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Plume Rise from a Stack Based on the Volkov Formula

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Abstract: Plume rise from most sources is an important factor in determining ground-level concentration of air pollutants. Various attempts have been done to compute plume rise from stationary sources. Volkov (1979) proposed a formula for calculation of plume dimensions (height and length) from a stack, while most of the well-known plume rise equations can only compute plume rise or plume height. Both plume height and plume length should be determined in some cases, for example in study of stack and cooling tower plume mergence, plume behavior (lofting, fanning, coning, looping, trapping and fumigation) etc. Because there are little studies in the world regarding the accuracy of the Volkov equation, the aim of the present work is to investigate the validity of the Volkov formula based on 5 statistical tests including the relative error, mean square error, root mean square error, coefficient of determination and Nash-Sutcliffe coefficient. The results revealed that (1) the Volkov equation better predicts plume rise at the distance of 60 m than 30 m from a typical stack, (2) considering the value of 0.5 instead of 0.4 or 0.65 for *n* in the Volkov formula will lead to more accurate results and (3) plume dispersion pattern was categorized as lofting. Overall, the Volkov equation can be an acceptable method to study of plume rise; nevertheless more studies must be conducted in the future with regard to the accuracy of the Volkov formula.

Keywords: plume rise; stack; Volkov equation

1 INTRODUCTION

Air pollution is defined as the presence of contaminants or pollutant substances in the air that interfere with human health or welfare, or produce other adverse environmental effects. For example, fossil fuels have an impact on human health and emit harmful emissions to the environment when burned. Air pollutants reach receptors through being transported and perhaps transformed in the atmosphere. The location of receptors with regard to sources and atmospheric effects influences pollutant concentrations, and the sensitivity of receptors to these concentrations determines the influences. The location, height, and duration of release, as well as the amount of pollutant released, are also of significance [1, 2].

In order to accurately compute air pollutant concentrations and plume trajectory in the atmosphere, it is necessary to consider the effects of interactions between plume and the surrounding environment [3].

Plume rise or plume height from most sources is an important factor in determining ground-level concentration of air pollutants since it increases effective stack height by a factor of 2-10 times the actual release height. Effective stack height is defined as the physical stack height plus plume rise. Because ground-level concentration is roughly proportional to the inverse square of the effective stack height, it is clear that plume rise can reduce ground-level concentration by a factor of as much as 100 [4, 5]. Ground-level concentration of air pollutants can be calculated via the following formula [6]:

$$C_x = \frac{Q}{\pi \sigma_y \sigma_z u} \mathrm{e}^{-\frac{1}{2}} \left[\frac{H}{\sigma_z}\right] \mathrm{e}^{-\frac{1}{2}} \left[\frac{y}{\sigma_y}\right]^2 \tag{1}$$

where C_x is the ground level concentration of air pollutants at some distance x downwind (gr/m^3), Q is the average emission rate of air pollutants (gr/sec), u is the mean wind speed at the stack top (m/sec), H is the effective stack height (m), σ_y is the standard deviation of wind direction in the horizontal (m), σ_z is the standard deviation of wind direction in the vertical (m), y is the off-centerline distance (m) and e is the natural log (2.71828). Plume rise depends on the number of factors such as: gas flow rate, temperature of the effluent at the top of the stack, the stack exit diameter, wind speed at the top of the stack, air temperature at the top of the stack, wind speed gradient with height and atmospheric stability [7]. Guevara et al. [8] reported that in order to maximize the precision of plume rise computations, the use of stack parameters based on real-world data is mandatory. Various attempts have been made to predict plume rise from stationary sources. Two types of equations have been resulted: theoretical and empirical. Theoretical models/equations are generally derived from the laws of momentum and buoyancy. They are often adjusted for empirical data. Empirical models are developed from large amounts of observed data including tracer studies, wind tunnel experiments and photographic evidence [9]. Most of the proposed plume rise equations are empirical in nature, as the theory has not been developed sufficiently. The plume rise theory can be expressed as follows [10]:

$$\Delta h = K \frac{Q^{\alpha}}{\bar{u}^{\beta}} \tag{2}$$

Where Δh is the plume rise (m), α, β and K (dimensional) are constant, Q is the heat emission rate from the stack, $\bar{u}$ is the mean wind speed at the stack height. In the CCRL (Canadian Combustion Research Laboratory) formula $\alpha = 1/4$, $\beta = 1$, $K = 66.4$ and Q and $\bar{u}$ are expressed in kcal/s and m/s respectively. A series of observations at the Tilbury power plant indicate that $\alpha = 1/4$, $\beta = 1$, $K = 450 - 500$ and Q and $\bar{u}$ are expressed in MW and m/s respectively. It is also observed that K is a function of the height of emission source.

