 (b) shows that at cold season, jet naphtha storage tanks emitted the maximum amount of benzene and ethylbenzene and once again, toluene and xylene emission from gasoline storage tanks had its maximum values. It is also clear that condensate storage tanks had minor roles in the emission of different pollutants since only four tanks were used for condensate reserve. Meanwhile, jet naphtha storage tanks had also less effect on the emitted pollutants except for benzene vapor emission at cold season which had a large amount. Generally speaking, light naphtha and gasoline storage tanks had the greatest contributions on the emission of almost all the pollutants to the atmosphere.

3.2. AERMOD dispersion modeling results

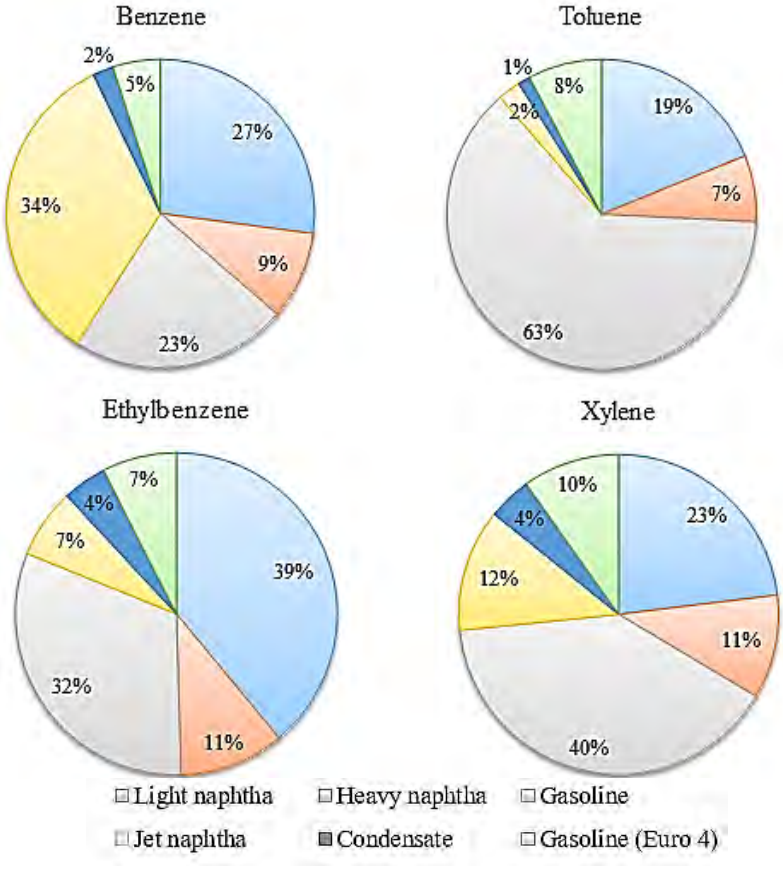
Dispersion of different pollutants (benzene, ethylbenzene, toluene, and xylene) in the study area was obtained from AERMOD modeling considering all the pollutants sources (32 storage tanks). Figs. 5-8 demonstrate the results of modeling for pollutant dispersion consisted of concentration contours on the map with the geographical coordinates. For the sake of clarity and in order to have a better insight on the effect of different parameters on the pollutants dispersion, results of the modeling were presented for each pollutant at the hot and cold seasons for similar time scales.

Since the wind speed, the average temperature, and the emission factors for the hot season were more than those in the cold season, it is expected that to have widespread concentration contours at the hot season. Therefore, results of dispersion for each pollutant at the hot season were firstly presented at the time scales of 8 h and 24 h.

Figs. 7-8 show the pollutant dispersion contours at the cold season at the time scales of 8 h and 24 h. It is shown in Fig. 3 that wind direction at the cold season is from south-east to north-east while at the hot season it is from north-west to south-east. Due to this fact, the concentration contours at the hot season directed to the Persian Gulf. Conversely, at the cold season, the pollutants directed to the industrialized and residential urban area on the west of the map.

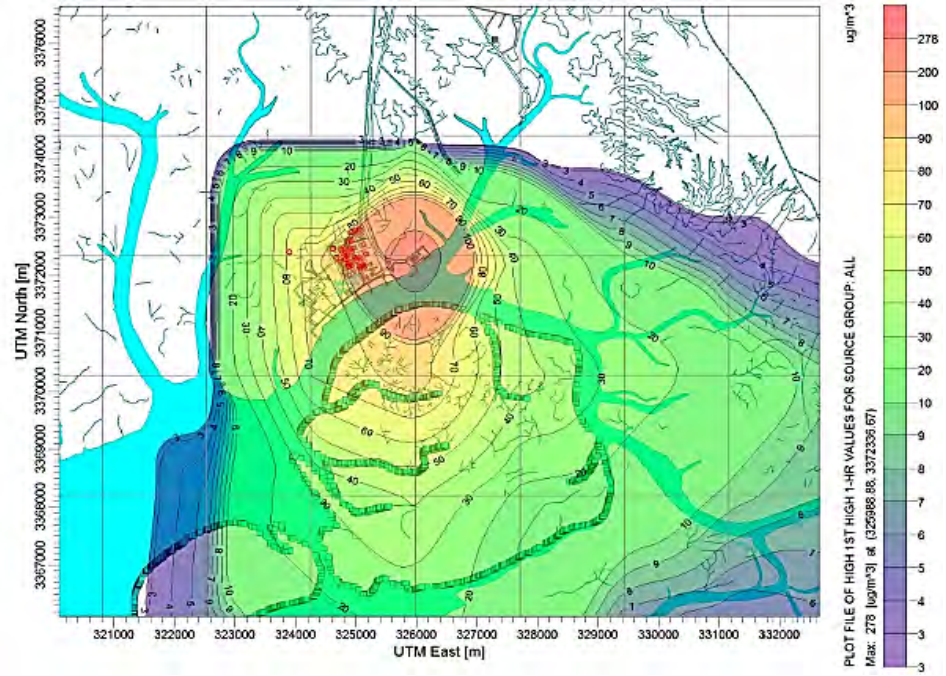


(a)

