Safety Precautions in Chimneys for Industrial and Nuclear Facilities Using a Statistical Model

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ABSTRACT

The height of mechanical mixing layer is one of the parameters of the safety analysis report of any nuclear facility due to its relation to the dispersion factor of pollutants. It can provide information about lower atmospheric dispersion, which is usually used to study the pollutants released from nuclear facility, risk analysis and emergency planning. The height of mixing layer is difficult to be measured; therefore, mathematical methods are introduced to calculate the height of this layer. Different Fortran Programs have been developed to calculate the Monin–Obukhov length, universal stability function and the friction velocity; these parameters are used to calculate the height of mechanical mixing layer. The analysis of the results showed that the variation of the height of the mechanical mixing layer for different seasons depends on the stability condition and wind speed, where the height of the mechanical mixing layer equals 2433 m at wind speed of 14.5m/s, 1952m at wind speed of 14m/s and 1700m at wind speed of 13m/s. The purpose of this work is concerned to calculate the height of mechanical mixing layer (H_{ABL})$_{mech.}$ by several models during stable/neutral conditions, because this value is one of the key parameter of the safety analysis report of any nuclear facility and important in the prediction of pollutants concentration released from any nuclear facility and the scaling of turbulence.

Key words: Meteorological Conditions /Mechanical Mixing Height /Atmospheric Dispersion Modeling

INTRODUCTION

The region of the atmosphere which governs the vertical and horizontal exchanges and the dispersion of pollutants is called the mixed layer or the atmospheric boundary layer (ABL)[(1)]. The height of the mixed layer determines the vertical extent of dispersion for pollutants releases from industrial and nuclear facilities, where all the primary pollutants coming from. The greater the vertical extent of the mixed layer, the larger the volume available to dilute pollutants emission. The greater efficiency of energy transfer from the sun to the earth's surface and returned back to the low layer of atmosphere by mixing[(2)]. Generally, in a typical day, the ABL height (H_{ABL}) growths range from approximately 300 m in the early morning hours to 4000 m in the early afternoon[(3-5)]. The height of mixing layer is not measured on a routine basis. Therefore, indirect methods are introduced to calculate this layer[(6)].

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The meteorological data are important for understanding the transport and dispersion of pollutants within an air shed and across its boundaries**,** where atmospheric turbulence, indicates the dispersive ability of the atmosphere[7]. In general, the parameters measured are: the wind speed and direction, atmospheric pressure, solar radiation, humidity, solar radiation (during the day) and cloud cover during the night. The so-called Pasquill-Turner stability classes[8] include six stability classes, can be segmented into the following categories (A-very unstable, B-unstable, C-slightly unstable, D-neutral, E-stable and F-very stable)[9], each one of them has a direct impact on the height of mixing layer. For neutral and stable conditions, the height of mixing layer was calculated by[10]. While in unstable condition during day for each hour there are two separate heights of mixing layer(H_{ABL}) values: a convective, $(H_{ABL})_{conv}$. and mechanical, $(H_{ABL})_{mech.}$[11]. Convective turbulence is caused by the rising of air heated at ground level and calculated by [12] and the mechanical turbulence is a function of wind speed and surface roughness[7]. The criterion for stability classifications are given in table (1)[13], where $\partial^{-}/\partial z$ is the temperature gradient and ^{o}K is the temperature in Kelvin.

Table (1). The criterion for stability classification

Stability Class	**Specification**
Stable	$\partial^{-}/\partial z \geq 0.85\, ^{o}K/100m$
Neutral	$-0.22 \leq \partial^{-}/\partial z \prec 0.85\, ^{o}K/100m$
Unstable	$\partial^{-}/\partial z \prec -0.22\, ^{o}K/100m$

The aim of this work is to establish a relatively simple procedure to calculate the (H_{ABL}) in neutral/stable conditions from theoretical model aspect. Because this value is one of the key parameters of the safety report of any nuclear facility as well as in the prediction of concentration profiles of pollutants in the atmosphere, that released from the nuclear facility and scaling of turbulence. The suggested model successfully calculate the pollutants profiles during the monthly seasons study depends on the degree of instability conditions and wind speed, and predicted the maximum height of mixing layer.

