Numerical Simulation of Plume Rise in Neutral Atmospheric Stability Condition

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Introduction
Air pollution has harmful effect on human health and the environment. Accordingly, considerable effort has been put to analyze the air pollutants. One important issue is the spatial distribution of these pollutants. Dispersion of the pollutants released from sources on the ground is mostly driven by the planetary boundary layer where turbulent flow causes mixing of the content of the stationary ground layer of atmosphere with higher moving layers and thereby clears out the pollutants rapidly. To predict the dispersion of air pollution in the atmosphere, researchers investigate the behavior of plume rise under certain conditions.

Two factors critically affect the result of the test: primary plume rise and its dispersion. In this work, we study the effective height of emission which determines the dispersion of the pollutants. The height of the plume has been subjected to semi-empirical and to more accurate numerical studies. These approaches suffer from some shortcomings. For instance, the gravitational effects and fluctuations of the wind speed are neglected. Numerical approaches are typically based on a Gaussian plume rise model so called ISC3 (published by EPA).

In this paper plume rise of emission of an air pollutant is simulated using Fluent software which allows one to input natural wind velocity profile and to consider the gravity. Another advantage of this approach lies in the usage of turbulent kinetic energy (TKE) and temperature profiles. In this work, theoretical plume rise using the ISC3 model were being calculated at first. The calculated values of \( x_f \) and \( \Delta h \) are equal to 437.85 m and 50.87 m, respectively. Then, the dispersion was being simulated accordingly using Fluent and the results were compared with those of the numerical studies.

Materials and methods
To simulate the plume rise, first a sample stack has been designed and meshed in gambit and then transferred to Fluent. Without loss of the generality of the approach, the following assumptions were made for physical factors of the chimney and weather condition. The simulation was performed in two dimensions (2D) on an area with a length of 2000 m and a height of 1000 m. The opening of the chimney was modeled at a height of 60 m and in an area of 500 m far from the entrance. The exit velocity is assumed to be 10 m/s with a temperature of 450 K. The wind velocity at 10 m height is 4 m/s.

Generating a good mesh is an essential part of any CFD problem. We generated the geometry by the use of GAMBIT, the preprocessing module of the FLUENT. In the present simulation, a standard k-ε model is used and neutral stability condition of the atmosphere is setup using user defined function (UDF) facility of the Fluent software by defining temperature, wind, and turbulence kinetic energy (TKE) profiles at the inlet of the atmospheric boundary layer.

The wind velocity profile was obtained from AERMOD and has a logarithmic form. The vertical profile of the temperature for neutral stability condition is as follow:

\[
T = -0.0098 \Delta Z + T_0
\]

Where, \( T \) and \( \Delta Z \) represent the temperature and the elevation gradient, respectively.

One of the significant steps is to insert the turbulence kinetic energy (TKE) profile which depends on heat transfer, momentum, and moisture in the boundary layer and the TKE obtained from the following try and error method.
In order to evaluate the effect of the gravitational acceleration on the plume rise, the simulation has been done with considering the gravitational acceleration and then the results have been compared to the results when the gravitational acceleration has been ignored.

Results and discussions
To better compare the simulation results with the ones for semi-empirical equations, the maximum concentration and the geometric mean concentration have been averaged. The plume rise with the effect of the gravitational acceleration is shown in Figure 1. Simulation repeated with ignoring the effect of the gravitational acceleration and the results were shown in Figure 2. The maximum concentration reached its highest value approximately at 20 meter far from the stack with an effective plume height of 2.43 m when the gravitational acceleration affected the flow of the plume. But as shown in Figure 2, when gravitational acceleration has been ignored in the simulation, the plume height reached to its highest point at about 450 meter far from the stack with an effective plume height of 8.43 m.
Conclusions

The quantity of $\Delta h$ as a function of $x_f$ was presented in Table 1. $\Delta h$ is obtained from the average of maximum concentration and geometric mean concentration. For the neutral atmospheric stability condition, the results give better agreement with the semi-empirical equations when the gravitational acceleration has been ignored. But, the plume rise became 2.5 times larger than the values obtained from the semi-empirical equations when the gravitational acceleration was applied. This occurs because the gravitational acceleration drawn most mass of the outlet flow; therefore, buoyancy force applied to less concentration of the outlet flow and dispersed it much more in the vertical and horizontal directions. As the presented simulation considers actual wind velocity profile, actual temperature profile, TKE profile, and gravitational acceleration effect, the results are more close to the reality.

Table 1. Comparison of different approaches for estimation of plume rise

<table>
<thead>
<tr>
<th></th>
<th>Semi-empirical relations</th>
<th>Plume rise (ignoring the effect of gravitational acceleration)</th>
<th>Plume rise (with the effect of gravitational acceleration)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta h$</td>
<td>50.87</td>
<td>84.53</td>
<td>128.94</td>
</tr>
<tr>
<td>$x_f$</td>
<td>437.85</td>
<td>437.85</td>
<td>437.85</td>
</tr>
</tbody>
</table>

Keywords: numerical simulation, plume rise, turbulence kinetic energy.