Evaluation of Industrial Biofilter Emissions on Health Effects through Dispersion Model Predictions

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ABSTRACT
This research investigates the dispersion of air pollutants that are accidentally released from industrial biofilters. For this study, a commercial biofilter that is installed in an industrial plant located in Hickson, Ontario, Canada is considered as an example. The accidental releases could happen due to failure in biofilter performance. Dispersion model CALPUFF was used in this study at different biofilter removal efficiencies to predict pollutant concentrations, dispersion and health effects under various atmospheric conditions. The study shows geographical variations (i.e. flat surface versus elevated) of the location of a biofilter have effect on the pollutant dispersion. The results confirmed that the wind direction has a direct impact on the pollutant plume path whereas atmospheric conditions have an influence on the pollutant dispersion. Also, the results elucidated that the high concentration of pollutants that obtained at a low removal efficiency of biofilter can cause serious health problems. The results of this investigation can be used as a basis to evaluate biofilter performance under different atmospheric and geographical conditions and to improve biofilter design.

Author Keywords
Biofilter; CALPUFF; Dispersion; Air pollution; Health effects.

ACM Classification Keywords
I.6.1 SIMULATION AND MODELING; I.6.4 MODEL VALIDATION AND ANALYSIS

1. INTRODUCTION
The air pollution that accompanies different industrial activities has affected the environment quality and thus human health. It can cause a variety of environmental problems such as climate change, ozone depletion, and damage to crops and the forest. Also, the emissions of volatile organic compounds (VOCs) and inorganic odors, which are considered as major air pollutants,(such as dimethyl sulfide, amines, hydrogen sulfide, ammonia, dimethyl sulfide, and dimethyl disulfide), cause many sub-chronic health effects including eye and nose irritation, headache, and drowsiness [1]. High concentrations of these odors with long-term exposure can cause serious diseases such as cancer and liver damage [2].

Biological methods, including biofilters, bio-trickling filters, and bio-scrubbers, are more desirable than other air pollution control methods due to their effective removal of VOCs, biodegradable odorants, operational simplicity, and economical costs [3]. The biofiltration is a promising technology for gas and odor treatment and its concept relies on eliminating the air pollutants by bacterial populations. The system contains two main processes, which are sorption and degradation. When the contaminated air passes through a biofilter, the pollutant absorbed on the surface of biofilter media particles (biofilms) are degraded by the bacteria into harmless products such as carbon dioxide (CO_2), Water (H_2O), and biomass [4]. The success of the biofilter processes depends on three important parameters that are (1) the moisture of media (2) Empty bed time (EBRT), which needs to be large enough to achieve complete removal of contaminants [5] and (3) the packing materials of biofilter, which should have certain physicochemical properties such as a high porosity, a large surface area, a suitable mechanical resistance, and a high water holding capacity to increase bacterial growth and biofilm adhesion [6]. Any shortage of the above parameters could increase the potential of pollutants release into the atmosphere.

In Canada, biofilters are installed across the province of Ontario by various industries for removal of different types of contaminated and odorous pollutants [1]. Although the biofilters are designed to eliminate pollutants with greater than 90% efficiency, accidental releases do occur due to failure in biofilter performance; hence, putting the people who live in the vicinity of biofilter locations at risks. Air dispersion models such as CALPUFF and AERMOD, which are numerical tools, can be applied in such cases to estimate the total pollutant concentrations for specific location and time, as well as to assess the potential health and environmental impacts of harmful air pollutants around the areas. Since these dispersion models can explain the underlying relationship between different factors such as

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emissions, meteorology, atmospheric conditions, and deposition, and define the results of accidental discharges of harmful or toxic pollutants, they are considered more accurate and reliable than the other air dispersion models, and used more in different air quality investigations [7].

In this study, a unsteady state Lagrangian puff model, CALPUFF (California Puff Model) has been used to predict the total concentration of different odors that can be accidently released from a biofilter installed in a meat rendering plant located at Hickson, in Ontario Province, Canada as well as to assess the pollutants health effects on people who live in adjacent areas of this biofilter.