Briggs recognised the need to express plume height as a function of plume length as a way to address the issue of unobservable maximum plume height [11]. Essa et al. [12] observed maximum value of ground level concentration in unstable stability when plume height was a function of plume length. Knudson's results [13] revealed that smoke plumes emitted from stacks frequently merge with vapor plumes released from cooling towers in a power plant in USA, where the height and length differences between stacks and cooling towers were about 100 m and 1000 m respectively. Shalkouhi et al. [14] reported that most of the studies with regard to vapor and smoke plume mergence are dated back to the 70s and 80s. Recently, Shalkouhi et al. [15] found that mergence of smoke and vapor plume occurs in a power plant in Hungary. It should be pointed out that mergence of vapour and smoke plume can lead to formation of sulfuric acid which can corrode metals and building materials [13, 16].

Volkov [17] proposed a formula for calculation of plume dimensions (height and length) from a stack, while most of the well-known plume rise equations (e.g. Holland, Rauch, Stone and Clarke etc.) can only compute plume rise or plume height. Because there are little studies in the world with regard to the validity of the Volkov formula, the aim of the present work is to investigate the accuracy of the Volkov equation.

2 METHOD

Volkov [17] proposed the following equation for calculation of plume rise from a stack:

$$z = Kx^{n} \tag{3}$$

where

$$K = \sqrt{0.42\frac{w_0 D_0}{u} + 0.3\frac{g w_0 D_0^2}{u^3 \varepsilon}\frac{\Delta T}{T_\mathrm{g}}} \tag{4}$$

$$\varepsilon = \frac{\sqrt{u'^2}}{u} \tag{5}$$

$$x = \frac{K^2 + 2h\varepsilon + K\sqrt{K^2 + 4h\varepsilon}}{2\varepsilon^2} \tag{6}$$

In Eqs. (3)-(6) z is the plume rise (m), w_0 is the exit gas velocity (m/s), D_0 is the inside stack top diameter (m), u is the mean wind speed at the stack top (m/s), g is the gravitational acceleration (9.8 m/s^2), ΔT is the difference between exit gas temperature and ambient temperature (K), T_g is the exit gas temperature (K), x is the plume length (m), u' is the wind speed fluctuation at the stack top (m/s), h is the stack height (m) and n for $x/D_0 \leq 120$ is 0.5 (averaged over 0.4-0.65) and for $x/D_0 > 120$ is 0.35. Meanwhile, the variable ε in Eq. (5) is called the atmospheric turbulence.

Fig. 1 shows schematic diagram of study methodology. Accordingly, for prediction of plume rise based on the Volkov formula mean data presented in Tab.1 were used. Moreover, as stated sooner, n for $x/D_0 \leq 120$ is 0.5 (averaged over 0.4-0.65), hence the Volkov plume rise was computed for $n = 0.4$, $n = 0.5$ and $n = 0.65$. Finally, for data analysis 5 statistical tests including the relative error [19], mean square error (*MSE*), root mean square error (*RMSE*) ($\sqrt{MSE}$) [20], coefficient of determination (R^2) [21] and Nash-Sutcliffe coefficient [22] were taken into consideration.

