Prediction of Air Pollutants Emitting from Chimney of A CHP Using CFD

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Abstract- Thermal power plant is the main source of base electric power generation for domestic and industrial use. The baseline pollutants emitted from the chimney stacks undergo dispersion in the atmosphere with its supporting meteorological condition and deteriorates the quality of the ambient air and hence a serious threat to the biotic and abiotic elements. The current research work involves the estimation of the ground level concentration (GLC) for the baseline pollutants (NO, N_2O and SO_2) obtained due to the burning of G-grade coal through fluidised combustion process. These pollutants are emitted from 2 chimneys in the study domain. The problem has been simulated using ANSYS CFX 15.0 based on Gaussian dispersion model, to quantify the steady ground level concentration up to 10km radius areal domain. This simulation process requires the input as the meteorological data obtained through online weather monitoring centres at the plant and also the thermo physical properties of the exhaust gases along with the chimney specifications of a combined heat and power plant (CHP). The simulated results show that the maximum steady ground level concentration of NO, N_2O and SO_2 are 34.39µgm/m^3, 50.79µgm/m^3 and 31.01µgm/m^3 respectively. The ground level concentrations of baseline pollutants obtained by simulation through ANSYS CFX 15.0 are within acceptance level as per the National Ambient Air Quality Standards (NAAQS) guidelines and accordingly the concerned industry has been intimated regarding the ambient air quality at the onsite and offsite of their plant.

Keywords: Air pollutants, ANSYS CFX, GLC, Dispersion, CHP, Chimney stack, NAAQS

1. Introduction

Pollution is now a common term, that our ears are attuned to. We hear about the various forms of pollution and read about it through the mass media. Air pollution is one such form that refers to the contamination of the air irrespective of indoors or outside. A physical, biological or chemical alteration to the air in the atmosphere can be termed as pollution, it occurs when any harmful gases, dust, smoke enters into the atmosphere and make it difficult for plants, animals and humans to survive as the air becomes dirty. Recently air pollution is the major problem around the globe, all the people are very much conscious towards the prevention of air pollution. The main pollutants from the chimney stack of thermal power plant is SO_x, NO_x and PM. Due to the increasing demand of the electricity from thermal power plant, the pollutants are increasing day by day. It is very much required to quantify the pollutants over spatial domain in offside of the industries so as to take different measures to reduce it. In the current research prediction of the dispersion phenomenon of chimney exhaust gas (SO_2, NO and N_2O) has been simulated using computational fluid dynamics model.

Computational fluid dynamics software is a powerful tool for thermal modelling and simulation of complex problems in the field of fluid mechanics and heat transfer. In the dispersion model this tool has been solving many complex problems using higher degree of turbulence model in Navier Stoke equation and Advection diffusion equation. Oliver Maruntalu et al [1] have used ANSYS CFX as the simulation tool for prediction of air pollutants coming from an electric thermal power plant. They have accounted the effect of chimney height, obstacles (building) in dispersion of air pollutants (SO_2, NO_x and PM). They have compared the results of ANSYS CFX with the test data. Shiv Lal et al [2] have used computational fluid dynamics (CFD) software (ANSYS) for the simulation of solar chimney, which is used for building space heating. They have conducted mesh adaption technique for grid independent solution. They compared CFD simulation data with the experimental data.

