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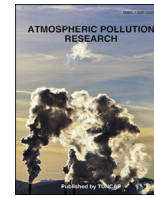

Direct effect of atmospheric turbulence on plume rise in a neutral atmosphere

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The direct effect of atmospheric turbulence on plume rise in the current research work is studied through examining the turbulence intensity parameter. A hybrid unsteady Reynolds averaged Navier Stokes (RANS) and large eddy simulation (LES) numerical approach is applied with a new mixed scale sub-grid parameterization technique in the commercial ANSYS Fluent software in order to simulate the buoyant plume behavior in a turbulent crossflow. The accuracy of the simulation method is crosschecked against the wind tunnel data available in the literature. The numerical simulation results in various operating conditions are used to derive a new plume rise formula in which the direct effect of atmospheric turbulence intensity at stack height (I_{Air}) is explicitly introduced in the plume rise formula. Furthermore, the buoyancy parameter of the flue gas is determined at some distances upstream of the stack top surface to include the whole effects of source buoyancy on the plume rise. The value of I_{Air} at stack height is obtained by measuring the standard deviation of wind velocity at stack height. The sensitivity analysis showed that by increasing the atmospheric turbulence intensity, the final plume rise decreases because of the updraft and downdraft motions of turbulence and it has been found that there is a linear dependency between the plume rise and $(I_{Air})^{-1.22}$. The quantile-quantile plots show that the new model can predict the simulated plume rise with a deviation factor of 1.0025 whereas the conventional models overestimate the final plume rise at least by a factor of 2.2.

1. Introduction

According to the models predicting dispersion of elevated emitted pollutants, the ground level concentration of pollutants changes inversely with the square of plume effective height. Hence, the first step for evaluating the accurate surface pollutants concentration, a major factor in human health risk assessment, is plume rise estimation. There is not a universal model to predict plume rise in all conditions using meteorological data and stack operating parameters. Over past half century, a large number of plume rise models are developed for some specific cases with appropriate assumptions and limitations. Some of these models are based on dimensional analysis (Briggs, 1969; Chu and Goldberg, 1974), and some others are empirical plume rise formulas which are obtained from field experiments and physical modeling (Davidson, 1949; Holland, 1953; Bosanquet, 1957; Moses and Carson, 1968). Beside these models, integral plume rise models are also developed to predict the centerline trajectory of plumes. In integral plume rise models, the buoyancy, drag force between the plume and its surroundings and entrainment of ambient fluid into the plume are the most important factors. Despite several shortcomings of integral models such as internal turbulence omission and linear impact of entrainment, verification and modification of basic integral models in different operating conditions is one of the major fields of interest during past decades (Tao et al., 2013; Marro et al., 2014). Pournazeri et al. (2012) modified the conservation equations to account for updrafts and downdrafts in the integral plume rise models and verified the results with field data. Decrop et al. (2015) studied momentum dominated and buoyancy dominated regimes' feature of a two phase plume experimentally and numerically. They also modified the coefficients of integral plume rise models using numerical simulation results. The effects of power law wind velocity profile instead of uniform wind velocity on near field behavior of highly buoyant plumes in a non-turbulent

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atmosphere is studied by Tohidi and Kaye (2016). According to their research, the wind profile has a significant effect on smoke plume behavior in case of low wind velocity. As previously mentioned, the problem of plume rise has been studied since 1960. The effect of mean flow parameters on plume rise can be studied well by using these models. But the direct effects of atmospheric and plume turbulence are not explicitly considered in the plume rise formulas. Introducing the effect of turbulent parameters on plume rise model in the neutral atmospheric stability condition is the main aim of this paper. It should be noted that not only the parameters in the model should be representative of turbulence, but also must be measureable or computable. Approaching this goal requires data in various atmospheric conditions. Field measurement is the best method to get the most realistic data, but it requires a lot of manpower and equipment. On the other hand, the cost of this large number of experiments via physical modeling is extremely high. The third opportunity is computer numerical simulation method which not only is less expensive than the former two methods, but also is very suitable for parametric study in various physical conditions. Therefore, the data gathering in this paper is investigated by simulation results of a high quality turbulent flow model. The reliability of the data gathered from computational fluid dynamic (CFD) results can be achieved by validating the numerical simulation results with some experimental data. According to Slawson and Csanady (1967), a plume behavior in atmosphere can be divided into three distinct phases. In the initial phase, self-generated turbulence of plume is dominated. In the intermediate phase, the inertial subrange part of atmospheric turbulence (convective or shear induced turbulence) has major role in plume dynamics. Finally, energy containing eddies of atmospheric turbulence are dominated in the last phase. This theory shows that turbulence in all scales has an important effect on the plume rise. Therefore, in order to have a reliable CFD data, the applied simulation method should be able to predict the role of these turbulent structures properly. So far, direct numerical simulation (DNS) (Muppidi and Mahesh, 2007, 2008), Reynolds averaged Navier-Stokes (RANS) (Reynolds, 1895) and large eddy simulation (LES) (Haren and Nieuwstadt, 1989; Nakayama et al., 2014; Decrop et al., 2015) are the well-known methods commonly used to simulate plume dynamics and atmospheric processes. The most distinguishing feature of these simulation schemes is their turbulence parameterization approach.