Table 1 Stack and meteorological parameters*

Wind speed (m/s)	Ambient temperature (K)	Stack exit gas velocity (m/s)	Stack exit gas temperature (K)	Plume rise at 30 m from stack (m)	Plume rise at 60 m from stack (m)
3.94	304.0	8.03	320.0	3.7	3.9
1.00	297.9	12.25	314.7	9.3	11.7
1.61	297.6	12.53	311.9	4.7	6.3
1.39	298.2	6.49	326.9	9.9	13.1
1.25	298.2	4.83	320.8	3.2	5.2
4.47	297.5	4.73	330.2	1.3	1.4
0.98	301.8	9.63	320.0	8.3	10.2
1.12	301.6	9.65	321.0	10.7	16.9
1.12	301.4	6.71	326.0	3.6	5.3
3.40	304.7	12.68	319.7	6.5	5.7
2.21	303.4	8.15	330.0	4.7	6.6
2.26	302.8	8.27	327.0	4.8	7.1
1.98	303.5	13.18	326.0	4.1	2.6
6.50	299.7	10.33	323.0	3.8	6.4
5.50	292.0	12.94	313.0	2.6	3.8
7.02	291.5	10.54	314.7	4.2	7.9
6.17	291.4	7.70	319.7	6.7	9.0
7.30	291.5	7.70	319.7	1.6	2.2
6.17	291.5	4.87	327.4	3.6	6.8
6.35	292.9	13.00	308.0	1.2	1.7
5.94	292.8	10.78	310.0	2.0	2.3
5.50	292.6	7.98	317.0	2.0	3.1
3.67	280.1	13.00	297.4	2.2	2.1
3.95	281.0	12.94	295.2	3.6	4.9
4.47	281.4	12.97	295.8	3.9	5.8
3.42	282.1	13.03	299.1	3.2	4.4
2.83	282.7	13.07	300.8	4.2	4.0
2.07	283.2	13.08	301.3	5.9	6.6
5.59	291.4	12.94	309.0	4.6	6.7
5.36	291.8	12.83	308.0	6.1	7.7
5.36	291.9	12.83	308.0	5.4	7.9
Min=0.98 Max=7.30 Mean= 3.87 Median= 3.94 Coefficient of Variation= 53.11% Confidence Interval= 3.87±0.72 Normal Distribution: shifted right Skewness= 0.013(right-skewed)	Min=280.1 Max=304.7 Mean= 294.0 Median= 292.8 Coefficient of Variation= 2.57% Confidence Interval= 294±2.66 Normal Distribution: shifted right Skewness= -0.41(left-skewed)	Min=4.73 Max=13.18 Mean= 10.31 Median= 10.78 Coefficient of Variation= 28.15% Confidence Interval=10.31±1.02 Normal Distribution: shifted right Skewness= -0.61(left-skewed)	Min=295.2 Max=330.2 Mean= 314.9 Median= 317 Coefficient of Variation= 3.34% Confidence Interval=314.9±3.71 Normal Distribution: shifted right Skewness= -0.42(left-skewed)	Min=1.2 Max=10.7 Mean= 4.6 Median= 4.1 Coefficient of Variation= 53.31% Confidence Interval= 4.6±0.86 Normal Distribution: shifted right Skewness= 0.99(right-skewed)	Min=1.4 Max=16.9 Mean= 6.1 Median= 5.8 Coefficient of Variation= 56.94% Confidence Interval= 6.1±1.22 Normal Distribution: shifted right Skewness= 1.19(right-skewed)

*Stack height and inside diameter are 111 feet and 17.5 inches respectively. Meanwhile, all the data except the calculated values (mean, median, coefficient of variation, confidence interval, normal distribution and skewness) are transcribed from the Moses and Strom's paper [18].

