Impact of gaseous and particulate matter emission for fluid catalytic cracking units

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IMPACT OF GASEOUS AND PARTICULATE MATTER EMISSION FOR FLUID CATALYTIC CRACKING UNIT

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KEYWORDS
Dispersion model, Aermod, emissions, FCC, pollutants exceedance

ABSTRACT

Fluid catalytic cracking unit is a major part of petroleum refineries as it treats heavy fractions from various process units to produce light ends (valuable products). FCC unit feedstock consists of heavy hydrocarbon with high sulphur contents and the catalyst used is zeolite impregnated with rare earth metals i.e. Lanthanum and Cerium. Catalytic cracking reaction takes place at an elevated temperature in fluidized bed reactors generating sulphur-contaminated coke on the catalyst with large quantity of attrited catalyst fines. In the regenerator, coke is completely burnt producing SO2. PM emissions are mainly due to high attrition of cold makeup catalyst charge and operating conditions, vapour velocity particle velocity, particle collision and particle degradation. This study is dedicated to the quantitative analysis of the impact of harmful emissions resulting from FCC units on the environment.

INTRODUCTION

Fluid catalytic cracking (FCC) of heavy ends into high value liquid fuels is commonly carried out in the oil refining industry. In this process the heavy feedstock containing sulphur as a major contaminant is cracked to light products. Sulphur is redistributed in the liquid and gaseous products and coke on the catalyst. In the regenerator, coke with sulphur contamination is completely burnt and flue gas containing SO2 is discharged with catalyst fines produced, mainly due to high attrition of cold makeup catalyst charge and operating conditions i.e. vapour velocity, particle velocity, particle collision and particle degradation (Abdul Wahab et al., 2002).

In the present work, a comprehensive emission inventories from FCC unit in an oil refinery have been prepared. These inventories are calculated based on complete combustion of sulphur and coke impregnated on the catalyst in the regenerator. Mainly for SO2 and Particulate matter (PM) emission rates are calculated accurately using material balances for a yearlong period considering seasonal variations in the operation of the process unit, Yateem et al., (2010). PM emission inventory is used in dispersion model to assess its impact on the immediate surroundings of the refinery.

The most advanced dispersion model Aermod (Caputo et al., 2003; Isakov et al., 2007; Kesarkar et al., 2007) has been selected for prediction ground level concentration of PM based on comprehensive year long emission inventory of FCC unit.

Aermod is a dispersion model that uses Gaussian distribution for the stable conditions and non-Gaussian probabilities density function for the unstable conditions. Aermet (Aermod pre-processor) provides planetary boundary layer parameters over a high altitude to yield accurate predicted concentration values for a given meteorological conditions. It can accommodate large meteorological data (multiple years). Aermap (Aermod pre-processor) generates regular receptors over a given terrain for the evaluation of pollutants ground level concentrations. The meteorological data for year 2008 are obtained and are used in pre-processor Aermet to generate planetary boundary layers parameters. These generated data are used in Aermod for actual emission rates to predict ground level concentrations of PM and study the influence of prevailing meteorological conditions at this particular site.

MODEL APPLICATION

1. Input Data

Aermod dispersion model implementation requires the following items of data:
1. Source information: including pollutant emission rate (g/s), location coordinates in Universal Transverse Mercator (UTM) (m), base elevation from the sea level (m), stack height (m), exit stack inner diameter (m), exit stack gas velocity (m/s), and exit stack gas temperature (°K).
2. Meteorological information for the region of interest: includes anemometer height (m), wind speed (m/s), wind
direction (flow vector from which the wind is blowing) (in degrees clockwise from the north), ambient air temperature (°C), stability class at the hour of measurement (dimensionless) and hourly mixing height (m).

3. Receptor information: This can be specified or generated by the program to predict the pollutants’ concentrations at the selected receptors.

The entire required source input data are obtained from FCC unit in the refinery. A stack of 80 m height, an inner diameter of 2.3 m, with an average exit gas velocity of 20 m/s and exit gas temperature of 550 °K are fed into the model. Monthly emission variation is considered with total SO2 emission rate of 6089.2 g/s and total PM emission rate of 302 g/s as presented in detail (Yateem et al. 2010).