Lavanya G., Shamily B.M et al [3] have done the assessment of vehicular pollution in the streets of Mysore city. They have used ANSYS Fluent as the tool for simulation of air pollutant (SO_2, NO_2 and SPM) dispersion. Konstantinos E. Kakosimos et al [4] have applied a prognostic flow model for the understanding of dispersion conditions governing highest pollutant loads. They have used CFD tool with MISKAM of pollutant dispersion for the simulation. They compared the CFD results against a wind tunnel study. Z. Mrsa and M. Cavrak et al [5] have used ANSYS Fluent tool for calculation of ground leve; concentration of SO_2, CO_2 on a complex terrain around Bakar's bay. They have taken the box model with tetrahedral mesh for the simulation; also they have accounted the turbulent flow using K-ε turbulent model. P. Neofytou et al [6] have investigated the flow field and NO_x concentration in the urban street- Canyon area. They have used CFD simulation using ADREA-HF code for the determination of air pollution level. The results of CFD analysis and measured data were compared. D.cirtina et al [7] have evaluated pollutant emissions resulting from an aluminium foundry starting from data on concentrations and pollutant mass flow rates estimated for each phase of the technological process also they have measured the ambient levels for the area of influence. They have found from the analysis that the emission of SO2, NO2, CO, total dust in suspension fall into the limit values stipulated by Order of the 462/93. Dejene Alemayehu et al [8] have run the U.S. Environmental protection agency regulatory air quality model called AERMOD (Version 15181) to estimate the concentration of $PM_{2.5}$ and SO_2. They have used AERMET program for pre-processing of hourly meteorological data. They have found that 19-26% of $PM_{2.5}$ and SO_2 released from the stacks of the power plants, refinery and carbon black plant into the atmosphere

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reaching the tribal land. Chih-Rung chen et al [9] have examined the performance of Industrial Source Complex Short-Term Model (ISCST3), USEPA nonreactive Gaussian air quality dispersion model in simulating roadside air pollution concentrations on daily and vacation traffic flow in Taoyuan, Taiwan. They simulated the concentration of five air pollutants (CO, NO_x, PM_{10}, $PM_{2.5}$ and SO_x) and presented as dispersion map. They found that the concentration of five pollutants is higher on daily traffic flow that on vacation traffic flow. M.S. Priyanka Yadav et al [10] have selected the AERMOD (the American Meteorological Society/Environmental Protection Agency Regulatory Model Improvement Committee's Dispersion Model, version 7.0.3 for prediction of ground level concentration of particulate matter µg/m3, sulphur dioxide (SO_2) µg/m^3, and oxides of nitrogen (NO_x)- µg/m3 from point source emissions. They have compared the predicted and field sampled downwind concentrations of PM, SO_2 & NO_x (µg/m^3) to predict the average downwind ground level concentrations. J.Smerkar et al [11] have taken about 9 days real data of a coal based power plant for the prediction of NO_x emission. They have compared the linear and non linear modelling approaches for the prediction of NO_x emission. Finally a linear model (ARX) with an optimally selected set of input variables and extracted features is recommended for the multistep NO_x prediction of the coal based boiler. Amitava Bandyopadhayay et al [12] have used ISCST3, model to predict the ground level concentration of SO_2 under various scenarios of Mangalore region covering a wide range of mountains. Seema Awasthi et al [13] developed General Plume Dispersion Model (GPDM) using Java and Visual basic tools based on Gaussian plume dispersion equation. It has the flexibility o9f using five atmospheric stability schemes i.e. Lapse Rate, Pasquill Gifford (PG), Turner, _Y_ and Richardson number. Also it can use 2 types of plume rise formulations i.e. Briggs and Holland's. GPDM is applicable for both rural and urban roughness conditions. They found that Turner scheme used with Holland's equation is giving best outcome degree of agreement. A. Khalaifi et al [14] have developed an easy to implement model based on Gaussian model of Pasquil to calculate the spatial distribution of SO_2 in coastal city Sfax (Tunisia). They have used this model to develop iso-concentration maps for different weather type in a day. Also they have superimposed the simulated SO_2 concentrations on land cover maps. Reem S. Ettouney et al [15] have focused on modelling of emission inventory, pollutant dispersion by the industrial source complex short term model (ISCST), and neural network analysis of air pollution in Kuwait. They have used two feed forward artificial neural networks (ANN) for improvement in the performance of time series predictions. They found that the forecasting technique represents a significant improvement over the conventional ANN approach. Sabah A. Abdul Wahab et al [16] have used ISCST model to predict the concentration of sulphur dioxide (SO_2) in and around Mina Al-Fahal refinery considering the terrain effect and they have examined the performance of ISCST model for the prediction of SO_2 concentration. They compared the ISCST model results with the WHO guideline values.