The ABL Height in Stable Conditions:

Figure (1) depicts the temporal profiles of the ABL height calculated from meteorological data and particle dispersion model by[14]. From figure (1) the unstable mixing layer is characterized by a deeper and the stable mixing layer is shallower and steeper vertical gradients in wind speed and potential temperature[15]. The curve has, until certain limits, a universal form for H_{ABL}=H(t) in stable atmospheric conditions, as can be observed in H(t) versus t line shape reported in literature [16-21]. In order to fit the H experimental data, we used a Boltzmann function:

$$H(t) = B + \frac{A}{1 + \exp\left(\frac{t - t_2}{t_1}\right)} \qquad (1)$$

where B represents the afternoon value of ABL height, A is the subtraction between the early morning and the late afternoon ABL height values, t is the curve width, and t_o is the curve center. Figure (1) shows a good fit (R^2 = 0.99022) of Boltzmann function with the curve of experimental[14] data, with B = 2761 m, A = **-**2533 m, t_1 = 0.70 h, and t_2= 13.13 h.

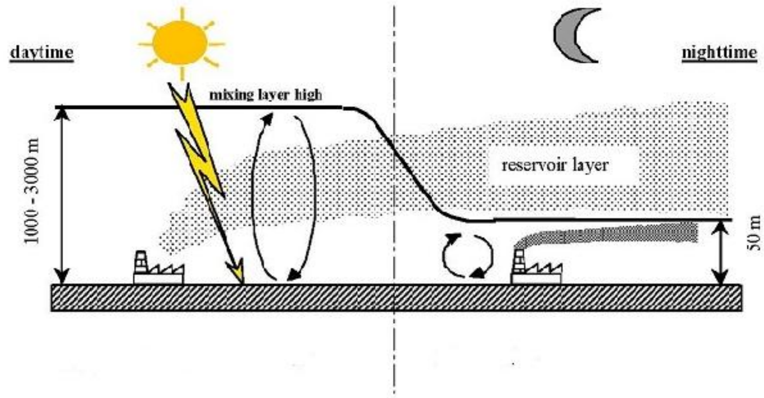

Fig.(1):H versus daytime plot calculated for experimental data[14]. The thick line represents the Boltzmann function fitting.

Influence of Meteorological Parameters on Mixing Height:

Meteorological parameters such as wind speed, wind direction, surface temperature, humidity, solar radiation and rainfall can affect the mixing height. Therefore, the influence of wind speed on mixing height was studied. Mixing height is defined as the height of the layer adjacent to the ground over which pollutants enter into this layer get mixed up by convection or mechanical turbulence, emitted air pollutants are diluted. It is a fundamental parameter that characterizes the structure of the lower atmosphere and determines the volume of air available for dispersion of pollutants. Higher the mixing height, the higher is the volume available for dispersion of pollutants and vice versa. The stable boundary layer is indeed quite shallow compared to convective boundary layer or unstable boundary layer.

Methodology and Theoretical Background:

The height of mechanical atmospheric boundary layer$(H_{ABL})_{mech.}$ was calculated by[22]. A computer program was developed using this model to estimate this layer. We have used data gathered from the National Ocean Atmospheric Administration[23] such as wind speed and stability class for the months of 2011 of the north western part of Egypt (Al-Dabaa) and the user selected the data concerning neutral/stable stability classes[24].

The day time mechanical height $(H_{ABL})_{mech.}$ was determined by applying the following equations[25] for neutral and stable class, respectively:

$$(H_{ABL})_{mech.} = \frac{0.133 \cdot V_f}{f} \qquad (2)$$

$$(H_{ABL})_{mech.} = \frac{0.125 \cdot V_f}{f} \qquad (3)$$

Where,

$(H_{ABL})_{mech.}$ is day time height of mechanical atmospheric boundary layer,

f is the Coriolis Parameter $f = 2\Omega \sin(¨)$,

Ω is Earth's rotation rate $\Omega = 7.29 \times 10^{-5}\ rad \cdot s^{-1}$,

¨ is latitude $¨ = 31^{\circ} : 04''$,

The friction velocity V_f is given by the following equation[6,22], we proposed the following formula:

$$V_f = \frac{k \cdot V_{ref}}{\ln\left(\frac{Z_{ref}}{Z_o}\right) - \Phi_m\left(\frac{Z_{ref}}{L}\right) + \Phi_m\left(\frac{Z_o}{L}\right)} \qquad (4)$$