1.1. Case study

A case study is chosen for our research to demonstrate the dispersion on health effects and using the methodology described any similar biofilter applications can be evaluated. A 15000 cfm capacity biofilter was installed in 1998 in a meat rendering facility that is located in Hickson (ON), CANADA to control air pollution. The significant pollutants that emit from this facility are ammonia (NH_3), hydrogen sulfide, methanethiol, ethylamine, and dimethyl sulfide. There are many health effects associated with high concentrations of these pollutants in the atmosphere. For instance, the main concern of ammonia (NH_3) is the possibility of rising health risks because of a growth in $PM_{2.5}$ linked with ammonium nitrate [8], leading to heart attacks and strokes, and premature death [9]. Hydrogen sulfide H_2S is an extremely toxic odor; high concentration could cause loss of consciousness and death [10]. Although Methanethiol (CH_4S) is considered to be relatively non-toxic, high concentration and long exposure affects the nervous system, and can cause convulsion and narcosis [11]. Similarly, inhalation of Ethylamine ($CH_3CH_2NH_2$) with high concentration causes nose and throat irritation as well as headaches [12]. The strong garlic odor from dimethyl sulfide $(CH_3)_2S$ causes headache, nausea and irritation to the eyes and respiratory system [13]. In addition to health effects, nuisance odors also affect the people who live in the neighborhood of the biofilter.

2. MATERIAL AND METHODS

2.1. CALPUFF Dispersion Model

In our analysis, we have used CALPUFF, non-steady-state meteorological and air quality modeling technique that has been approved by the U.S. Environmental Protection Agency. It is the most appropriate model for assessing transport of pollutants and their dispersion in near field complex terrain settings. Also, this model has the capability to characterize wet and dry deposition of the pollutants. The modeling system contains three major modules; pre-processing, simulation modeling, and post-processing packages. The pre-processing package includes a set of processors for geophysical, surface meteorological, upper air meteorological, precipitation, and overwater data. In general, the CALPUFF modeling system contains three components, CALMET, CALPUFF, and CALPOST. CALMET is a meteorological model package with hourly wind and temperature generators. CALPUFF is a Gaussian puff model with different effects such as chemical removal, wet and dry deposition, and complex terrain algorithms. CALPOST is a post-processing package for the CALPUFF output file that contains meteorological data, concentrations and deposition fluxes.

2.2. Input Data Requirement

Surface Meteorological Data

The hourly surface observations for the case study were obtained from the historical climate records in the Canadian government website (climate.weather.gc.ca). The surface station was chosen based on the closeness from the point source and upper air station. Each hourly record contains the date and the time, temperature, wind speed, wind direction, ceiling height, cloud cover, and station pressure. The hourly data for three modeling periods from January 14, 2013 at 0000h to January 16,2013 at 2300h; May 14,2013 at 0000h to May 16, 2013 at 2300h; and September 14, 2013 at 0000h to September 16, 2013 at 2300h were excreted and prepared in a certain format to be used with CLAMET. The information of the surface meteorological station selected in the region of study is shown in Table 1. The three modeling periods are chosen to account for the effect of seasonal variations on the pollutant dispersion.

Parameter	Hickson
Station Name	Kitchener/Waterloo
Latitude	43 27 39
Longitude	80 22 43
Elevation	321.6
Climate ID	6144239
WMO ID	71368
TC ID	YKF

Table 1. Surface station information used to obtain surface meteorological data.

Upper air meteorological data

The upper air meteorological information for the study location was obtained from the radiosonde station records in the NOAA/ESRL radiosonde database (esrl.noaa.gov /raobs/). These data records contain station ID number, date and time, and information of sounding level followed by pressure, temperature, elevation, wind direction, and wind speed for each sounding level. The hourly data for Hickson was taken from one radiosonde station that is close to this location, for the three modeling periods mentioned above and was then prepared a format suitable to use in the CALMET program. Table 2 lists information about the radiosonde station from which upper air meteorological data were extracted.

Geophysical data

The geophysical data, including land use and terrain were obtained from the Geographic Information Systems Resource website and used to generate output file GEO.DAT, which is to be used in the CALMET program as discussed above.

Parameter	Hickson
Station Name/Location	Moosone PQ
UTM latitude	51.27
UTM longitude	80.65
X location on grid	808.3 km
Y location on grid	1 km
Elevation	10 m
WBAN	15803
WMO ID	71836
INIT	YMO

Table 2. Radiosonde station information used to obtain upper air meteorological data.

Emission rates and source parameters

The pollutant emission rates for this case study were obtained from the reference [1]. Table 3 and Table 4 contain the values of source parameters, and emission rates of pollutant at 90% removal efficiency of biofilter, respectively. These values were used in the CALPUFF model and specified for the three modeling periods.

