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Study of Fugitive Emissions in Petroleum Processing Plants

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Abstract

Due to their detrimental impact on air quality and climate change, fugitive emissions originating from the unintentional escape of gases and vapors from industrial processes have generated concerns. The present study investigates the effects of fugitive emissions from petroleum processing facilities on the workplace and global warming. A bitumen plant and a condensate refinery were selected for case studies. Process flow diagrams and piping and instrumentation diagrams were used to estimate the fugitive emissions from different units of the plants with the help of emission factors. The emissions from the refinery were four times higher than those from the bitumen plant. The cancer risks of the plant employees exposed to fugitive emissions were assessed considering worst-case scenarios. Workers in both plants were found to be susceptible to cancer risk to a certain degree. Additionally, the contribution of fugitive emissions to global warming was estimated using yearly equivalent carbon dioxide (CO_2) emissions. The present study demonstrates ways to approximate fugitive emissions and their impacts at the design stage facilitating corrective measures with minimum cost implications.
Keywords: Fugitive Emission, Cancer Risk, Global Warming, Occupational Safety, Petroleum Industry

1. Introduction

Regulating industrial emissions in the atmosphere is now a top priority due to their environmental pollution and global warming potential. The term "fugitive emissions" refers to unforeseen emissions, which certainly comprise a sizeable amount of release [1]. Fugitive emission is the unintended release of gases or vapors from equipment or processes, typically caused by leaks, spills, or other defects. Fugitive emission generally occurs at any solid barrier in the process equipment and/ or piping systems such as a valve, pump seal, compressor, pressure relief valve, flange, and open-ended line causing discontinuities in containment. These emissions can comprise a wide spectrum of gases, such as volatile organic compounds (VOCs), hazardous air pollutants (HAPs), and greenhouse gases (GHGs), among others.

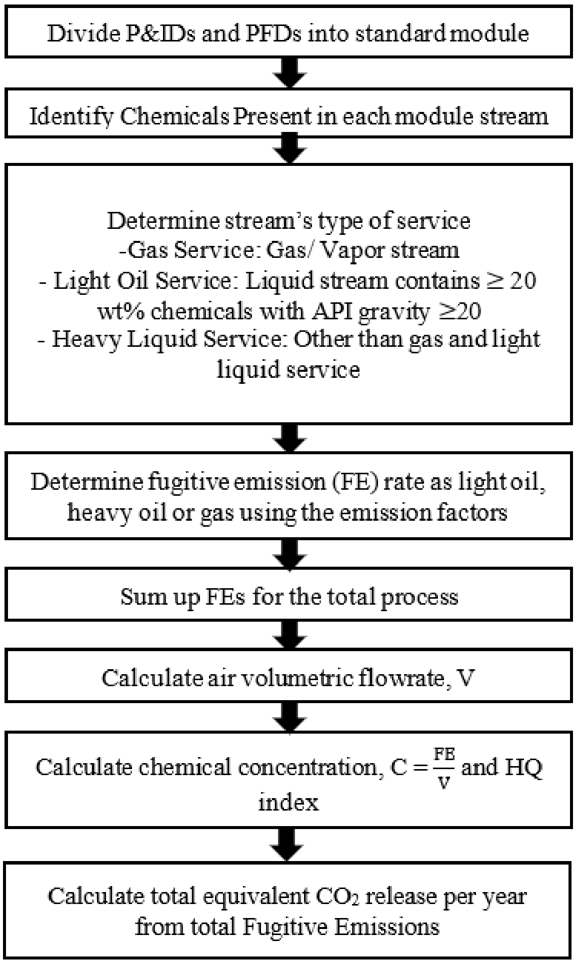
Occupational health is concerned with all elements of health and safety in the workplace and heavily emphasizes hazard prevention. Workers' health is influenced by several elements, including occupational risk factors that lead to malignancies, accidents, musculoskeletal illnesses, respiratory diseases, hearing loss, circulatory diseases, stress-related disorders, infectious diseases, and others. Occupational health and fugitive emissions are closely related as fugitive emissions can significantly impact the health and safety of workers in certain industries. In the EU countries, harmful chemicals are reported to contribute to the 350 million working days lost owing to occupational sickness[2]. For the industry, the loss of products or raw materials due to leaks or other unintended releases may incur economic consequences. Annual fugitive emissions from industrial applications exceed one million metric tons globally. In the U.S. emissions from gas production facilities were estimated to be 17.4 Bscf (492.8 x 10^6 m^3) [3]. In addition, fugitive emissions have economic consequences for the entire population. For instance, they can contribute to air pollution and climate change, resulting in significant health concerns and environmental harm. In some cases, firms that violate legislation regarding fugitive emissions may be subject to fines or other penalties, potentially having economic repercussions.