2. Mathematical Modelling

The concentration equation of pollutant is:-

$$C(x,y,z,H) = \frac{Q}{2\pi u\sigma_y\sigma_z} exp\left[-\frac{y^2}{2{\sigma_y}^2}\right]\left\{exp\left[-\frac{(z-H)^2}{2{\sigma_z}^2}\right] + exp\left[-\frac{(z+H)^2}{2{\sigma_z}^2}\right]\right\}$$

The governing differential equation for the Gaussian plume concentration equation is Advection-Diffusion equation.

$$\frac{\partial C}{\partial T} + u_x\frac{\partial C}{\partial x} + u_y\frac{\partial C}{\partial y} + u_z\frac{\partial C}{\partial z} = \frac{\partial}{\partial x}\left(D_t\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_t\frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(D_t\frac{\partial C}{\partial z}\right)$$

The equations solved in the simulation process are-

Continuity Equation

$$\frac{\partial \rho_m}{\partial T} + \frac{\partial(\overline{u_x} + u_x')}{\partial x} + \frac{\partial(\overline{u_y} + u_y')}{\partial y} + \frac{\partial(\overline{u_z} + u_z')}{\partial z} = 0$$

X-Momentum

$$\rho_m\left[\frac{\partial \overline{u_x}}{\partial t} + \overline{u_x}\frac{\partial \overline{u_x}}{\partial x} + \overline{u_y}\frac{\partial \overline{u_x}}{\partial y} + \overline{w}\frac{\partial \overline{u_x}}{\partial z}\right] = -\frac{\partial \overline{p}}{\partial x} + \mu\nabla^2\overline{u_x} - \rho\left[\frac{\partial}{\partial x}\overline{{u_x}'^2} + \frac{\partial}{\partial y}\overline{u_x'u_y'} + \frac{\partial}{\partial y}\overline{u_x'u_z'}\right] + S_t$$

Y-Momentum

$$\rho_m\left[\frac{\partial \overline{u_y}}{\partial T} + \overline{u_x}\frac{\partial \overline{u_y}}{\partial x} + \overline{u_y}\frac{\partial \overline{u_y}}{\partial y} + \overline{u_z}\frac{\partial \overline{u_y}}{\partial z}\right] = -\frac{\partial \overline{p}}{\partial y} + \mu\nabla^2\overline{u_y} - \rho\left[\frac{\partial}{\partial x}\overline{u_x'u_y'} + \frac{\partial}{\partial y}\overline{{u_y}'^2} + \frac{\partial}{\partial y}\overline{u_y'u_z'}\right] + S_t$$

Z-Momentum

$$\rho_m\left[\frac{\partial \overline{u_z}}{\partial T} + \overline{u_x}\frac{\partial \overline{u_z}}{\partial x} + \overline{u_y}\frac{\partial \overline{u_z}}{\partial y} + \overline{u_z}\frac{\partial \overline{u_z}}{\partial z}\right] = -\frac{\partial \overline{p}}{\partial y} + \mu\nabla^2\overline{u_z} - \rho\left[\frac{\partial}{\partial x}\overline{u_x'u_z'} + \frac{\partial}{\partial y}\overline{u_y'u_z'} + \frac{\partial}{\partial y}\overline{{u_z}'^2}\right] + S_t$$