2. Area of Study

The area of study in this work covers portion of Ahmadi governorate in the state of Kuwait. Fahaheel area is adjacent to the petroleum refinery has one of the Kuwait EPA air quality monitoring station located at a polyclinic. Both areas Fahaheel and Ahmadi are surrounded by arid desert in the west side and bordered by the Persian Gulf from the east.

Two different types of receptor coordinates are used as input to the Aermod model to predict the ground level concentration of SO2 and PM, these are:

1. Discrete Cartesian receptors specified at the sensitive areas viz., a school, a shopping area and EPA monitoring stations in Fahaheel. A hospital and petroleum services companies’ offices are selected in Ahmadi.

2. Uniform Cartesian Grid receptors covering the entire area of study, where the FCC stack (emissions source) is located almost in the centre of the mesh grid.

The receptors selected are based on the actual sites in a UTM location coordinate of the area of interest map. Table 1 shows the selected discrete receptors information.

The uniform grid receptors of a total 1764 (42 x 42) were divided into (Δx = 300 m x Δy = 250 m) to cover about 12 x 10 km area of study. The optimum selection of the mesh size is based on the computational accuracy and time.

Table 1 the selected discrete receptors information

<table>
<thead>
<tr>
<th>ID Number</th>
<th>Discrete receptor identity</th>
<th>X-coordinate</th>
<th>Y-coordinate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fahaheel Polyclinic</td>
<td>219854.25</td>
<td>3219765.79</td>
</tr>
<tr>
<td>2</td>
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<td>216666.87</td>
<td>3220105.63</td>
</tr>
<tr>
<td>3</td>
<td>School in Fahaheel</td>
<td>220130.08</td>
<td>3219820.85</td>
</tr>
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<td>4</td>
<td>Ahmadi Hospital</td>
<td>213458.86</td>
<td>3221523.64</td>
</tr>
<tr>
<td>5</td>
<td>Shopping area in Fahaheel</td>
<td>219274.32</td>
<td>3219554.21</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSION

A yearlong comprehensive metrological data are processed by Aermet to generate boundary layer parameters and to pass all meteorological observations to Aermod.

Figure 1 shows wind direction and magnitude for a period of year 2008. It is observed that most of the time; the prevailing wind direction is from North West. There is strong influence from the neighbouring Persian Gulf as the refinery is located at the coast, resulting into strong sea breeze blowing from East direction. Wind class frequency distribution for the entire year confirming 2 % calm conditions, while 39.8 % is between 3.6 - 5.7 m/s. the highest wind class 8.8-11.1 m/s is less than 1%.

Table 2 SO2 monthly emission factors

<table>
<thead>
<tr>
<th>Month</th>
<th>January</th>
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<th>March</th>
<th>April</th>
<th>May</th>
<th>June</th>
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</thead>
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<th>October</th>
<th>November</th>
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<td>0.067</td>
<td>0.088</td>
<td>0.077</td>
<td>0.1</td>
<td>0.75</td>
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</table>

Table 3 PM monthly emission factors

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<th>March</th>
<th>April</th>
<th>May</th>
<th>June</th>
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<td>0.097</td>
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<td>0.079</td>
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<table>
<thead>
<tr>
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<th>November</th>
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<tbody>
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<td>0.063</td>
<td>0.085</td>
<td>0.079</td>
<td>0.079</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Hourly predicted ground level concentrations at specified discrete receptor showed large scatter due to variation in meteorological conditions and the recorded values influenced by the contribution of various emission sources has made the comparison impracticable. Therefore, daily average measured concentrations of SO2 were compared with the daily-predicted concentrations to validate the model output.

Figure 2 shows the plot between the measured top 20 daily average values versus the daily predicted top 20 values at the discrete receptor, Kuwait-EPA monitoring station.
The slope is equal to 0.72, reflecting high measured values compared to predicted values, depicting the contribution of other emission sources. The correlation coefficient is equal to 0.91 reflecting an acceptable validation of the model output with measured average daily SO$_2$ concentrations.