Where,

V_f is the friction velocity,
k is Von Karman's constant =0.42(6, 22),
V_{ref} is the wind velocity at z_{ref} ,
Z_{ref} is the reference height at 30 m,
Z_o is roughness height = 0 .03m (26, 27) (for urban or rural area),
Φ_m is a function depends on Z_{ref} and L the Monin – Obukhov length, for neutral and stable

$$\Phi_m = \left(1 + 5 \cdot \frac{Z_{ref}}{L}\right),$$

L is the Monin – Obukhov length calculated using the following equation(28).

$$\frac{1}{L} = a\, z_o{}^b \qquad (5)$$

Monin–Obukhov length Scale L is given, the constants a and b depends on the stability classes. The values of the constants a and b for different stability classes are given in Table 2.

Table (2): The values of a and b for different stability classes

Stability Classes				Parameter value
D	C	B	A	
0.0	-0.00807	-0.03849	-0.0875	a
0.0	-0.3049	-0.1714	-0.1029	b

Table (3) presents a summary of the data sources, subdivided according to atmospheric stability classification into neutral and stable classes. The criterion for stability classification is done according to the temperature gradient as elucidated in table (3). The measurements were obtained from the National Ocean Atmospheric Administration(23) are the sources of data upon which this investigation had carried out. In this analysis, a regression among all prevails from expected uses and applications including different type chimneys. Due to appreciable non-uniformity among the data from the chimneys in published literatures because of different procedures used in averaging times of plume rise measurements, plume definitions, techniques of measurement were varied; wind measuring levels and procedures were not always comparable. To achieve this study, all winds were corrected to represent the wind speed at the top of the chimney.

Table (3):Summary of Data Used Height of $(H_{ABL})_{mech.}$ at Different Wind Speeds and Stability Classes during Days of Year 2012, shows the stability classes classifications.

Year Days	Wind Speed (m/s)	$(H_{ABL})_{mech}$ (m)	Individual Class		Total Individual Records
			Neutral Class	Stable Class	
01/01/12 : 31/12/12	0-2	200-350	23	1	24
	3-4	350-500	81	34	115
	5-6	500-650	36	28	64
	7-8	650-800	32	4	36
	9-10	800-950	18	2	20
	11-12	950-1100	12	-	12
	13-14	1100-1250	9	1	10
	15-16	1250-1400	5	1	6
	17-18	1400-1550	2	1	3
	19-20	1550-1700	3	-	3
	21-22	1700-1850	4	-	4
Total			225	72	297

These data provide a general picture of the scope of the total sets of data involved in various applications. No attempts were made to apply weights to the data in spite of the differences in averaging periods. Among the data there are numerous instances where consecutive readings were taken and each is considered as an independent measurement. Where consecutive readings are correlated, the assumption of independence is of course invalid. In spite of these shortcomings, the data do bring out plume rise and meteorological chimney design parameters.

RESULTS AND DISCUSSION

The height of mechanical atmospheric boundary layer$(H_{ABL})_{mec.}$ during the period from the beginning until the end of the year 2012, was calculated using the afore mentioned models. The stability condition varies from neutral class, which dominates in major months, shows that the model suggested by[25] according to equation (2) and a stable class gives the best results when the wind speed at the chimney (4 m/s ≤ ws<6 m/s). Whereas,$(H_{ABL})_{mech.}$ was observed reaching depths of up to 500 m on average at ws = 4-6m/s, up to 1000 m on average at ws =8-12 m/s, and up to 1500 m on average at ws =12-17 m/s and by minor percentage up to 2000 m on average at ws =17-23 m/s as shown in figure (2).