Although in DNS the Navier–Stokes equations are solved directly without any turbulence parameterization and the smallest dissipative scale (Kolmogorov scale) is resolved, the computational cost is high. On the other hand, RANS turbulence model decomposes the flow variables into mean component and the fluctuating component. It only solves the averaged Navier-Stokes equations while the role of fluctuating part is introduced using predefined turbulent models. As the consequence, the disadvantage of the RANS turbulent model is that it cannot predict the unsteadiness and intermittency of the turbulent flow accurately (Hu et al., 2011). In terms of computational cost, accuracy and turbulence simulation, the two mentioned methods are two extremes and LES occupies an intermediate position between them in which the large-scale eddies are directly simulated and the less important sub-grid scale (SGS) dissipative processes are parameterized using sub-grid models (SGM). Most often, LES can predict the unsteadiness and intermittency of the turbulence structure, which is the most important feature of a buoyancy-driven plume. It should be noted that using full LES method in a problem with some unimportant zones is not efficient. Also, in case of strong turbulence, the scale of flow structures near rigid bodies is too small and LES method needs very fine grids which increase its computational cost as large as DNS (Gimbun et al., 2012). To overcome this drawback, during the past decade the hybrid method of RANS-LES is developed specially in atmospheric boundary layer (ABL) modeling (Khurram et al., 2012; Kakosimos and Assael, 2013; Lateb et al., 2014; Woodruff, 2015) to reduce the computational cost of LES method and provide a good prediction of turbulent flows. From the turbulent modeling point of view, the hybrid method switches from RANS to LES in detached zones of walls and in the parts of the problem where the turbulence accuracy is important.

According to the aforementioned issues, in this paper, numerical simulations are conducted by a combined RANS and LES method with a new mixed scale sub-grid parameterization in ANSYS Fluent software. The model accuracy is satisfied by experimental data in the literature and compared by default turbulence simulation methods in Fluent.

It should be noted that the ground surface is considered as a rough flat surface. The plume rise and pollutants dispersion problems become more complicated in case of the complex train (Hanjalic and Kenjeres, 2005; Oliver et al., 2013; Albani et al., 2015). This article is structured as follows. A brief review of the governing equations, combined RANS-LES method and the new mixed sub-grid scale model have been presented in Section 2. Next, the result obtained from the turbulence simulation method is validated with the wind tunnel data. After that, the sensitivity analysis is performed by using the above-mentioned high-resolution turbulent flow simulator to find the independent parameters (mean flow and turbulence parameters) affecting on plume rise. Finally, the plume rise formula is derived based on the simulation results data.

2. Governing equations and solution strategy

The behavior of a turbulent flow may be predicted by solving the conservation equations of mass, momentum and energy (White, 2006). In this paper, the hybrid RANS-LES method is applied for solving conservation equations that switches to RANS model when the turbulence length scale is small and switches to LES sub-grid scale model in massive detached regions where turbulence scale is large. The filtered Navier Stokes equations for a single phase and single component incompressible Newtonian fluid with Boussinesq assumption (Paulucci, 1982) using Einstein convention are as below:

$$\frac{\partial(\overline{U}_i)}{\partial x_i} = 0 \tag{1}$$

$$\left[\frac{\partial \overline{U}_i}{\partial t} + \frac{\partial(\overline{U}_i\overline{U}_j)}{\partial x_j}\right] = -\frac{1}{\rho_0}\frac{\partial \overline{P}}{\partial x_j} + \beta_T(T_0 - T)g_i + \upsilon\left[\frac{\partial^2 \overline{U}_i}{\partial x_j^2}\right] - \frac{\partial \tilde{\tau}_{ij}}{\partial x_j} \tag{2}$$

$$\left[\frac{\partial \overline{T}}{\partial t} + \frac{\partial(\overline{U}_j\overline{T})}{\partial x_j}\right] = \alpha\left[\frac{\partial^2 \overline{T}}{\partial x_j^2}\right] - \frac{\partial(\tilde{\tau}_{Tj})}{\partial x_j} \tag{3}$$

where $\overline{U}_i$ is the resolved velocity vector. $\rho_0, P, \beta_T, T, T_0, \alpha, \upsilon$ and g_i are reference density, reduced pressure, thermal expansion coefficient, temperature, reference temperature, thermal diffusivity, kinematic viscosity and gravity modulus, respectively. The Coriolis term is not included here, because of the microscopic scale study. To close the conservation equations, the turbulent stress terms ($\tilde{\tau}_{ij}$ and $\tilde{\tau}_{Tj}$) which contain the unresolved scales' effects, should be parameterized somehow by resolved scales parameters. In the LES region of the hybrid RANS-LES method, the turbulent stress terms are representative of sub-grid scales and in the RANS region, it represents the role of all turbulent scales. According to the Boussinesq hypothesis (Boussinesq, 1877), the turbulent fluxes can be defined as follow:

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