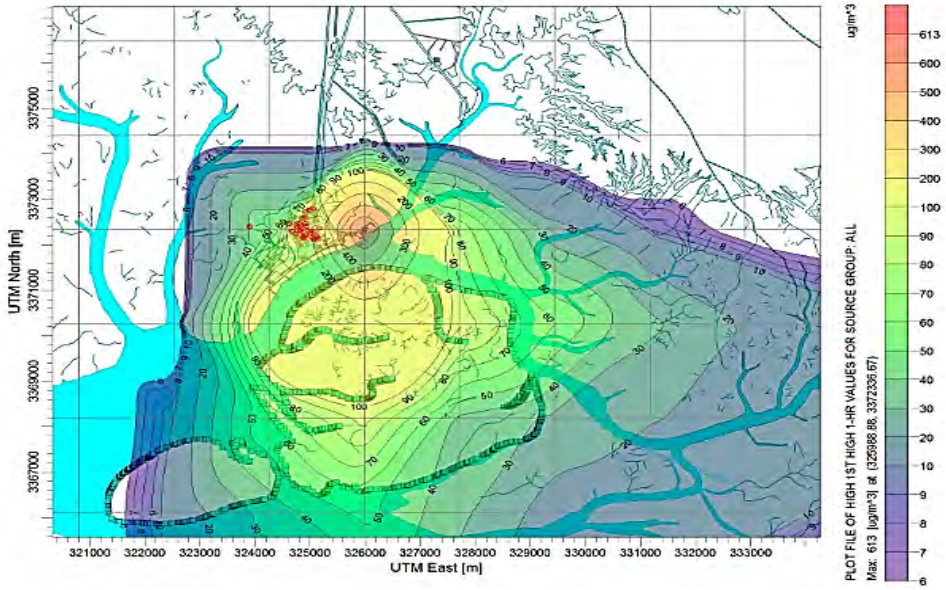


(b)

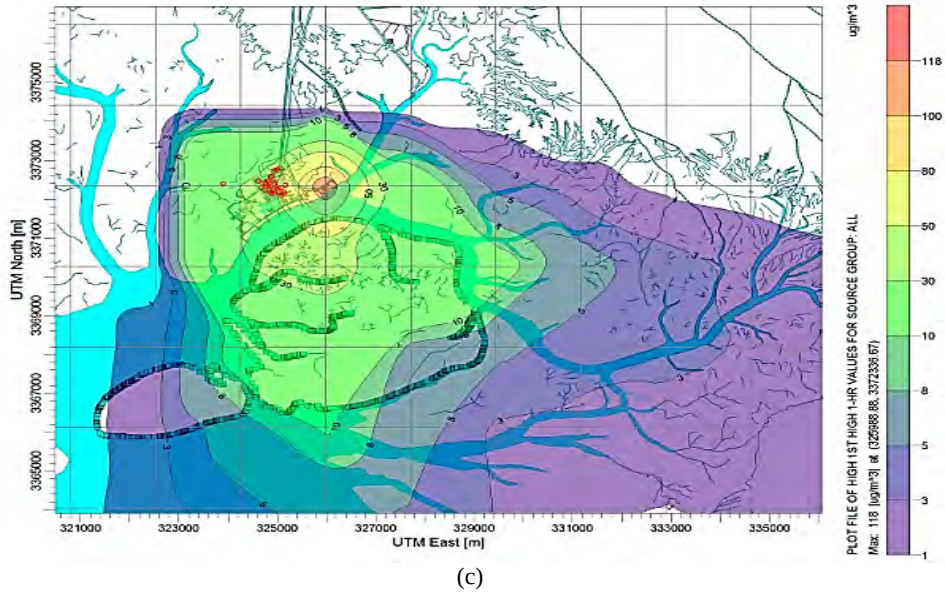
Fig. 4. Contribution of each type of tanks in the emission of BTEX at (a) hot season (b) cold season


UTM North [m]
UTM East [m]
ug/m^3
PLOT FILE OF HIGH 1ST HIGH 1-HR VALUES FOR SOURCE GROUP: ALL
Max: 278 [ug/m^3] at (325988.88, 3372336.67)

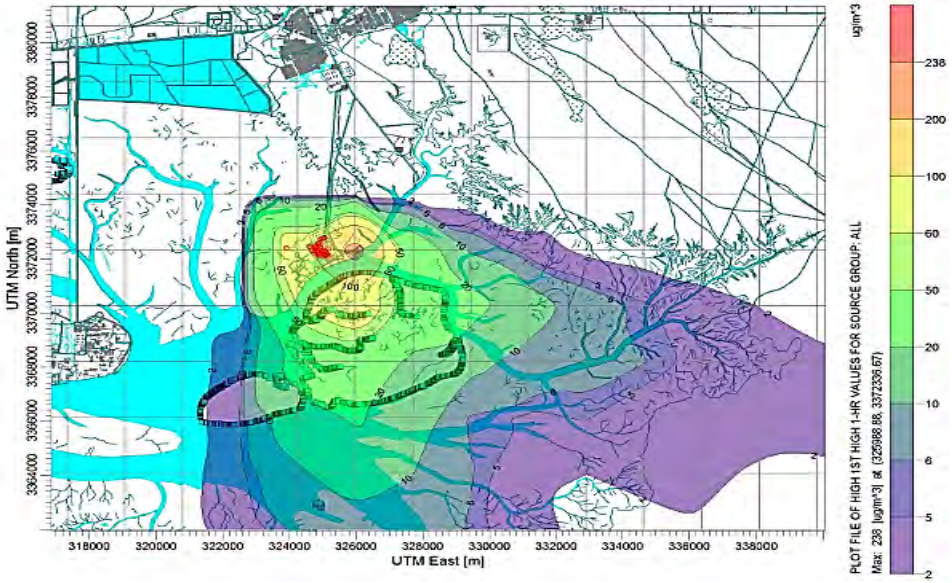
(a)


UTM North [m]
UTM East [m]
ug/m^3
PLOT FILE OF HIGH 1ST HIGH 1-HR VALUES FOR SOURCE GROUP: ALL
Max: 613 [ug/m^3] at (325988.88, 3372336.67)

(b)

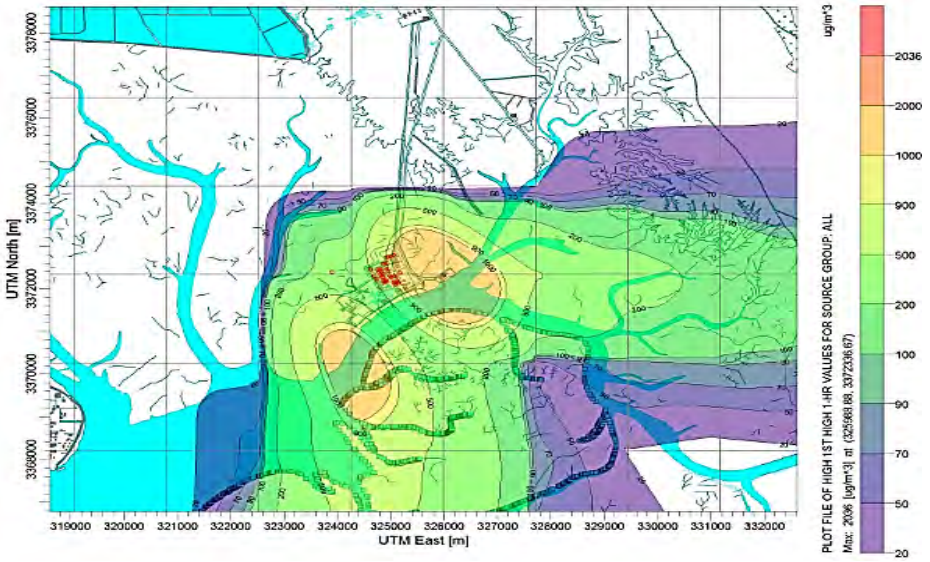

UTM North [m]
UTM East [m]
ug/m^3
PLOT FILE OF HIGH 1ST HIGH 1-HR VALUES FOR SOURCE GROUP: ALL
Max: 118 [ug/m^3] at (325988.88, 3372336.67)