Global warming is the rapid increase in the Earth's average surface temperature over the past century, mostly caused by the greenhouse gases emitted by the combustion of fossil fuels. The greenhouse effect, caused by greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), contributes to global warming and climate change [4]. These powerful greenhouse gases, particularly methane known to have a substantially larger warming potential than CO_2 during a specified period can be found in fugitive emissions [5]. Fugitive emissions of methane, such as those from natural gas extraction or coal mines, can contribute considerably to global warming. Methane can trap heat in the atmosphere more than CO_2, making it especially worrying for attempts to mitigate climate change. global warming potential (GWP) is used to estimate the impact of various gases on global warming. GWP assesses the capacity of a certain gas to absorb infrared heat radiation and contribute to the greenhouse effect relative to carbon dioxide (CO_2) over a given period. The greater a gas's GWP value, the greater its warming potential. GWP permits the comparison of the effects of different gases on global warming by quantifying their energy absorption relative to the same mass of CO_2. [6]. The 100-year GWP is frequently utilized as the preferred and standard version. [7].

As fugitive emission is related to the discontinuities between solid barriers i.e. piping and instrumentation of the plant, it is hard to change the emissions once the plant is established. The best possible outcome can be obtained if the fugitive emissions can be estimated during the design stage. Fugitive emissions can be calculated using the following four methods: direct measurement, mass balance, engineering computation, and emission factor. The direct measurement only applies to existing processes; the mass balance technique is less accurate because only minimal amounts of material losses are involved. Engineering calculation, based on theoretical and complex equations or models on material loss estimation from equipment or facilities, is challenging, requires detailed inputs, and typically uses software tools. Thus, leaving the emission factor as the most appropriate technique for design stage application.[8] Four methods have been developed by the U.S. Environmental Protection Agency (U.S. EPA) for calculating fugitive emissions depending on emission factors. The most practical choice is the Average Emission Factor since it only needs a small amount of process knowledge, which may be acquired even at a very early conceptual design stage. In contrast to the other three, which need screening values, this technique requires average emission factors in addition to the equipment and pipe item count, piping element count, and P&ID[8]. Therefore, the average emission factors method was applied for estimating fugitive emissions in this work.

2. Methodology

The following methodology was developed to carry out the present study [8]



Typically, in the petroleum industry, oils having an API gravity of less than 20 are considered heavy oil, and oils with an API gravity of more than 20 are considered light oil. [9]. The emission factors were used from the values presented in Table 1. The air volumetric flow rate was calculated assuming the plot has a square shape. The height of the equipment was assumed to be a maximum of 7 meters. [8]. The average air velocity was assumed to be 4 ms^{-1}. The air volumetric flow rates were calculated by multiplying the velocity with the vertical area. The hazard quotient, H.Q., is calculated for individual carcinogenic substances using the following equation [10]:

$$HQ_{c\text{-}i} = \frac{Ci}{C(Eli)}$$

Here, $HQ_{c\text{-}i}$ = hazard quotient index for long-term exposure to carcinogen i, c_i = concentration of the carcinogen, and $c_{(Eli)}$ = occupational exposure limit.

Table 1: Average emission factors for plant items [11]

Equipment	Service	Emission factors (kg/ hr) *	
		Refineries	**Synthetic organic chemical manufacture**
Valves	Gas	0.27	0.0056
	Light liquid	0.11	0.0071
	Heavy liquid	0.00022	0.00023
Pump seals	Light liquid	0.11	0.0494
	Heavy liquid	0.021	0.0214

Compressor	Gas/ vapour	0.64	0.228
Pressure relief valves	Gas/ vapour	0.16	0.104
Flanges	All	0.00025	0.00083
Open-ended lines	All	0.0023	0.0017

3. Case Studies

Two different petroleum processing plants were selected for case studies. For anonymity, we named them Plant A and Plant B.

Plant A: Plant ‘A’ is a heavy crude refining plant that produces bitumen. It is located in Dhaka Division, Bangladesh with an ISBL area of approximately 4500 m^2. Its annual capacity is 500 kilo-tons. In this plant, the heavy crude oil separation is accomplished in two steps. At first, the total crude oil is fractionated at atmospheric pressure. After that, high boiling bottoms from atmospheric distillation are fed to a second fractionator operating at high vacuum. Thus, the plant has two major units, namely, the atmospheric distillation unit (ADU) and the vacuum distillation unit (VDU).

In atmospheric distillation, various components of crude oil are separated based on their boiling points. Lighter fractions with lower boiling points, such as gasoline and diesel, are collected at the top, while heavier components like bitumen and residual fuel oil settle at the bottom. The residual material obtained from atmospheric distillation containing bitumen and other heavy hydrocarbons, undergoes further processing in a Vacuum Distillation Unit (VDU). Vacuum distillation is performed under reduced pressure of 25 to 40 mm hg, which lowers the boiling points of the heavy components, including bitumen. By reducing the pressure, the temperature required for distillation can be lowered, preventing thermal cracking of the bitumen. The bitumen is separated from the residue and collected for storage or additional processing. Both ADU and VDU are sources of fugitive emissions.