Energy Equation

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$$\rho_m S\left[\frac{\partial\theta}{\partial T}+u_x\frac{\partial\theta}{\partial x}+u_y\frac{\partial\theta}{\partial y}+u_z\frac{\partial\theta}{\partial z}\right] = K\left(\frac{\partial^2\theta}{\partial x^2}+\frac{\partial^2\theta}{\partial y^2}+\frac{\partial^2\theta}{\partial z^2}\right) + \mu\left\{2\left[\left(\frac{\partial u_x}{\partial x}\right)^2+\left(\frac{\partial u_y}{\partial y}\right)^2+\left(\frac{\partial u_x}{\partial x}\right)^2 + \left(\frac{\partial u_z}{\partial z}\right)^2\right]+\left(\frac{\partial u_y}{\partial x}+\frac{\partial u_x}{\partial y}\right)^2 + \left(\frac{\partial u_z}{\partial y}+\frac{\partial u_y}{\partial z}\right)^2+\left(\frac{\partial u_x}{\partial z}+\frac{\partial u_z}{\partial x}\right)^2\right\}$$

Turbulent Kinetic energy

$$\frac{\partial}{\partial T}(\rho_m k_t)+\frac{\partial}{\partial x}(\rho_m k_t u_x) = \frac{\partial}{\partial x}\left[\left(\mu+\frac{\mu_T}{\sigma_k}\right)\frac{\partial k_t}{\partial x}\right]+G_k+G_b-\rho_m\varepsilon_t - Y_m$$

Turbulent Dissipation

$$\frac{\partial}{\partial T}(\rho_m \varepsilon_t)+\frac{\partial}{\partial x}(\rho_m \varepsilon_t u_x) = \frac{\partial}{\partial x}\left[\left(\mu+\frac{\mu_T}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon_t}{\partial x}\right]+C_{\varepsilon_1}\frac{\varepsilon_t}{k_t}(G_k+C_{\varepsilon_3}G_b) - C_{\varepsilon_2}\rho_m\frac{\varepsilon_t^2}{k_t}$$

Advection Diffusion Equation

$$\frac{\partial C}{\partial T}+u_x\frac{\partial C}{\partial x}+u_y\frac{\partial C}{\partial y}+u_z\frac{\partial C}{\partial z} = \frac{\partial}{\partial x}\left(D_t\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_t\frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(D_t\frac{\partial C}{\partial z}\right)$$

3. CFD ANALYSIS

The modelling of the chimney stack has been done using Skin-Loft option in the design modeller with proper dimensions, the dimensions of the chimney stack has been enclosed in the annexure. The chimney is placed 100m from the positive Z-axis and centrally along X-axis. The domain of analysis has been created using Extrude option with dimensions 1000m×500m×10100m (X×Y×Z). 10000m length along Z-direction has been given for dispersion of pollutants.

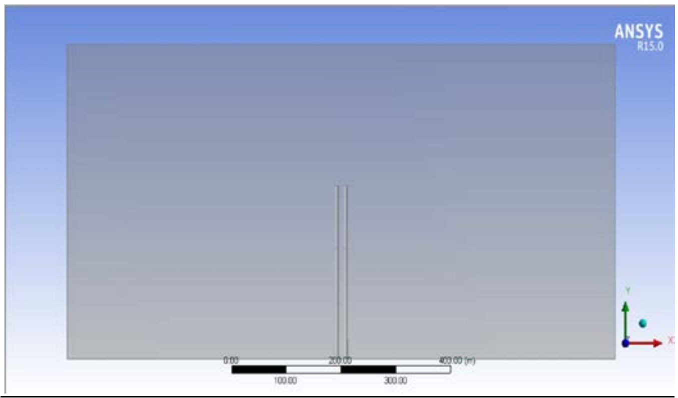

Figure 1: Model of the Chimney Stack

The meshing of the model has been performed using ANSYS Mesh 15.0 with 71357 nodes, 396434 elements and below mentioned controls-

- Physics preference – CFD
- Solver preference – CFX
- Relevance centre – Fine
- Skewness – 0.8478 (maximum)
- Aspect Ratio – 1.1607 (minimum), 9.5212 (maximum)

The pre-processing of the current problem includes creation of domain, creation of boundary, applying the boundary conditions and global initialisation in ANSYS CFX 15.0. Different boundaries created- Air Inlet, Gas Inlet and Atmosphere etc. The simulation has been carried out for three different wind speed and temperature (i.e. Maximum, Average and Minimum wind speed (6.93m/sec, 3.33m/sec, 0.4m/sec and 302.4K, 296.8K, 288.7K respectively).
The post processing process has been done using CFD POST and steady concentration line contours of the air pollutants have been plotted from the Gas Inlet.