(c)

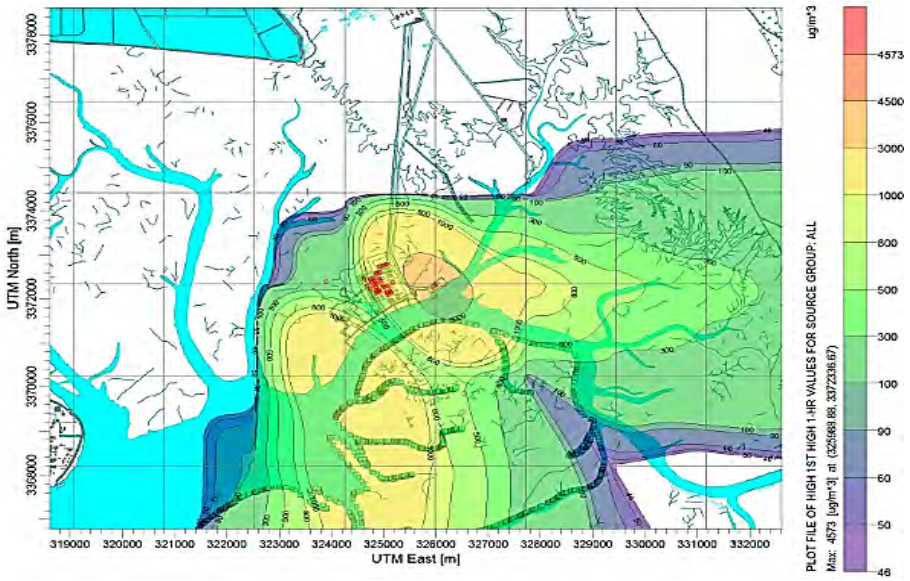


(d)

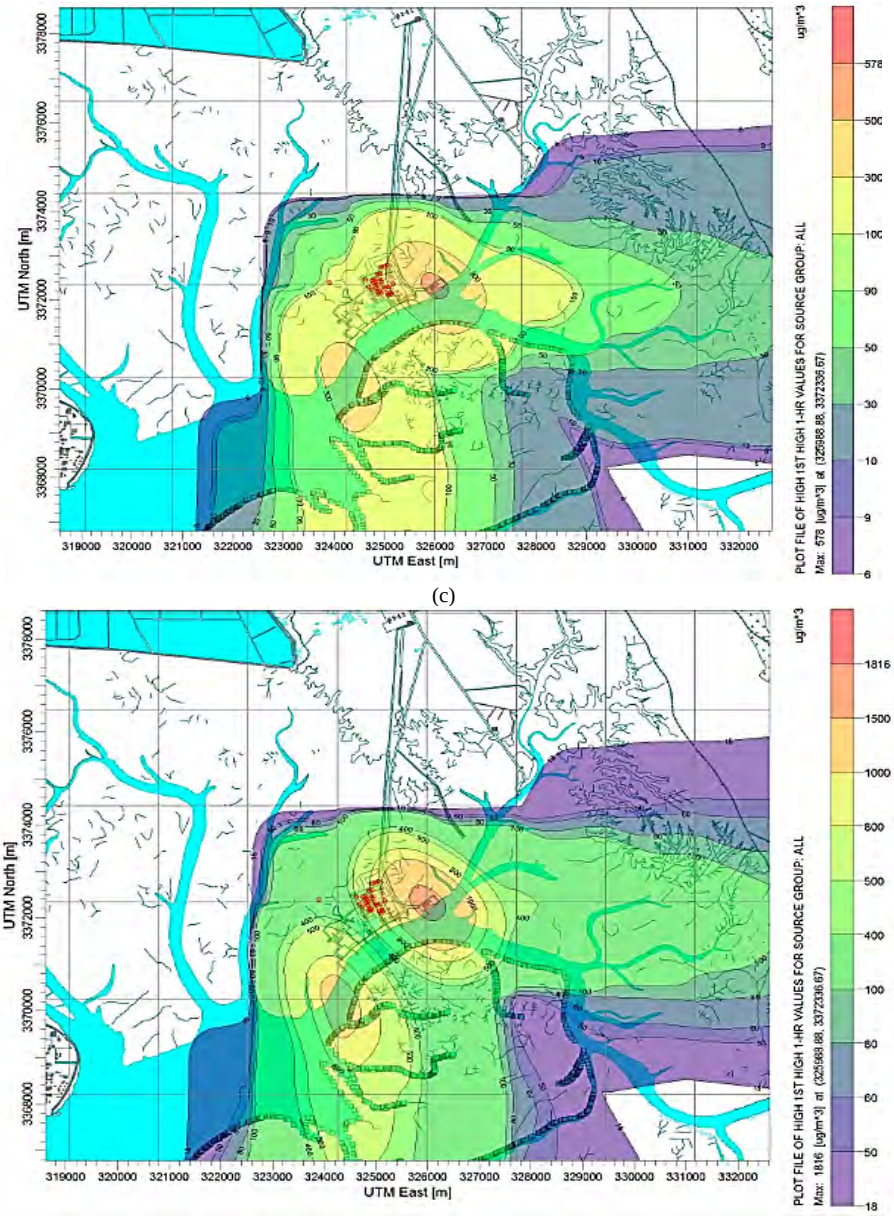
Fig. 5. Dispersion of pollutants at hot season for the time scale of 8 h (a) benzene (b) toluene (c) ethylbenzene (d) xylene



(a)



(b)



(c)

(d)

Fig. 6. Dispersion of pollutants at hot season for the time scale of 24 h (a) benzene (b) toluene (c) ethylbenzene (d) xylene