Plant B: Plant B is a condensate refinery plant. It is located in the Khulna Division, Bangladesh. There are several units in the plant, namely, condensate fractionation unit, catalytic reforming unit, and naphtha hydrotreatment unit.

The condensate fractionation unit (CFU) of the refinery performs the crucial function of separating the different components of condensate through fractional distillation. It separates the hydrocarbon mixture based on the boiling points, resulting in fractions such as light gases, naphtha, kerosene, diesel, and heavier components.

The catalytic reforming unit (CRU) converts low-octane naphtha into high-octane gasoline blending components. This unit utilizes a catalyst to facilitate the chemical reactions that transform the naphtha. The catalytic reforming process enhances the quality of the gasoline produced in the condensate refinery by increasing its octane number.

The function of the naphtha hydrotreatment unit (NHU) is to remove impurities and improve the quality of naphtha. The unit employs a hydrotreating process that involves the use of hydrogen and a catalyst to remove sulfur compounds, nitrogen compounds, and other contaminants present in the naphtha.

The distillation columns that belong to CFU are the major source of fugitive emissions in plant B.

4. Results and Discussions

4.1 Average concentration and loss of materials

From the ‘Plant A’ i.e., bitumen plant, VOC is emitted from heavy oil, light oil, and gas. From the ‘Plant B’, i.e., condensate refinery, VOC is emitted from light oil and gas. The total VOC emitted from both plants is shown in Figure 1

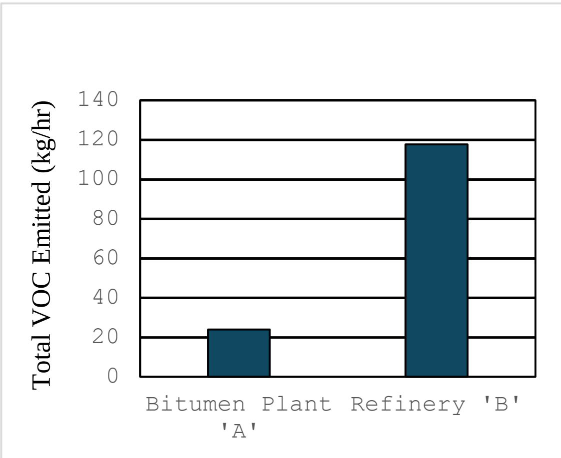


Figure 1: Comparison of Total VOC Emission between the bitumen plant (A) and condensate refinery (B)

From the emission values, the average VOC concentrations in both plants were calculated and presented in Figure 2.

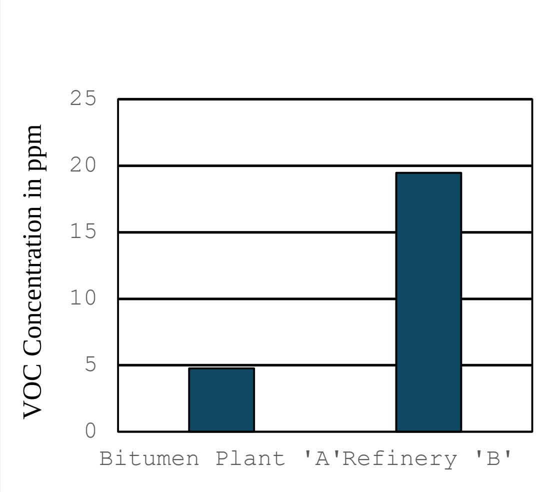
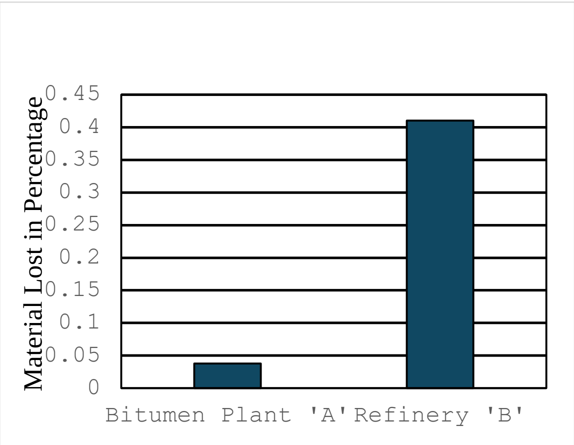


Figure 2: Comparison of average VOC concentration between the bitumen plant (A) and condensate refinery (B)

Figure 2 shows that the average VOC concentration in the condensate refinery (B) is approximately four times the respective concentrations of the bitumen plant (A). Both feed and product of the bitumen plant (A) are heavy liquids with some light liquids as by-products. On the other hand, both feed and products of the refinery (B) are light liquid. Since the emission factor for light liquid is almost 500 times the emission factor for heavy liquid, it is expected that 'Plant B' will have a higher emission compared to 'Plant A'.