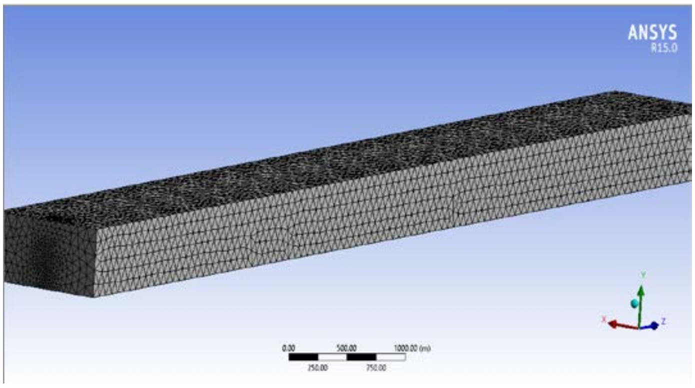

Figure 2: Meshing of the Chimney stack and domain of analysis

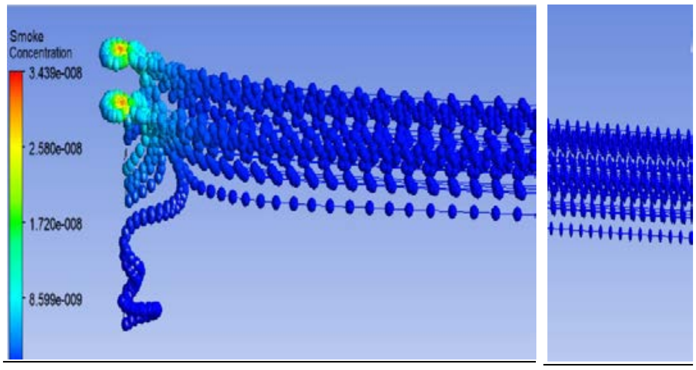

Figure 3: Steady concentration contour of N_2O with maximum speed

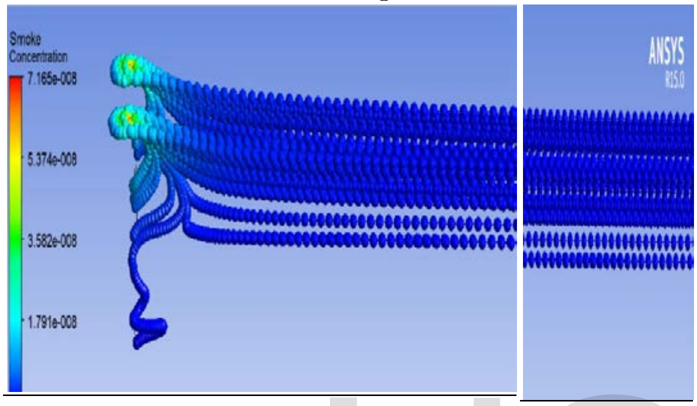

Figure 4: Steady concentration contour of N_2O with average speed

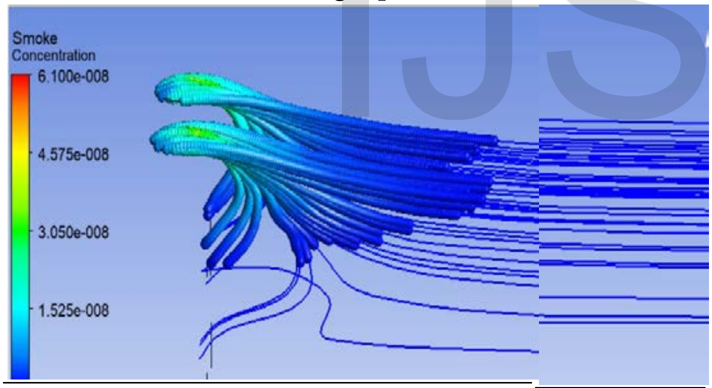

Figure 5: Steady concentration contour of N_2O with minimum speed

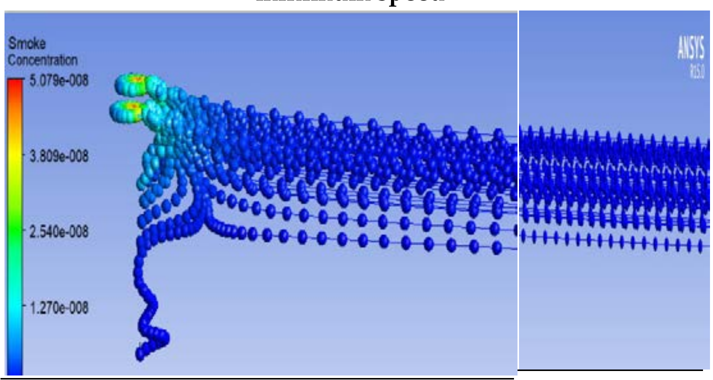

Figure 6: Steady concentration contour of NO with maximum speed

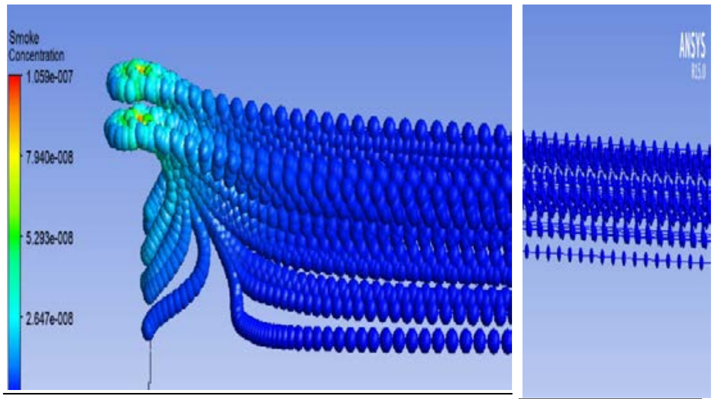

Figure 7: Steady concentration contour of NO with average speed

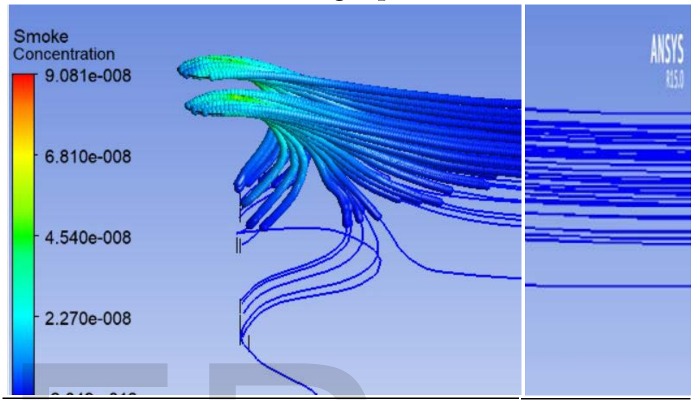