Source Parameters	Hickson
X Coordinate (km)	511.94
Y Coordinate (km)	478.61
Base Elevation (m)	353.6
Stack Height (m)	14
Stack Diameter (m)	0.31
Exit Velocity (m/s)	25.05
Exit Temperature (K)	308

Table 3. Source parameters information.

Species	Rates (g/s)
NH_3	0.137
H_2S	0.005
CH_4S	0.009
$CH_3CH_2NH_2$	0.01
$(CH_3)_2S$	6.2

Table 4. The emission rates of pollutants (at Hickson).

3. RESULTS AND DISCUSSION

3.1. CALPUFF Model

The CALPUFF model system was used to predict the concentration of different pollutants released from this biofilter, as well as to simulate the transport and dispersion of these pollutants. The CALPUFF model can simulate the effect of spatial and temporal varying meteorological conditions on pollutant concentration, transport, transformation, and removal. Hence more data such as terrain, surface and upper area data for the selected period are required to run the CALPUFF model.

The case study is located in Hickson, which is a village in Southwestern Ontario, CANADA with a population around of 12,000 according to the 2011 census of Canada. In order to evaluate the health effects on the individuals reside around the biofilter location, the domain of study was selected to be 25 by 25 km of the source with the source at the center of this area. The CALPUFF model was used for the three modeling periods. Then, CALPOST postprocessor was used to show the spatial distribution of predicted concentrations for the above-modeling periods. Figure 1 represents the characteristics of the study area. In this figure, it can be seen the capability of CALPUFF model to simulate geographical condition of the area of interest. Since this area is considered even, the geographic variations in this domain have slight effect on the wind nature. In this case study, the CALPUFF dispersion model was conducted for all pollutants emitted from the biofilter, and the results show that concentrations of the following compounds NH_3, H_2S, CH_4S, and $CH_3CH_2NH_2$ are in the allowed limit range and they do not have any health concerns. However, the $(CH_3)_2S$ concentration was very high which prompts more health concerns. Therefore, the evaluation of only this compound's health effects is presented in this paper.

By monitoring the wind field vectors that were produced by CALMET processes it was found that during the modeling period of January, the wind vectors headed different directions on this day of January 15th. However, a significant shift in the wind direction and wind speed happened between 1900 and 2300 hours as the wind vectors changed their direction from south to north. Also, at 2300h the wind vectors headed in the northeast direction, and the speed of wind lessened. During the period of May, the wind vectors heading east and southeast directions most of the time. However, the wind vectors changed their direction into the north at 1700h. Finally, on September 15, 2013, a shift in wind direction occurred between 1500 and 2300 hours where the wind changed direction from east and southeast to the south.