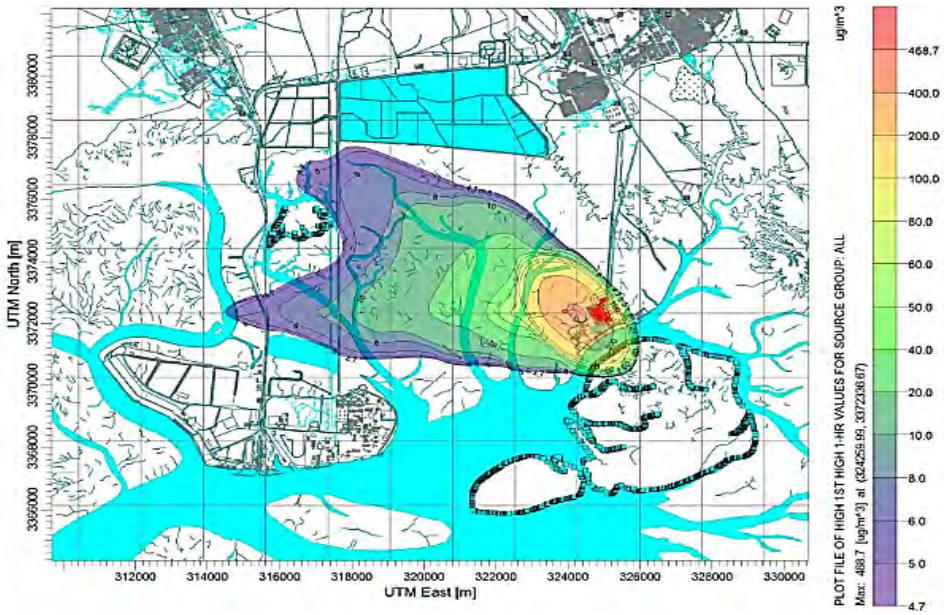
So, it may be more important to precisely consider the pollutants dispersion at the cold season. In order to have a better insight on the dispersion of pollutant towards the industrialized area (petrochemical industries on the west of the export port) and also the residential area on the north-east and north-west of the export port, wider scale base plot was considered for the cold season in comparison with the hot season to clearly show the diffusion of pollutants to this area.

As can be seen, concentration contours at the 24 h time scale are wider than those at the 8 h time scale. Since the dominant wind direction was similar at the 8 h and 24 h time scales, dispersion direction and movement of concentration contours were the same. It is also clear that pollutants concentration in different points at the hot season were greater than that at the cold season. It can be attributed to the higher average temperature and greater emission rates (Tables 2 and 3) at the hot season.

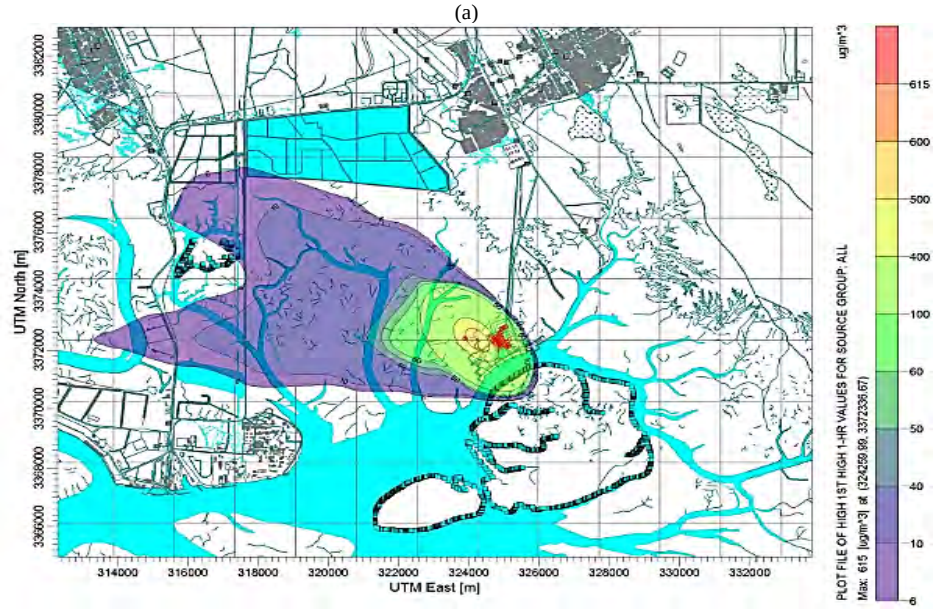
As previously stated, in order to evaluate the model prediction, pollutants concentrations were experimentally determined at six different locations around the study area for 8 h and 24 h time scales. Table 4 compares the modeling results with the field measurements. Also, to quantify the comparison, absolute average relative deviation (AARD) was calculated for each data point as follows (Eq. 1):

$$AARD = \frac{100}{M}\sum_{i=1}^{M}\left|\frac{x_{cal} - x_{\exp}}{x_{\exp}}\right|_i \qquad (1)$$

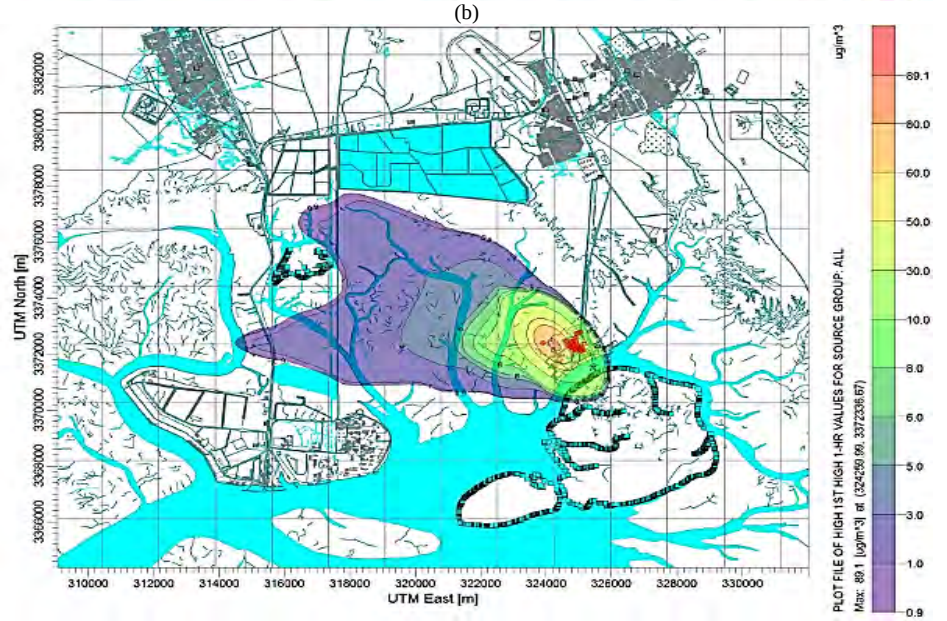
where: M is the number of data points, x_{cal} and x_{exp} are modeling results and field measurement results, respectively.