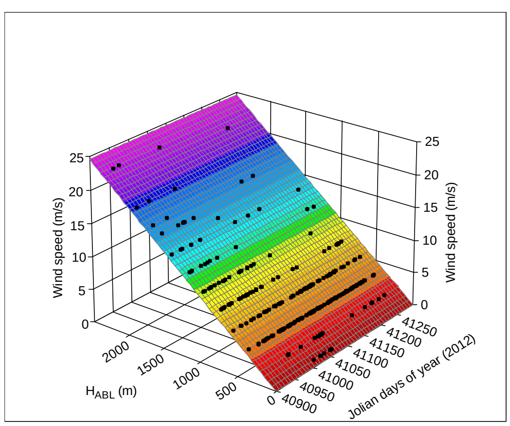

Fig.(2):The height of mechanical atmospheric boundary layer$(H_{ABL})_{mech.}$ during year 2012 at different wind speeds

The height at neutral class shows that the model by[25] related to equation (2) gives the best repeated results occur when the wind speed is greater than or equal to 4m/s, where mixed layer was observed reaching depths of up to 2338 m on May 22th at ws =23 m/s due to monsoon winds, while the model by[25] according to equation (2) gives the highest result when the wind speed is less than 6m/s**,** where mixed layer was observed reaching depths of up to 1931 m on April18th at ws = 19 m/s. For neutral and stable classes the model by[25] related to equation (2) gives the best results when the wind speed is greater than or equal to 6 m/s and when the wind speed is less than 6 m/s and the mixing depths observed reaching depths of up to 407 m on May 16th at ws =4 m/s, up to 610 m on June14th at ws = 6 m/s and from 1423 m on June 20th at ws =14 m/s, up to 1624 m on October10th at ws =17 m/s, respectively.

In May 2012 the mechanical mixing height calculated for neutral class (C) which dominate in this month shows that the model by[25]according to equation (2) gives the best results when the wind speed is greater than or equal to 6 m/s and when the wind speed is less than 6 m/s**,** where mixed layer was observed reaching depths of up to 407 m on May 26th at ws = 4 m/s and up to 1525 m on May 23th at ws = 15 m/s. This results correlate with that obtained by[1, 29-31].A general equation which takes into account both buoyancy and momentum components is:

$$H_{eff} = p_1 + p_2 \cdot d + p_3 \cdot \ln\left(\frac{Q_h}{V_C}\right) + p_4 \cdot \ln\left(\frac{Q_h}{W_S}\right) + p_5 \cdot \ln(W_S) \quad (6)$$

where, H_{eff} is the calculated plume rise (meters),

$p_1, p_2, \ldots, p_6$ are regression coefficients,

V_C is chimney effluent velocity (m/sec.),

W_S is the wind velocity (m/sec.),

Q_h is the heat emission rate (cal./sec.),

d is the chimney diameter (m).

The purpose of these studies is to investigate the basic relations between plume rise and such factors as the momentum of the chimney effluent, buoyancy and weather parameters. Insight into the basic processes is necessary to develop a sound technique for calculating plume rise from chimney and meteorological data. A very preliminary form of this equation was first suggested by[13].

$$\Delta H = 1.5 \cdot d \cdot \left(\frac{V_C}{Q_h}\right) + 0.44 \cdot \left(\frac{Q_h}{W_S}\right) \quad (7)$$

In this work, another formula is suggested as:

$$\Delta H = p_1 + p_2 \cdot d + p_3 \cdot \log\left(\frac{V_C}{Q_h}\right) + p_4 \cdot \log\left(\frac{Q_h}{W_S}\right) + p_5 \cdot \log(W_S) \quad (8)$$

In the selection of a criterion for a prediction equation, the accuracy to which it can predict is of course most important. Other considerations are simplicity or ease of computation, applicability to a wide range of conditions, and the availability of the necessary chimney and meteorological measurements. From the obtained results, it was found that when chimneys are compared, they vary over a wide range of heat emission rate, diameters, effluent velocity and chimney height. A useful guide to the plume may be obtained from an equation of the form of eq. (8). The data mentioned in table (4) are taken from[13, 32,33].