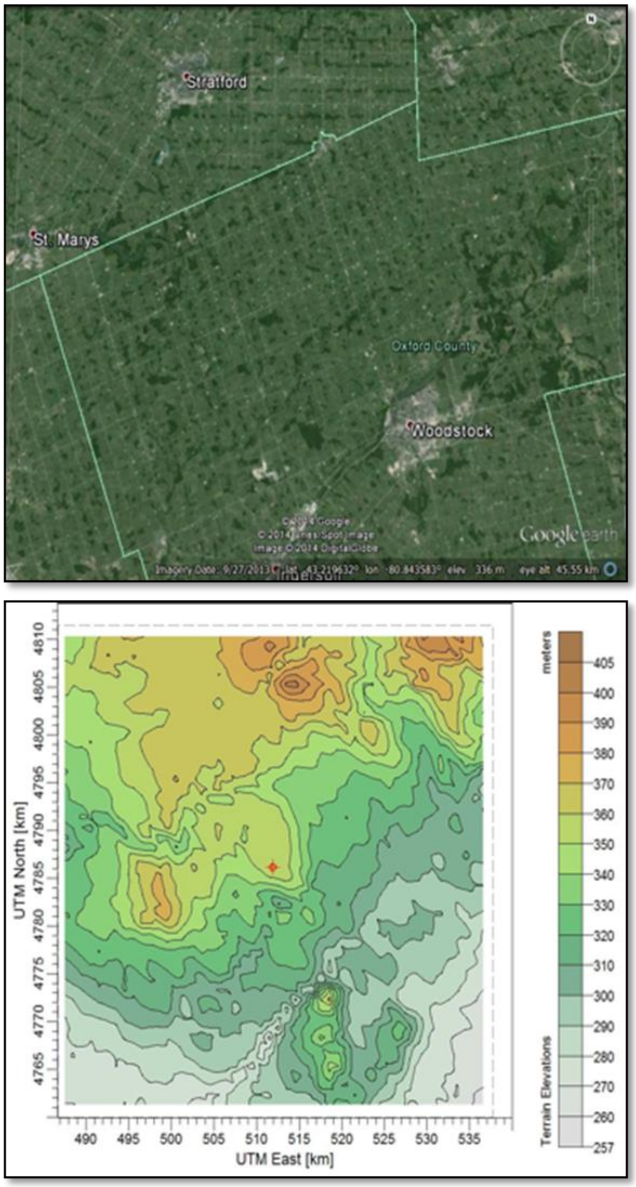

Figure 1. The characteristics of the study area (A) google map (B) elevation.

When biofilter removes the pollutants with 90% efficiency, the highest hourly average concentration of $(CH_3)_2S$ on January 15, 2013 was 316 mg/m^3. This concentration was obtained at 0300h of this day at a distance of 1 km from the source. Figure 2 shows that the plume of $(CH_3)_2S$ emission dispersed in the direction of wind toward the southeast, affected the population living in that area. On the other hand, the highest 24h average concentration of $(CH_3)_2S$ on this date was 13.5 mg/m^3, occurring at the location of 1 km south of the plant. The pollutant plume dispersed north and south sides as shown in Figure 3.

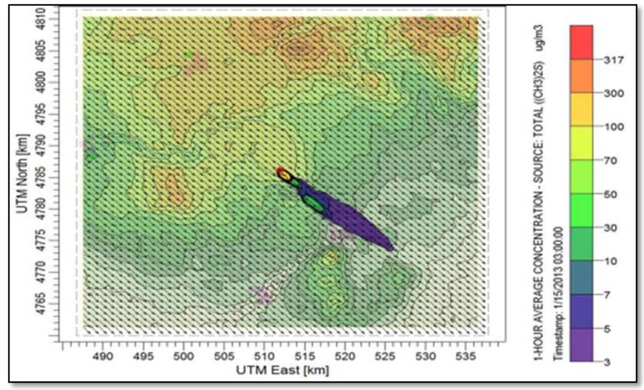

Figure 2. The wind field vectors and the maximum hourly average $(CH_3)_2S$ concentration on January 15, 2013 at 0300h.

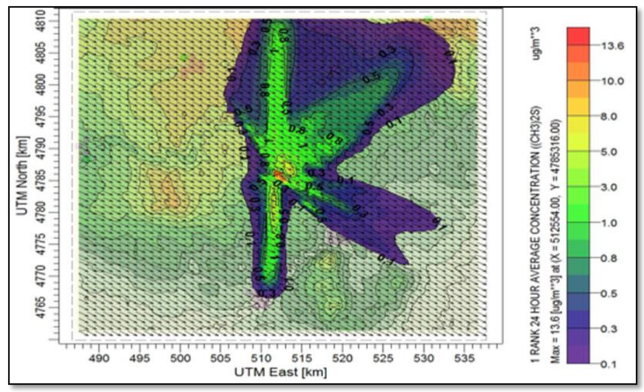

Figure 3. The wind field vectors and the maximum daily average $(CH_3)_2S$ concentration on January 15, 2013.

On May15, 2013, the maximum hourly concentration of $(CH_3)_2S$ at each receptor in the domain was 241 mg/m^3,which was predicted at 2000h in the range of 0.5 km of the point source. Figure 4 presents the plume dispersion at 2000h of this day headed in the same wind direction to the northeast. On the other hand, the highest daily concentration of $(CH_3)_2S$ was found to be 16.6 mg/m^3, and observed at a coordinate 0.5 km from the source, and the pollutant scattered in northeast and southeast directions as shown in Figure 5.

As seen in Figure 6 the pollutant plume gathered around the source and scattered slightly toward the northeast. The highest 24-h average concentration of $(CH_3)_2S$ obtained in the middle of September 2013, reached 19.15 mg/m^3 within 0.5 km northeast of the source. The dispersion of $(CH_3)_2S$ is heading in the northeast and southeast directions as indicated in Figure 7, affecting residents in those regions.