UTM North [m]
UTM East [m]
ug/m^3
PLOT FILE OF HIGH 1ST HIGH 1-HR VALUES FOR SOURCE GROUP: ALL
Max: 468.7 [ug/m^3] at (324259.99, 3372336.67)

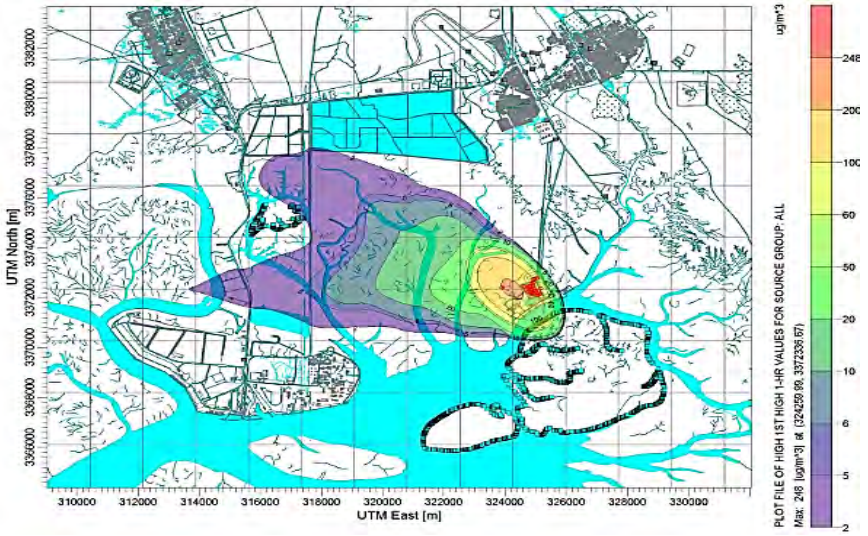
(a)


UTM North [m]
UTM East [m]
ug/m^3
PLOT FILE OF HIGH 1ST HIGH 1-HR VALUES FOR SOURCE GROUP: ALL
Max: 615 [ug/m^3] at (324259.99, 3372336.67)

(b)

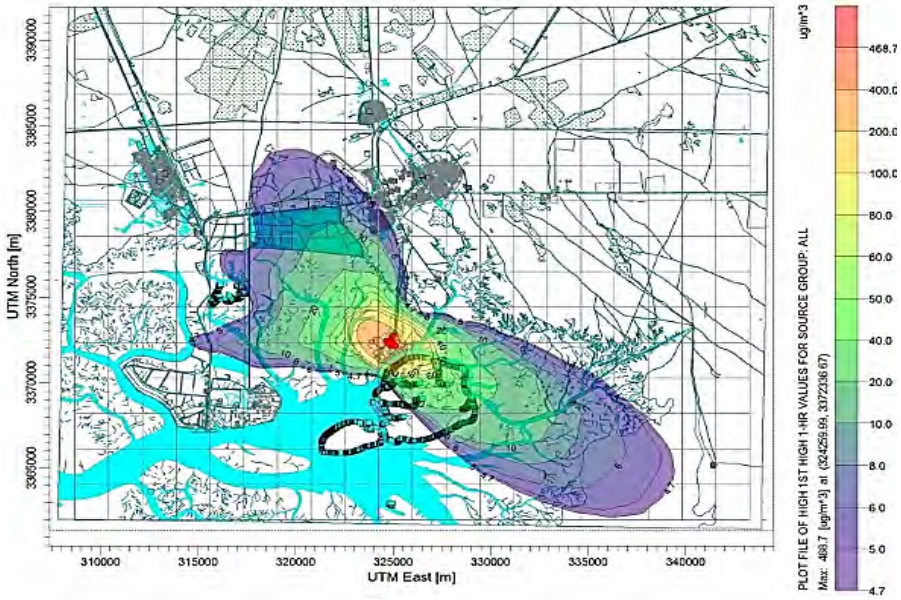

UTM North [m]
UTM East [m]
ug/m^3
PLOT FILE OF HIGH 1ST HIGH 1-HR VALUES FOR SOURCE GROUP: ALL
Max: 89.1 [ug/m^3] at (324259.99, 3372336.67)

(c)

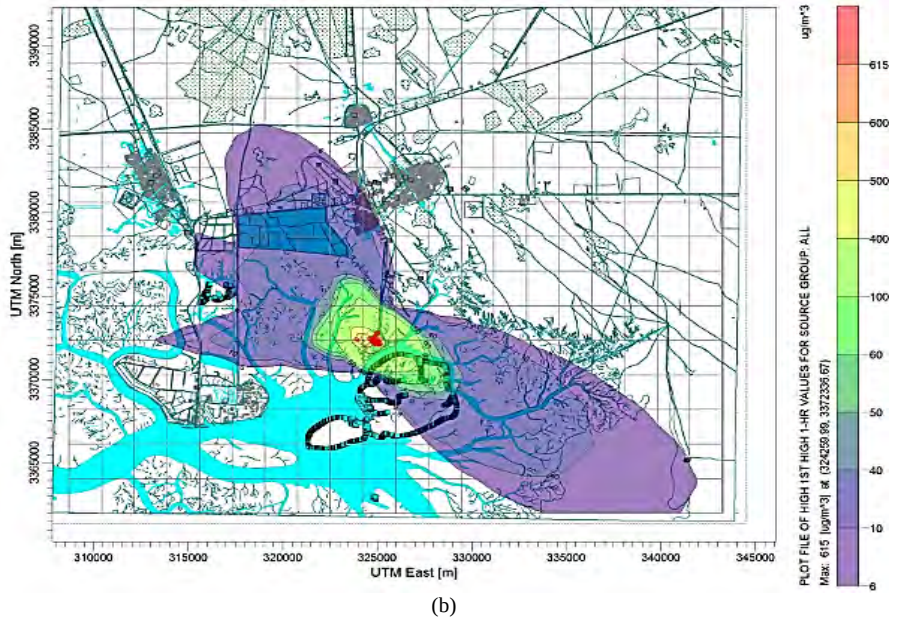


(d)

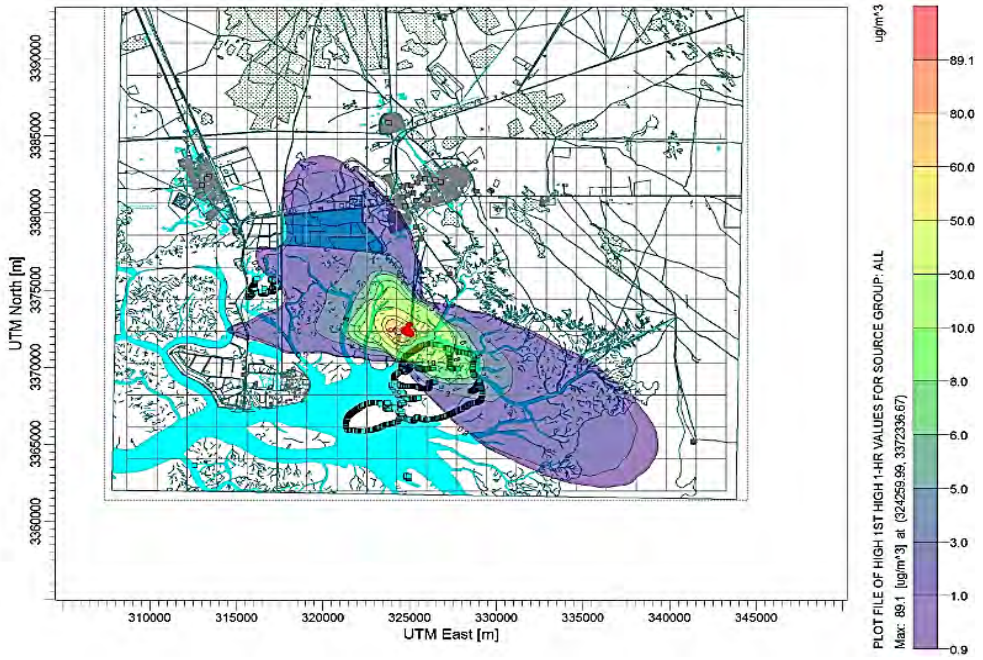
Fig. 7. Dispersion at cold season for the time scale of 8 h (a) benzene (b) toluene (c) ethylbenzene (d) xylene