Table (4):The range of proposed meteorological and chimney parameters prevails during data acquisition period.

Wind Speed (m/s)	$(H_{ABL})_{mech}$ (m)	Effluent Velocity (m/s)	Heat Emission Rate (kcal./sec.)	Observed Plume Rise range (m)	Chimney Diameter (m)	Chimney Height (m)	Observed Chimney Height (m)
3-4	350-500	4-5	2.0-12.0	1.4-16.9	0.44	34.08	34
4-5	500-650	6-7	3.0-30.0	1.6-23.0	0.77	51.22	47
5-6	650-800	8-9	70-200	2.0-34.3	1.76	58.67	61
6-7	800-950	5-6	400-600	14.0-61	2.42	71.66	75
7-8	950-1100	7-8	800-1000	21.0-78	2.75	77.66	80
8-9	1100-1250	9-10	$2000\text{-}4\text{x}10^3$	9.0-112	3.08	82.43	85
9-10	1250-1400	11-12	$6\text{x}10^3\text{-}8\text{x}10^3$	18.0-116	4.73	123.25	125
10-11	1400-1550	13-14	$1\text{-}2 \text{ x } 10^4$	73.0-356	6.38	156.45	153
11-12	1550-1700	15-20	$3\text{-}4 \text{ x } 10^4$	81.0-476	7,04	169.08	169
12-13	1700-1850	21-25	$5\text{-}6 \text{ x } 10^4$	64.0-457	8.03	187.83	183

The data were then further subdivided into the two stability classifications given in table (2) and the regression parameters for calculating equations were obtained and the results were summarized in table (5). This table also provides the estimate standard deviation which applied for all data in equations (6, 8). As the same equation used to represents the neutral and stable classes the standard estimate of errors are 1.31 and 2.51, respectively, our single equation based on all data would be necessary.

Table (5): Chimney height and plume rise regression parameters, as related to stability classifications.

Data from Neutral and Stable Classes	p_1	p_2	p_3	p_4	p_5	Sample N size	Standard deviation	Correlation Coefficients R	R^2
Chimney height	1.67E+01	1.92E+01	-6.26E+00	6.38E+00	4.82E+00	297	1.31	0.9997	0.9994
Plume rise	-1.49E+02	2.87E+02	2.60E+00	-1.00E-01	1.00E-01	297	2.51	0.9999	0.9999

CONCLUSIONS

From the stand point of goodness of fit and ease of computation, one is inclined to suggest eq. (8), as the preferred plume rise equation. It should be emphasized that these equations were not tested for day to day operation with a single chimney. They are to be used for general design consideration. As more data are accumulated it is quite possible that the regression coefficients like p2 and p4 could change. Further, the recommended value of p3 and p5 may also be adjusted as a results of further study and measurements. Since the equation recommended is an empirical equation, it is important to caution that it only be used over the range upon which it is based. It is also essential to realize that these results apply to relatively smooth terrain without the undue influence of buildings.

The mixing height along the days of the year varies between 50 m to 2338 m with a neutral to stable classes, covering the period of summer, fall, winter and spring. In all indicating that, the emission of pollutants during four seasons from any industries either in operation or likely to be established in this area will have a less impact on surrounding habitations. The mixing height was the highest in 22 January with wind speed 23 m/s in winter indicating that, the highest volume of air will be available for the dispersion of pollutants during this season. Neutral class was the predominant class in the different seasons. This class could be used to find out the dispersion coefficients required for the computation of emission rate of pollutants, emission velocity, chimney parameters and plume rise. This could be used to minimize the impact of air pollutant over the surrounding area. The equations do represent a least squares fit that should serve as a useful tool in building chimney design. The services of a competent professional meteorologist should be obtained for the final chimney design. Simple corrections of chimney parameters with the mixing height evaluation showed a different degrees corrections, step wise regression analysis of data revealed the wind speed, mixing height significantly influence the chimney parameters. The performance of the developed statistical model indicated that it could be used to predict the proper chimney parameters for different used to predict the proper chimney parameters for different industrial and nuclear facilities.

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