Similarly, the predicted daily average ground level concentration of SO$_2$ is compared with Kuwait EPA ambient air quality standards at all receptors. The allowable level for the daily average concentration of SO$_2$ is 157 µg/m$^3$. Fig. 4 shows the isopleths of the predicted daily average ground level concentration of SO$_2$ calculated at the selected uniform grid receptors.

The isopleths indicate the daily predicted spatial variations of the ground level concentrations of SO$_2$. The highest daily predicted concentration is equal to 335µg/m$^3$, observed on the 9$^{th}$ of November 2008 and about 0.75 km in the SE direction from the stack, at a receptor coordinates of X = 220357.94, Y = 3217419 affecting the neighbouring Shuaiba industrial area, Kuwait main industrial complex. This high value of the daily predicted SO$_2$ concentration is exceeded the allowable level by 157 µg/m$^3$ and obviously influenced by the prevailing meteorological conditions, especially the predominant North West wind and other meteorological factors.

Discrete receptor 3 shows the highest SO$_2$ hourly concentration equal to 279µg/m$^3$ on 30$^{th}$ April at 3:00 hours. The daily predicted concentration is equal to 45µg/m$^3$ on 22$^{nd}$ April. Both hourly and daily predicted values are below Kuwait EPA hourly and daily ambient air quality standards.
1. Model Sensitivity
To observe the computational model sensitivity, another run is performed using two finer meshes consisting of 21 x 21 uniform receptor points, the first covering hourly highest ground level concentration area, the second covering daily highest predicted ground level concentration area. The output accuracy has improved for both pollutants due to application of interpolation using small values of $\Delta x = 150$ m, $\Delta y = 110$ m for the first mesh and $\Delta x = 100$ m, $\Delta y = 100$m for the second mesh. There is 0.65% increase in the hourly highest ground level concentration and 2.8% increase in the daily highest ground level concentration, which are insignificant.

2. Parametric Study
FCC stack sensitivity analysis is performed on 3 scenarios (stack height, $SO_2$ emission rate and stack diameter). In scenario 1, analysis for stack heights 50 m, 80 m, 120 m, 160 m and 200 m is conducted while keeping the emission rate, exit flue gas velocity, exit temperature and stack diameter constant. The influence of stack height is shown in fig. 5. It is obvious from the figure that the highest predicted hourly and daily ground level concentrations of $SO_2$ are reduced substantially as stack height is increased. The reduction in the highest computed hourly ground level concentration of $SO_2$ is almost 50% when stack height is doubled. The decrease in evaluated hourly $SO_2$ concentration as a function of stack height is given as an exponential expression $C(\mu g/m^3) = 1600.7 e^{-0.071 x 10^{-7} h}$ and $r^2$ is 0.999, where $h$ is the stack height (m). The hourly gradient $dC/dh = 14.52 e^{-0.071 x 10^{-7} h}$ becomes insignificant at higher stack elevations. The daily highest predicted concentration gradient is $24.42 e^{-1.732 x 10^{-7} h}$. The locations of hourly highest predicted concentrations of $SO_2$ from the stack, as a function of stack height is shown in figure 7 and related as $D(km) = 0.597 e^{1.6x10^{-7} h}$ and $r^2$ is 0.9.

In scenario 2, $SO_2$ emission rate effect from FCC stack is tested at stack height of 80 m for different total monthly emission rates of 3000 g/s, 4000 g/s, 5000 g/s, 6000 g/s, 7000 g/s and 8000 g/s, taking into consideration the monthly emission variations (by using emission factors, table 2) and fixing other stack parameters i.e. exit temperature, exit flue gas velocity and stack diameter. It is noticed from fig. 8 that the highest predicted hourly and daily ground level concentrations of $SO_2$ is substantially decreased as $SO_2$ emission rate is reduced. At 50% reduction in the emission rate, the highest hourly and daily ground level concentrations decreased by 50%.

Kulkarni et al., (2009) have reported that Lanthanum and Lanthanides are used as markers for particulate matters pollution as PM$_{2.5}$ in petroleum refineries, mainly from FCC units. US EPA daily PM$_{2.5}$ standard is 35$\mu g/m^3$. In the present work, the application of Aermod to predict ground level concentration of PM is considered as PM$_{2.5}$ for rare earth elements i.e. Lanthanum and Cerium. PM$_{2.5}$ is inhalable and has adverse impact on public health causing cardiovascular diseases. Kuwait EPA has no standard for PM$_{2.5}$ and has only specified daily and yearly standard for PM$_{10}$. Figure 5 shows the isopleths of the predicted hourly average ground level concentration of PM calculated at the selected uniform grid receptors.