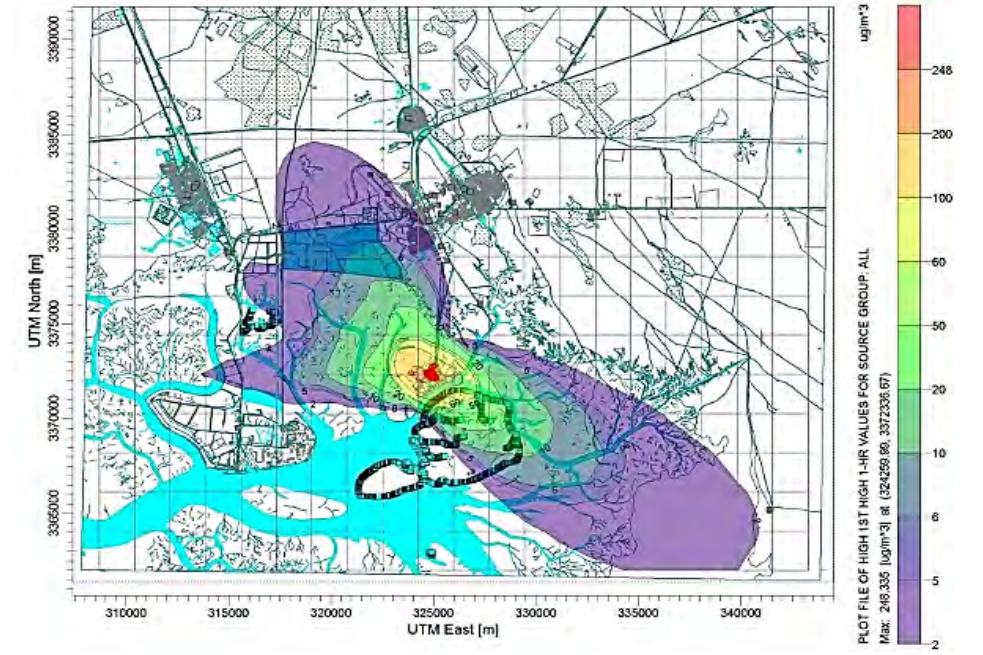
(a)



(b)



(c)



(d)

Fig. 8. Xylene dispersion at cold season for the time scale of 24 h (a) benzene (b) toluene (c) ethylbenzene (d) xylene

The average values of AARD for each time scale and each pollutant is presented in Table 5. As can be seen in Table 4, in almost all of the data, the field measurements were higher than the model predictions with AERMOD. It is due to the presence of other pollution sources around the study area which were not considered in the modeling. As previously explained, Mahshahr export port is in the vicinity of industrialized plants like the large-scale petrochemical industries. The probable emission from those industries can enhance the results of field measurements in comparison with the modeling results. However, it can be concluded that according to the results of Table 5, the deviations between the modeling results and the field measurements were acceptable and for different pollutants were in the range of 7-16%.

Finally, it is very important to compare the measured concentrations of BTEX with some standards for permissible concentrations of these pollutants. Table 6 summarized some of these standards. If the results of Table 5 were compared with those presented in Table 6, it can be concluded that some of the pollutants existed at higher concentrations than permissible concentrations. For example, benzene and xylene concentrations in both hot and

cold seasons were higher than USPEA (RFC) recommendations but at the allowable ranges of other standards. On the other hand, toluene and ethylbenzene concentrations especially in cold season were passed all the standards even USPEA (RFC). Oil storage tanks are one of the most important sources of BTEX emissions. As a result, it was predicted that the tanks farm of Abadan oil refining company would be contaminated with BTEX compounds, which are harmful to the environment and workers' health.

Emission modeling with efficient software is a scientific method for environmental study. Therefore, in this study, modeling with AERMOD software along with field sampling was used for environmental studies of the tanks farm. The results of this study can provide the following suggestions to industry experts in controlling the emission of environmental pollutants.

In future repairs, they should focus more accurately on the quality and performance of roof sealing and tank roof connections. It should also be mentioned that although the amount of pollution in polluted areas in the port is less than the standard effect on workers' health. It is recommended that workers in the area be monitored and that diagnostic tests for BTEX exposure be added to routine workers' annually tests to completely eliminate contamination of the site.

4. Conclusions

Hydrocarbon storage tanks are one of the main sources of pollutant emission. In this investigation, BTEX emission rates from 32 storage tanks at the hot and cold seasons were measured and the obtained results were then used accompanied with the metrological and the topographical data in AERMOD to analyze the dispersion of these pollutants in the atmosphere around the study area. The following main conclusions were obtained:

- Maximum quantities of emission of benzene, 0.0649 g/s and ethylbenzene, 0.0189 g/s were occurred from light naphtha storage tanks, and maximum quantities of emission of toluene, 0.1635 g/s and xylene, 0.0593 g/s were occurred from gasoline storage tanks at the hot season.
- At the cold season, maximum emission of benzene, 0.0335g/s was observed from jet naphtha storage tanks and ethylbenzene, 0.0093 g/s from light naphtha storage tanks. Maximum quantities of emission of toluene, 0.0826 g/s and xylene, 0.0314 g/s were observed from gasoline storage tanks.

Table 4. Comparison between the modeling and measured concentrations (μg/m^3)