The material lost due to emission from both plants is presented in Figure 3.



In both cases, benzene is of particular threat to human health. It is unlikely that a particular stream will be full of benzene but in some of the streams, benzene may be present in high concentration. It is important that within the plant battery limit, benzene concentration at different points be measured and precautions/preventive measures be taken to minimize the exposure. The other components i.e. xylene and naphthalene are not considered as harmful as benzene.

In the case of the bitumen plant, the material lost is 0.038% whereas for the condensate refinery, 0.41% of material is lost due to fugitive emissions demonstrating major economic implications.

4.2 Cancer risk

The exact cancer risk could not be determined as the exact composition of the different streams was not known. Considering the worst-case scenario, the calculation was done assuming that 100% concentration of the component of interest in the stream. Typical carcinogenic components present in crude oil plants and refineries are benzene, toluene, xylene, naphthalene, etc.[12]. The cancer risk is considered to be significant if HQ index is greater than 0.1. The results are shown in Tables 2 and 3. The refinery (B), with a higher quantity of volatile components, presents a higher cancer risk compared to that of the bitumen plant (A).

Table 2: Qualitative estimation of cancer risk for bitumen plant (A)

Component	TLV (ppm)	Worst-case scenario concentration (ppm)	HQ index	Remarks
Benzene	0.5	4.77	9.54	Cancer risk Present
Naphthalene	10		0.477	Cancer risk Present
Toluene	20		0.2385	Cancer risk present
Xylene	100		0.0477	Cancer risk not present

Table 3: Qualitative estimation of cancer risk for condensate refinery (B)

Component	TLV (ppm)	Worst-case scenario concentration	HQ index	Remarks
Benzene	0.5	19.48	39	Cancer risk Present
Naphthalene	10		1.95	Cancer risk Present
Toluene	20		0.97	Cancer risk present
Xylene	100		0.19	Cancer risk present

However, as they also possess cancer risk, their percentage should also be monitored at high aromatic concentration streams.

Although worst-case scenarios are an overestimation of any existing situation, they are particularly helpful for understanding the risk to human health and the environment and thus for taking necessary measures for prevention.

4.2 Contribution to global warming

In the worst-case scenario, light liquid can be considered hexane as it is the worst chemical considering the global warming potential and it is also a major component of naphtha. Gas can be considered as methane for the same reason. Hexane has a GWP value of 3.7 and methane has a GWP value of 21. For the bitumen plant, the total equivalent CO_2 release per year was found to be 2477 Metric Tons. For the refinery, the total equivalent CO_2 release per year was found to be 14327 Metric Tons. Figure 4 shows the comparison of equivalent CO_2 release from both plants.

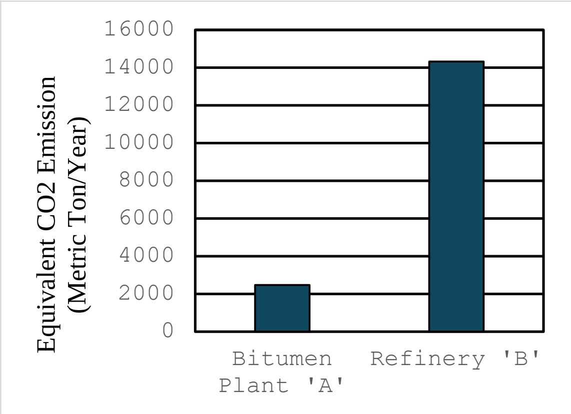


Figure 4: Comparison of the yearly equivalent CO_2 release between the bitumen plant (A) and condensate refinery (B)

5. Conclusion

The present study aimed to estimate fugitive emissions in petroleum processing industries, assess the working environment, and demonstrate the impact of fugitive emissions on global warming. The study was conducted on a bitumen plant and a condensate refinery. Process flow diagrams and piping and instrumentation diagrams were used to calculate the fugitive emissions from different components and units of the plants. The amount of material lost from plants due to fugitive emissions was estimated. Worst-case scenarios were considered for assessing the cancer risk of the workers. Finally, the annual carbon dioxide emissions from the plants were calculated to assess the global warming potential. This research contributes to the understanding of the diverse effects of fugitive emissions on the workplace environment and global warming. The results and suggestions offered in this study are intended to aid the petroleum industry, policymakers, and environmental practitioners in implementing measures that reduce the negative impacts of fugitive emissions, protect workers' health, and address global warming.

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