The isopleths indicate the hourly predicted spatial variations of the ground level concentrations of PM. The maximum hourly predicted average ground level
concentration of PM is equal to 45 μg/m³, observed on the 27th of February 2008 at 8:00 hour and about 1.56 km in the NW direction from the FCC stack, and at receptor coordinates of X = 218557.94, Y = 3218919.

Similarly, the predicted daily average ground level concentration of PM is compared with US EPA ambient air quality standards for PM₁₀ at all receptors. Figure 6 shows the isopleths of the predicted daily average ground level concentration of PM computed at the selected uniform grid receptors.

Fig. 8 Isopleths plot of the predicted daily average ground level concentration of PM
The isopleths indicate the daily average predicted spatial variations of the ground level concentrations of PM in the area of study. The highest daily predicted concentration is equal to 16 μg/m³, observed on the 29th of December 2008 and about 0.75 km in the SE direction from the stack, at a receptor coordinates of X = 220657.94, Y = 3217419 due to the influence of the prevailing meteorological conditions, especially the predominant North West wind and other meteorological factors.

To observe the computational model sensitivity, another scenario run is performed adding two finer meshes consisting of 21 x 21 uniform receptor points, the first one covering hourly highest ground level concentration area, the other one covering daily highest predicted ground level concentration area. The output accuracy has improved for both pollutants due to application of interpolation using small values of Δx = 150 m, Δy = 110 m for the first mesh and Δx = 100 m, Δy = 100m for the second mesh. There is 0.65% increase in the hourly highest ground level concentration and 2.8% increase in the daily highest ground level concentration, which are insignificant.

CONCLUSIONS
FCC unit in a refinery is a major contributor to SO₂ and PM emissions. These gases have adverse impact on the immediate neighbourhood of refineries. In this study a complete emission inventory for a year long period have been prepared for SO₂ and PM. A model run performed for actual monthly emission variation with total SO₂ emission rate of 6089.2 g/s and PM emission rate of 302 g/s, taking into consideration monthly emission factors for both SO₂ and PM.

The daily predicted ground level concentrations of SO₂ are compared with Kuwait EPA monitoring station daily measured SO₂ concentrations at the same discrete receptor and showed acceptable validation of the model output. The highest hourly predicted concentration of SO₂ is equal to 769 μg/m³. It is observed on the 8th of March 2008 at 8:00 hour, due to elevated SO₂ emission rate in this month and the prevailing meteorological conditions, especially sea breeze effect in the early morning hours. The highest daily predicted concentration is equal to 335 μg/m³. It is observed on the 9th of November 2008, and obviously influenced by the predominant North West wind and high SO₂ emission rate in the month of November.

The maximum hourly predicted average ground level concentration of PM is equal to 45 μg/m³. It is observed on the 27th of February 2008 at 8:00 hour. The highest daily predicted concentration is equal to 16 μg/m³, observed on the 29th of December 2008.

The stack sensitivity is explored by changing stack height, total emission rate and stack diameter independently. It is observed that the higher stack facilitated good dispersion, thus lowering the ground level average concentration of the pollutant up to 50% when the stack height doubled. It is noted that the highest predicted hourly and daily ground level concentrations of SO₂ are substantially decreased as SO₂ emission rate is reduced. At 50% reduction in the emission rate, the highest hourly and daily ground level concentrations decreased by almost 48%.

The influence of stack diameter inherently changed the exit flue gas velocity due to invariable flue gas flow-rate. The plume rise and dispersion are related to the exit flue gas velocity, which decreased with the increase of stack diameter because of proportionality to the square of diameter. For a fixed load there is no noticeable change in the average hourly and daily predicted ground level concentrations of SO₂. The study results presented in this paper provide, for the first time, a comprehensive quantitative analysis of the impact of a typical FCC unit on its surrounding environment.

References