	Benzene			***Toluene***			***Ethylbenzene***			***Xylene***		
point	***Model***	***field***	***AARD (%)***	***model***	***field***	***AARD (%)***	***model***	***field***	***AARD (%)***	***model***	***field***	***AARD (%)***
Hot season – 8 h time scale												
1	85	98	13.27	150	172	12.79	40	56	28.57	105	115	8.70
2	87	106	17.92	180	197	8.63	45	61	26.23	115	123	6.50
3	115	128	10.16	250	278	10.07	65	72	9.72	133	141	5.67
4	108	139	22.30	210	225	6.67	67	78	14.10	138	149	7.38
5	160	181	11.60	295	318	7.23	76	81	6.17	168	176	4.55
6	158	165	4.24	305	320	4.69	77	88	12.50	171	189	9.52
Hot season – 24 h time scale												
1	1110	1150	3.48	2170	2223	2.38	322	376	14.36	1072	1154	7.11
2	1027	970	5.88	1976	1845	7.10	273	323	15.48	846	970	12.78
3	1210	1160	4.31	2231	2345	4.86	358	310	15.48	1170	1089	7.44
4	911	970	6.08	1810	1765	2.55	271	300	9.67	811	780	3.97
5	1342	1387	3.24	2763	1660	66.45	367	420	12.62	1310	1430	8.39
6	1233	1310	5.88	2610	3100	15.81	352	310	13.55	1210	1278	5.32
Cold season – 8 h time scale												
1	112	145	22.76	183	210	12.86	23	29	20.69	65	70	7.14
2	242	213	13.62	136	145	6.21	45	55	18.18	141	132	6.82
3	132	121	9.09	211	190	11.05	25	29	13.79	71	90	21.11
4	273	232	17.67	281	320	12.19	50	47	6.38	132	145	8.97
5	116	128	9.38	172	190	9.47	22	24	8.33	60	55	9.09
6	211	230	8.26	251	210	19.52	38	36	5.56	118	125	5.60
Cold season – 24 h time scale												
1	227	243	6.58	382	410	6.83	45	54	16.67	141	156	9.62
2	310	323	4.02	468	489	4.29	65	78	16.67	170	189	10.05
3	231	245	5.71	415	400	3.75	55	50	10.00	172	162	6.17
4	320	335	4.48	481	512	6.05	67	77	12.99	181	210	13.81
5	221	182	21.43	391	423	7.57	46	52	11.54	51	69	26.09
6	234	230	1.74	400	411	2.68	55	66	16.67	62	79	21.52

Table 5. The average values of AARD (%)

Benzene	***Toluene***	***Ethylbenzene***	***Xylene***
Hot season – 8 h time scale			
13.5	8.35	16.2	7.02
Hot season – 24 h time scale			
4.81	16.52	13.52	7.5
Cold season – 8 h time scale			
13.46	11.88	12.16	9.79
Cold season – 24 h time scale			
7.33	5.19	14.09	14.54

Table 6. Some well-known standards for permissible concentration of BTEX

#	***Standard***	***Benzene (mg/m^3)***	***Toluene (mg/m^3)***	***Ethylbenzene (mg/m^3)***	***Xylene (mg/m^3)***
1	USEPA[a] (RFC[b])	0.03	5	1.0	0.1
2	OSHA[c] PEL[d]	3.2	754	435.0	435.0
3	NIOSH[e] STEL	3.2	560	545.0	655.0
4	ACGIH[f] TLV	1.6	188	435.0	435.0

a - United State Environmental Protection Agency; b - Reference Concentration for Chronic Inhalation Exposure (RFC); c - Occupational Safety and Health Administration; d - Permissible Exposure Limit; e - The National Institute for Occupational Safety and Health; f - American Conference of Governmental Industrial Hygienists

- The highest BTEX emission rate was related to gasoline tank #14 which was 0.2927 g/s in the hot season and 0.1497 g/s in the cold season. Technical inspections of tank #14 revealed that the reason for the high release rate of the tank was the high RVP of the gasoline and the misalignment of parts of the tank's foundation and it's out of roundness in some of the upper parts of the tank. Therefore, it was suggested that this tank was given priority in the first emergency repair program.
- Concentration contours from AERMOD modeling at the hot season indicated widespread dispersions of different pollutants in comparison with the cold season.
- At hot season, the concentration contours directed to the Persian Gulf on the south of the study area whereas at the cold season, the pollutants directed to the industrialized and residential urban area on the west of the study area.
- Comparison between the modeling results and field measurements at six points in the study area indicated the deviation between 7-16%.
- Comparison of measured (or calculated) concentrations in Abadan Oil Refining Export Port area with the available standards revealed that some pollutants like benzene and xylene existed in site at higher concentrations than that permissible.
- In 24-h emission of BTEX pollutants in the hot season, the highest concentration of benzene pollutant observed at point 5 (1387µg/m^3), the highest concentration of toluene pollutant at point 6 (3100 µg/m^3), the highest concentration of ethylbenzene pollutant at point 5 (420 µg/m^3), and the highest concentration of xylene pollutant at point 5 (1430 µg/m^3). So, points 5 and 6 were the most polluted environmental points in the port area in the hot season.
- In 24-h emission of BTEX pollutants in the cold season, the highest concentration of benzene pollutant observed at point 4 (335 µg/m^3), the highest concentration of toluene pollutant at point 2 (489 µg/m^3), the highest concentration of ethylbenzene pollutant at point 2 (78 µg/m^3), and the highest concentration of xylene pollutant at point 4 (210 µg/m3). So, points 2 and 4 were the most polluted environmental points in the port area in the cold season.
- In 8-h emission of BTEX pollutants in the hot season, the highest concentration of benzene pollutant observed at point 5 (181 µg/m^3), the highest concentration of toluene pollutant at point 6 (320 µg/m^3), the highest concentration of ethylbenzene pollutant at point 6 (88 µg/m^3), and the highest concentration of xylene pollutant at point 6 (189µg/m^3). So, points 5 and 6 were the most polluted environmental points in the port area in the hot season.
- In 8-h emission of BTEX pollutants in the cold season, the highest concentration of benzene pollutant observed at point 4 (232 µg/m^3), the highest concentration of toluene pollutant at point 4 (320 µg/m^3), the highest concentration of ethylbenzene pollutant at point 2 (55 µg/m^3), and the highest concentration of xylene pollutant at point 4 (145µg/m3). So, points 2 and 4 were the most polluted environmental points in the port area in the cold season.

References

Afzali A., Rashid M., Afzali M., Younesi V., (2017), Prediction of air pollutants concentrations from multiple sources using AERMOD coupled with WRF prognostic model, *Journal of Cleaner Production*, **166**, 1216-1225.

Askariyeh M.H., Kota S.H., Vallamsundar S., Zietsman J., Ying Q., (2017), AERMOD for near-road pollutant dispersion: Evaluation of model performance with different emission source representations and low wind options, *Transportation Research Part D: Transport and Environment*, **57**, 392-402.

Ceron Berton J., Ceron Berton R., Ucan R., Bazea C., Espinosa M., Lara E., Marron M., Montero Pacheco J., Guzman A., Ucchi M., (2017), Characterization and sources of aromatic hydrocarbons (BTEX) in the atmosphere of two urban sites located in Yucatan Peninsula in Mexico, *Atmosphere*, **8**, 107-130.

Chen H., Carter K.E., (2017), Modeling potential occupational inhalation exposures and associated risks of toxic organics from chemical storage tanks used in hydraulic fracturing using AERMOD, *Environmental Pollution*, **224**, 300-309.

Cheng Sh., Zhang J., Wang Y., Zhang D., Teng G., Chang-Chien G., Huang Q., Zhang Y., Yan P., (2019), Global research trends in health effects of volatile organic compounds during the Last 16 Years: A Bibliometric Analysis, *Aerosol and Quality Research*, **19**, 1834-1843.