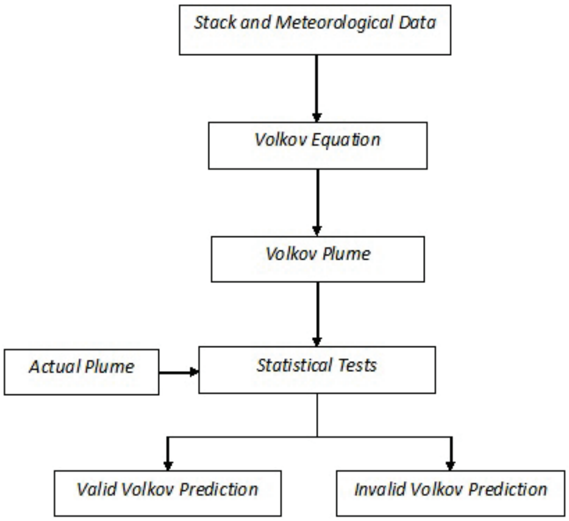

Figure 1 Flow chart of study methodology

3 RESULTS AND DISCUSSION

The results of predicted plume rise based on the Volkov formula are given in Tab. 2 and Fig. 2. As can be seen in Tab. 2, the relative error of the Volkov formula for 30 m ranges from 16.7 % to 40.7 % and for 60 m from 11.1 % to 64.3 %. Also, the mean square error of the Volkov formula for 30 m ranges from 0.59 to 3.5 and for 60 m from 0.46 to 15.37. Fig. 2 shows that the Nash-Sutcliffe coefficient between the Volkov and actual plume for $n = 0.4$, $n = 0.5$ and $n = 0.65$ are –7.66, 0.06 and –15.5 respectively. Moreover, the coefficient of determination between the Volkov and actual plume for $n = 0.4$, $n = 0.5$ and $n = 0.65$ are 0.2, 0.8 and 0.4 respectively.

Therefore, based on the findings of the present study it can be stated that the best prediction result is for $n = 0.5$; this suggests that Volkov correctly considered the mean of 0.4-0.65 for n in Eq. (3). Moreover, despite the Volkov prediction is not accurate, it can be statistically considered reasonable. In contrast, Carson and Moses [23] investigated the accuracy of 11 plume rise formulas including Holland, Stümke, CONCAWE, CONCAWE Simplified, Lucas-Moore-Spurr, Rauch, Stone and Clarke, Carson and Moses, Moses and Carson, Briggs Transitional and Csanady.

Table 2 Comparison between the Volkov and actual plumes

Distance from stack (m)	Actual plume [18] (m)	Volkov plume	Relative error	Mean square error	Root mean square error
30	4.6	2.73 m for $n = 0.4$	40.7 % for $n = 0.4$	3.5	1.87
		3.83 m for $n = 0.5$	16.7 % for $n = 0.5$	0.59	0.77
		6.39 m for $n = 0.65$	38.9 % for $n = 0.65$	3.2	1.79
60	6.1	3.60 m for $n = 0.4$	41.0 % for $n = 0.4$	6.25	2.5
		5.42 m for $n = 0.5$	11.1 % for $n = 0.5$	0.46	0.68
		10.02 m for $n = 0.65$	64.3 % for $n = 0.65$	15.37	3.92

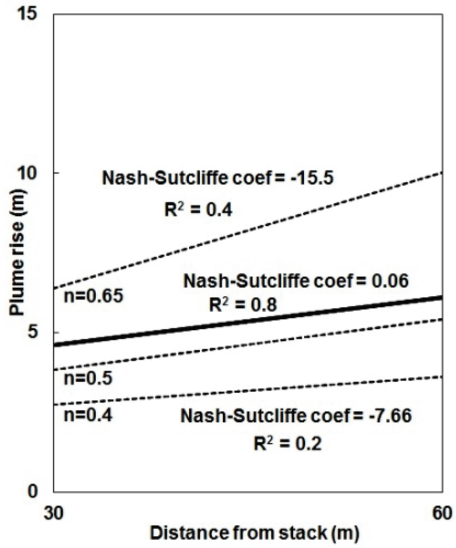

Figure 2 Comparison between the Volkov plumes (dashed lines) and actual plume (solid line)