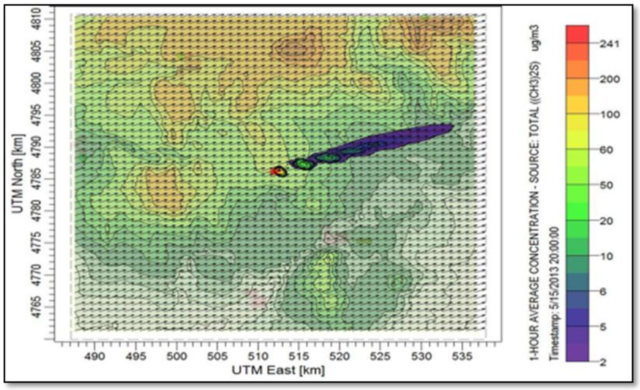

Figure 4. The wind field vectors and the maximum hourly average $(CH_3)_2S$ concentration on May 15, 2013 at 2000h.

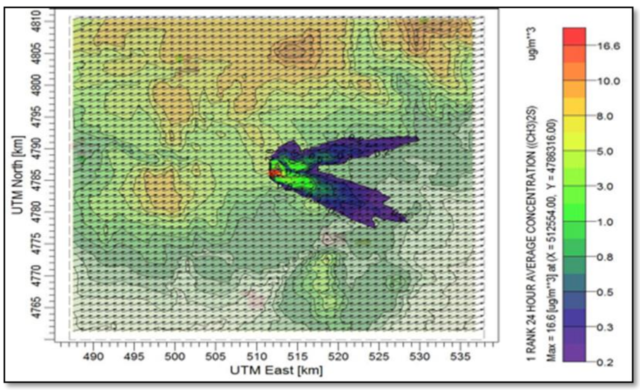

Figure 5. The wind field vectors and the maximum daily average $(CH_3)_2S$ concentration on May 15, 2013 2013.

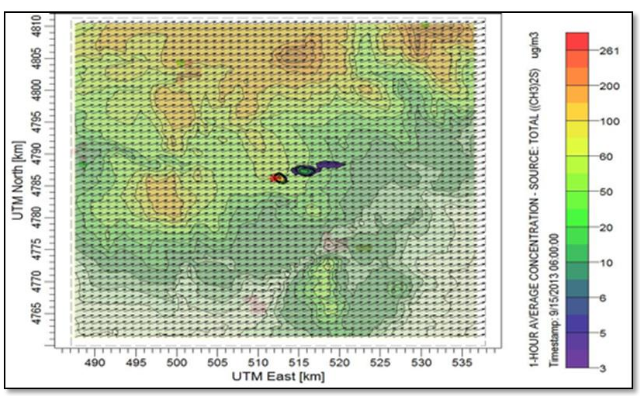

Figure 6. The wind field vectors and the maximum hourly average $(CH_3)_2S$ concentration on September 15, 2013 at 0600h.

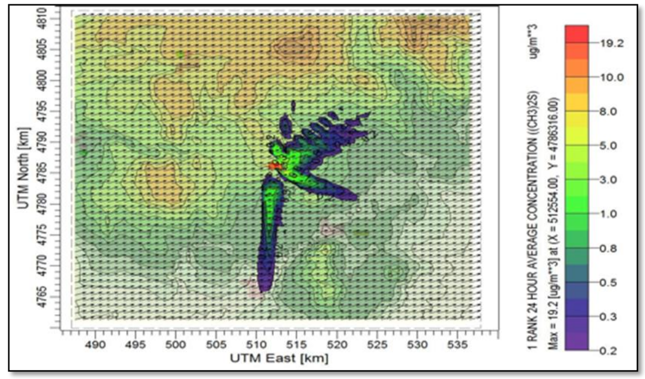

Figure 7. The wind field vectors and the maximum daily average $(CH_3)_2S$ concentration on September 15, 2013.

According to United States Environmental Protection Agency, the highest hourly average concentrations of $(CH_3)_2S$ for all three periods exceeded the exposure limit of $(CH_3)_2S$ which is 25 mg/m^3. People that are exposed to the range of concentration (241-316 mg/m^3) may experience the following health issues: severe damage to the lungs, Injures the liver, kidneys, heart, and central nerves system. However, the highest daily average concentration of $(CH_3)_2S$ for all three periods - January 15, 2013, May 15, 2013, and September 15, 2013 - are in the range between 13.5 to 19.15 mg/m^3, and no health symptoms are associated with this range of concentration.