Cimorelli A.J., Perry S.G., Venkatram A., Weil J.C., Paine R.J., Wilson R.B., Lee R.F., Peters W.D., Brode R.W., (2005), AERMOD: A dispersion model for industrial source applications. Part I: General model formulation and boundary layer characterization, *Journal of Applied Meteorology*, **44**, 682-693.

Cunningham D., (1996), Estimation of VOC emissions, *Journal of Cleaner Production*, **3**, 225-228.

Ding Y., Liu Z., Li, W., Chen J., (2020), Volatile organic compounds in Shihezi, China, during the heating season: Pollution characteristics, source apportionment, and health risk assessment, *Environmental Science and Pollution Research*, **27**, 16439-16450.

Donateo T., Licci F., D'elia A., Colangelo G., Laforgia D., Ciancarelli F., (2015), Evaluation of emissions of CO_2 and air pollutants from electric vehicles in Italian cities, *Applied Energy*, **157**, 675-687.

Font A., Hoogh K., Leal-Sanchez M., Ashworth D., Brown R., Hansell A., Fuller G., (2015), Using metal ratios to detect emissions from municipal waste incinerators in ambient air pollution data, *Atmospheric Environment*, **113**, 177-186.

Gibson M.D., Kundu S., Satish M., (2013), Dispersion model evaluation of PM2. 5, NOx and SO2 from point and major line sources in Nova Scotia, Canada using AERMOD Gaussian plume air dispersion model, *Atmospheric Pollution Research*, **4**, 157-167.

Hajizadeh Y., Teiri H., Nazmara Sh., Parseh I., (2018), Environmental and biological monitoring of exposures to VOCs in a petrochemical complex in Iran, *Environmental Science and Pollution Research*, **25**, 6656-6667.

Han D., Gao S., Fu Q., Cheng J., Chen X., Xu, H., Liang S., Zhou Y., Ma Y., (2018), Do volatile organic compounds (VOCs) emitted from petrochemical industries affect regional PM2.5?, *Atmospheric Research*, **209**, 123-130.

Hilpert M., Rule A.M., Adria-Mora B., Tiberi T., (2019), Vent pipe emissions from storage tanks at gas stations: Implications for setback distances, *Science of the Total Environment*, **650**, 2239-2250.

Howari F., (2015), Evaporation losses and dispersion of volatile organic compounds from tank farms, *Environmental Monitoring and Assessment*, **187**, 273-279.

Kalhor M., Bajoghli M., (2017), Comparison of AERMOD, ADMS and ISC3 for incomplete upper air meteorological data (case study: Steel plant), *Atmospheric Pollution Research*, **8**, 1203-1208.

Kesarkar A.P., Dalvi M., Kaginalkar A., Ojha A., (2007), Coupling of the Weather Research and Forecasting Model with AERMOD for pollutant dispersion modeling. A case study for PM10 dispersion over Pune, India, *Atmospheric Environment*, **41**, 1976-1988.

Khalaj F., Sattler M., (2019), Modeling of VOCs and criteria pollutants from multiple natural gas well pads in close proximity, for different terrain conditions: A Barnett Shale case study, *Atmospheric Pollution Research*, **10**, 1239-1249.

Krishna T., Reddy M.K., Reddy R.C., Singh R.N., (2005), Impact of an industrial complex on the ambient air quality: Case study using a dispersion model, *Atmospheric Environment*, **39**, 5395-5407.

Leite R.M., Centeno F.R., (2018), Effect of tank diameter on thermal behavior of gasoline and diesel storage tanks fires, *Journal of Hazardous Materials*, **342**, 544-552.

Manu M., Onete M., Bancila R.I., (2018), The effect of heavy metals on mite communities (acari: gamasina) from urban parks - Bucharest, Romania, *Environmental Engineering and Management Journal*, **17**, 2071-2081.

Masih A., Lall A.S., Taneja A., Singhvi R., (2018), Exposure levels and health risk assessment of ambient BTX at urban and rural environments of a terai region of northern India, *Environmental Pollution*, **242**, 1678-1683.

Matacchiera F., Manes C., Beaven R.P., Rees-White T.C., Boano F., Mønster J., Scheutz C., (2019), AERMOD as a Gaussian dispersion model for planning tracer gas dispersion tests for landfill methane emission quantification, *Waste Management*, **87**, 924-936.

Mei J., Lan Z., Xiao-Qian L., Fei Ch., Guo-Hua Zh., Gang L., Guo-Ning Z., (2015), Definition and Control Indicators of Volatile Organic Compounds in China, *Environmental Science*, **36**, 3522-3532.

Moustakas K., Mavropoulos A., Haralambous K.J., Loizidou M., (2019), Leachability of heavy metals from slag residues under intense temperature and stirring conditions, *Environmental Engineering and Management Journal*, **18**, 81-88.

Pandey G., Sharan M., (2019), Accountability of wind variability in AERMOD for computing concentrations in low wind conditions, *Atmospheric Environment*, **202**, 105-116.

Perry S.G., Cimorelli A.J., Paine, R.J., Brode R.W., Weil J.C., Venkatram A., Wilson R.B., Lee R.F., Peters W.D., (2005), AERMOD: A dispersion model for industrial source applications. Part II: Model performance against 17 field study databases, *Journal of Applied Meteorology*, **44**, 694-708.

Pirbadali-Somarin A., Peyghambarzadeh S.M., (2020), Air pollution by heavy metals from petrochemical incinerators: measurement and dispersion modeling, *Environmental Engineering and Management Journal*, **19**, 379-390.

Rattanajongjitrakorn P., Prueksasit T., (2014), Temporal variation of BTEX at the area of petrol station in Bangkok, Thailand, *APCBEE Procedia*, **10**, 37-41.

Rood A.S., (2014), Performance evaluation of AERMOD, CALPUFF, and legacy air dispersion models using the Winter Validation Tracer Study dataset, *Atmospheric Environment*, **89**, 707-720.

Saikomol S., Thepanondh S., Laowagul W., (2019), Emission losses and dispersion of volatile organic compounds from tank farm of petroleum refinery complex, *Journal of Environmental Health Science and Engineering*, **17**, 651-570.

Ting M., Yue-Si W., Jie J., Fang-Kun W., Mingxing W., (2008), The Vertical Distributions of VOCs in the Atmosphere of Beijing in Autumn, *Science of the Total Environment*, **390**, 97-108.

Wu X.M., Fan Zh.T., Zhu X., Jung K.H., Strickland P.O., Weisel C.P., Lioy P.J., (2012), Exposures to volatile organic compounds (VOCs) and associated health risks of socio-economically disadvantaged population in a "hot spot" in Camden, New Jersey, *Atmospheric Environment*, **57**, 72-79.

Zou B., Benjamin Zhan F., Gaines Wilson J., Zeng Y., (2010), Performance of AERMOD at different time scales, *Simulation Modelling Practice and Theory*, **18**, 612-623.