Figure 8: Steady concentration contour of NO with minimum speed

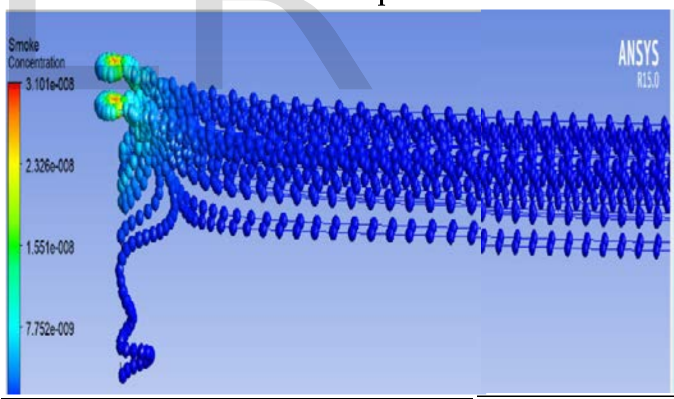

Figure 9: Steady concentration contour of SO_2 with maximum speed

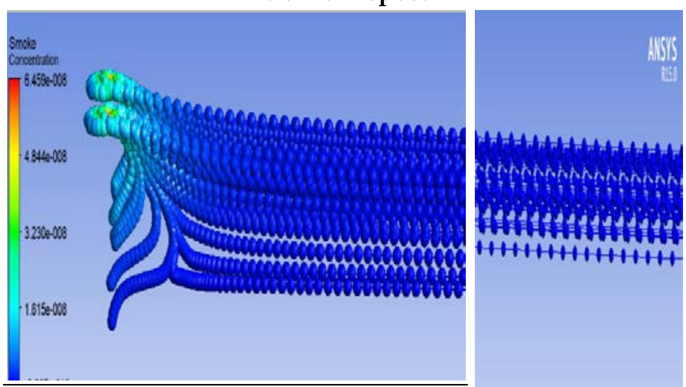

Figure 10: Steady concentration contour of SO_2 with average speed

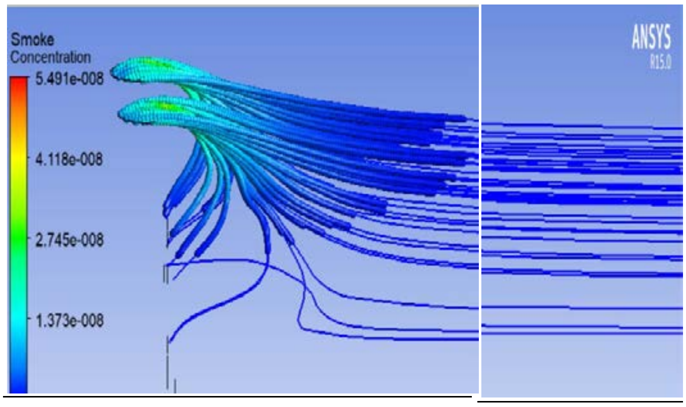

Figure 11: Steady concentration contour of SO_2 with minimum speed

The necessary input data to ANSYS CFX software has been given and executed to obtain the steady concentration contours of the baseline pollutants (N_2O, NO, SO_2) on the onsite and offsite of the thermal power plant. The concentration line contours have been depicted in pictorial form in figure 3, 4, 5, 6, 7, 8, 9, 10, 11. The concentration contours of different pollutants have been developed with maximum, average and minimum wind speed.

Figure 3, 4 and 5 depict the steady spatial distribution of N_2O with maximum, average and minimum wind speed respectively. This concentration contours for each case have been drawn over 10km spatial distance along wind direction. It is observed from the 3 figures the maximum concentration of N_2O occurs on and around the chimney over a small distance and then decreased drastically to minimum level along the wind direction. The maximum value of concentration of N_2O was found to be 34.39$\mu gm/m^3$ with maximum wind speed, 71.65 $\mu gm/m^3$ with average wind speed and 61$\mu gm/m^3$ with minimum wind speed.