As mentioned before in this paper, any a deficiency of biofilter parameters such as the moisture content of filter bed, temperature, pressure drop, air flow rate and humidity, could lead to a failure in biofilter performance and hence more discharge of pollutant into the atmosphere. The CALPUFF model has been used to estimate the concentration of $(CH_3)_2S$, assuming that the removal efficiency of biofilter dropped to 50% and 20%, as well as to assess the health effects at these stages. Overall, the CALPUFF model results for the case study, demonstrated that the average hourly concentrations of all pollutants- NH_3, H_2S, CH_4S, $CH_3CH_2NH_2$, and $(CH_3)_2S$- are higher in January period than the other months whereas the average daily concentrations are higher in May. Moreover, for the three modeling periods the highest hourly and daily concentration of all pollutants will not cause any health symptoms expect dimethyl sulfide. The high concentration of $(CH_3)_2S$, that obtained at different removal efficiency of biofilter, can cause serious health problems and risk of death.

4. CONCLUSION AND RECOMMENDATIONS

In order to assess the potential health impacts of the accidental release of pollutants from a biofilter installed in a meat rendering plant in Ontario, CANADA, it is imperative to use air dispersion models. In this work, the CALPUFF dispersion model was used to predict concentrations of different pollutants emitted. The CALPUFF model made it possible to identify which population areas the pollutant dispersed to and affected more. The results displayed that the highest concentration of the dimethyl sulfide, in this case study, can cause a coma, and increase risk of death. As in this study, the CALPUFF model conducted on closed biofilter (point source) with fixed parameters. It is recommended to conduct the CALPUFF dispersion model on open biofilters (area sources) case studies.

REFERENCES

1. Shareefdeen Z, Brian H, Derek W, Polenek S, Wilson S Removing volatile organic compound (VOC) emissions from a printed circuit board manufacturing facility using pilot- and commercial-scale biofilters. Environmental Progress, 21(3), 2002, 196-201.
2. Probert C. SJ, Ahmed I, Khalid T, Johnson E, Smith S, Ratcliffe N, Volatile organic compounds as diagnostic biomarkers in gastrointestinal and liver diseases. J Gastrointestin Liver Dis. 18(3), 2009, 337-43.
3. Shareefdeen Z, Brian H, Derek W, Verhaeghe L, Wilson S, An odor predictive model for rendering applications. Chemical Engineering Journal, 113, 2005, 215-220.
4. Shareefdeen Z, Singh A, *Biotechnology for odor and air pollution control.* Springer, New York, 2005.
5. Veillette M, Ramirez A, Heitz M Influence of ammonium concentration on the performance of inorganic biofilter treating methane. World Academy of Science, Engineering and Technology,72, 2012,12-21.
6. Gutiérrez-Acosta O, Arriaga S, Escobar-BarriosV, Casas-Flores S, Almendarez-Camarillo A, Performance of innovative PU-foam and natural fiber-based composites for the biofiltration of a mixture of volatile organic compounds by a fungal biofilm. Journal of Hazardous Materials, 2012, 202-208.
7. El-Harbawi M, Air quality modelling, simulation, and computational methods: a review. Environ. Rev. 21, 2013, 149-179.
8. Toro R. A, Canales M, Flocchini R. G., Morales R. G. Leiva G. M. Urban atmospheric ammonia in Santiago City, Chile. Aerosol and Air Quality Research, 14, 2014, 33-44.
9. Wang Y, Hopke P, A ten-year source apportionment study of ambient fine particulate matter in San Jose, California. Atmospheric Pollution Research, 4, 2013, 398-404
10. (U.S. EPA) U.S. Environmental Protection Agency (2003b) Toxicological Review of Hydrogen Sulfide. (No. EPA/635/R-03/005). Washington D.C.: U.S. Environmental Protection Agency. Available at http://www.epa.gov/ttn/atw.
11. Wei-Jinag S, Shu-Ping Z, Zi-Yan Z, Thermodynamic and kinetic investigations on the reaction of methanethiol with oxygen atom. Indian Journal of Chemistry, 52A, 2013, 1411-1415.
12. (AEGLs) Acute Exposure Guideline Levels for Ethylamine (CAS Reg. No. 75-04-7), http://www.epa.gov/oppt/aegl/pubs/ethylamine_tsd_interim_version_106_2008.pdf.
13. (MSDS for DMS) Material Safety Data Sheet for Dimethyl Sulfide (2004) http://bayouengineering.com/images/pdf/dimethyl_sulfide-dms.pdf