Their results revealed that none of the equations predicts plume rise significantly better than the others. Moses and Strom [18] evaluated the accuracy of 6 plume rise equations such as Holland, Davidson/Bryant, Sutton, Scorer, Bosanquet et al. and Bosanquet. They found that about 75% of the measured plume rises fall within the range of the calculated values. Macey [24] performed a study to investigate the validity of the Bosanequet plume rise formula using the Tennessee Valley Authority data. He reported that the mentioned formula can be a reliable method to predict plume rise provided that a minor change is made in the model. Guldberg [25] evaluated the accuracy of 3 plume rise formulas including Briggs, Carpenter et al. and Montgomery et al. and concluded that at low wind speed the Briggs equation best predicts plume rise and at higher wind speed the Montgomery et al.'s formula performs best. Okamoto et al. [26] investigated the ability of 26 plume rise equations and found that most of the formulas overestimate plume rise at low wind speed. Saxena [27] predicted plume rise from a boiler stack based on the Briggs and Holland formulas. She found that the Briggs and Holland equations tend to overestimate and underestimate plume rise respectively. Findings of Li et al. [28] showed that the Briggs formula underestimates plume rise. Shalkouhi [29] proposed a formula for calculation of plume rise. His equation overestimates plume rise by a factor of approximately two. Alessandrini et al. [30] and Kozarev and Ilieva [31] proposed methods for prediction of plume rise. Their results showed satisfactory agreements with experimental data. Results of Leroy et al. [32] revealed that the Holland formulation for plume rise calculation, combined with the Briggs model, allows a better agreement between the predicted and observed ATC (Atmospheric Transfer Coefficient) than combined with the Doury model. It must be pointed out that study of plume rise is not only limited to stack and/or chimney. For example, Pandey et al. [33] proposed an acceptable formulation of aircraft emissions. Also, Bogdanyuk et al. [34] performed a satisfactory simulation of supersonic gas-particle flows expanding from a nozzle into rarefied atmosphere. In the area of aerospace engineering, various instruments are used, during the operation of which jet flows develop. These include, in particular, devices that produce control forces necessary for the orientation of spacecraft.

Dispersion of pollutants can be described qualitatively simply by looking at the plume and categorizing it as looping, coning, fanning, lofting, fumigating and trapping. However, it is often necessary to estimate plume dispersion features quantitatively, such as by using the Briggs (1973) formula [35]. As can be seen in Fig. 2, the Volkov and actual plume shapes are analogue to lofting plumes, and this corresponds to the findings obtained by Shobakh and Widodo [36] and Achtemeier et al. [37]. Lofting plume is the most favorable plume type because it does not result in any significant ground-level concentration of air pollutants [6, 38]. Fig. 3 shows a 3D form of lofting plume in Rijeka oil refinery in Croatia. It was planned to modernize the mentioned refinery during the period of 2013-2023 [39]. Most plumes emitted from modern plants are virtually invisible [40]. Stacks with invisible plumes may still be in full operation, hence airspace in the vicinity should be treated with caution [41]. The results of the present paper revealed that the Volkov and actual plumes are more near to each other in 60 m than in 30 m, and this implies that the variable "distance from stack" had a significant influence on the Volkov plume. Hence to investigate the accuracy of the Volkov equation in the future, it is recommended to consider multiple distances from stack.

Figure 3 Stack plume rise in Rijeka oil refinery in 2007

For discussion goals, stacks are divided into two categories: small (<100 feet) and tall (≥100 feet) [42]. Therefore, as can be seen in Tab.1, the stack considered in the present paper is categorized as tall. In contrast, Flori and Milostean [43] and Bhargava [44] considered tall stacks for study of smoke plumes. Taller stacks disperse pollutants better than shorter ones because the plume has to travel through a greater depth of atmosphere before it reaches ground level [45]. In the present study despite a large data set with regard to each of the variables "wind speed, ambient temperature, stack exit gas velocity and actual plume" was considered, it was unfortunately not possible to consider multiple stack heights and diameters.

This study used 5 statistical tests to investigate the validity of the Volkov equation; while few studies (e.g. Moses and Strom [18] and recently Wheida et al. [46]) used several statistical methods to examine the accuracy of plume rise formulas. Apart from statistical analysis, one can consider the EVA (Earn Value Analysis) method to performance evaluation of any plume rise equation. The mentioned method can be used in various areas of science. For example, Ugural and Burgan [47] recently used the EVA technique in civil engineering.

4 CONCLUSIONS

The validity of the Volkov equation was investigated based on 5 statistical tests including the relative error, mean square error, root mean square error, coefficient of determination and Nash-Sutcliffe coefficient. The results revealed that 1) the Volkov formula better predicts plume rise at the distance of 60 m than 30 m from the 111 feet stack, 2) considering the value of 0.5 instead of 0.4 or 0.65 for *n* in the Volkov formula will lead to more accurate results and 3) the Volkov and actual plume dispersion patterns were analogue to each other. Overall, the Volkov formula can be an acceptable method to study of plume rise; nevertheless more studies must be conducted in the future with regard to the accuracy of the Volkov equation.

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