Figure 6, 7 and 8 show the steady spatial distribution of NO with maximum, average and minimum wind speed respectively. It is observed from the 3 figures the maximum concentration of NO occurs on and around the chimney over a small distance and then decreased drastically to minimum level along the wind direction. The maximum value of concentration of NO was found to be 50.79$\mu gm/m^3$ with maximum wind speed, 105.9$\mu gm/m^3$ with average wind speed and 90.81$\mu gm/m^3$ with minimum wind speed.

Figure 9, 10 and 11 describe the steady spatial distribution of SO_2 with maximum, average and minimum wind speed respectively. It is observed from the 3 figures the maximum concentration of SO_2 occurs on and around the chimney over a small distance and then decreased drastically to minimum level along the wind direction. The maximum value of concentration of NO was found to be 31.01$\mu gm/m^3$ with maximum wind speed, 64.59$\mu gm/m^3$ with average wind speed and 54.91$\mu gm/m^3$ with minimum wind speed.

Table 1: Maximum and minimum concentration of 3 baseline pollutants predicted using ANSYS CFX with 3 different wind velocities

Concentration($\mu gm/m^3$)	N_2O		NO		SO_2	
	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum
Maximum wind speed	34.39	2.035×10^{-2}	50.79	3.005×10^{-2}	31.01	1.834×10^{-2}
Average wind speed	71.65	2.231×10^{-2}	105.9	3.195×10^{-2}	64.59	2.027×10^{-2}
Minimum wind speed	61	9.659×10^{-3}	90.81	2.049×10^{-2}	54.91	8.568×10^{-3}

4. Conclusion

The environment pollution is now the important concern and main focus area of the researchers.

- The maximum concentration of the baseline pollutants obtained from CFD simulation is occurring on and small distance around the chimney stack.
- The maximum concentration of the baseline pollutants occur on and a small distance around the chimney stack. But this maximum concentration of the baseline pollutants is more in case of the minimum wind speed. This is due to the less momentum diffusivity and hence less dispersion.
- Lastly it is found that the maximum concentration of all baseline pollutants is within National Ambient Air Quality Standards (NAAQS) acceptance level and hence the concerned industry is maintaining the ambient air quality in the workplace and offsite of the workplace and increases the quality of life of the people.

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Nomenclature

Symbol	Abbreviation
u_x	X-Component Velocity
u_y	Y-Component Velocity
u_z	Z-Component Velocity
v	Wind speed
$\overline{u_x}, \overline{u_y}, \overline{u_z}$	Time averaged Velocity components
u_x', u_y', u_z'	Fluctuating Velocity components
ϱ_m	Mass Density
k_t	Turbulent Kinetic Energy
D_t	Turbulent diffusion coefficient
S	Specific heat
Y_m	Compressibility related turbulent kinetic energy production
z_g	Vertical distance from the ground level
H_e	Effective height of the centreline of the pollutant plume
K	Thermal Conductivity
S_t	Source Term
μ	Dynamic Velocity
g	Acceleration due to Gravity
d_1	Distance from the puff centre to the receptor along the wind direction
d_2	Distance from the puff centre to the receptor in the crosswind direction
Q_p	Pollutant mass in the puff
Q	Temperature
ε_t	Turbulent Dissipation
C	Concentration of Species
G_k, G_b	Shear stress, buoyancy related turbulent energy production
$\sigma_k, C_{\varepsilon_1}, C_{\varepsilon_2}, C_{\varepsilon_3}, \sigma_\varepsilon$	Empirical constants
Q_e	Pollutant emission rate
T	Time
g_e	Vertical term of the Gaussian equation
h_m	Mixed layer height
σ_x	Standard deviation of the Gaussian distribution along the wind direction
σ_y	Standard deviation of the Gaussian distribution in the crosswind direction
σ_z	Standard deviation of the Gaussian distribution in the vertical direction
y_p	Horizontal distance from plume centreline
$\bar{p}$	Average pressure component
p	Pressure

$\sigma_k, C_{\varepsilon_1}, C_{\varepsilon_2},$	Empirical constants
Y_m	Compressibility related turbulent kinetic energy production