Meteorological Factors Affecting Chimney Design Parameters

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Abstract. The height of mechanical mixing layer is one of the parameter of the safety analysis report of any industrial (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. Mixing layer height is difficult to measure; therefore, mathematical methods are introduced to calculate this layer. The analysis of the results showed that the height variation of the mechanical mixing layer for different seasons depends on the degree of unstable condition and wind speed, where the height of the mechanical mixing layer equals 2433 m at wind speed of 14.5 m/s and 1952 m at wind speed of 14 m/s and 1700 m at wind speed of 13 m/s. The purpose of this work is to calculate the mechanical mixing layer height ($H_{mech}$) using different mechanical models during stable/unstable conditions. 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. The suggested model successfully calculate the pollutants profiles during the monthly seasons study depends on the degree of instability conditions, wind speed and predicted the maximum height of mixing layer.

Key words: Impact Assessment; Meteorological Conditions; Mechanical mixing height; Monin–Obukhov length; Atmospheric Dispersion modeling; Pollutants releases.
1. 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 are coming from. The greater the vertical extent of ABL height, the larger the volume is 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 ($H_{ABL}$) grows range from approximately 300 m in the early morning hours to 4000 m in the early afternoon [3, 4]. Indirect methods are introduced to calculate ABL heights [5].

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[6]. In general, the parameters measured are: the wind speed and direction, atmospheric pressure, humidity, solar radiation (during the day) and cloud cover during the night. The so-called Pasquill-Turner stability classes [7] 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 [8]. Each one of these category has a direct impact on the height of mixing layer ($H_{ABL}$). For neutral and stable conditions, the ($H_{ABL}$) was calculated by [9]. While in unstable condition during day for each hour there are two separate ($H_{ABL}$) values: a convective, ($H_{ABL}$)conv, and mechanical, ($H_{ABL}$)mech [10]. Convective turbulence is caused by the rising of air heated at ground level and calculated by [11]. The mechanical turbulence is a function of wind speed and surface roughness [6]. In this work, the stability classes are classified due to the criterion in table (1) [12].

Table (1). The criterion for stability classification

<table>
<thead>
<tr>
<th>Stability Class</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stable</td>
<td>$\frac{\partial T}{\partial z} \geq 0.85 \text{ K/100 m}$</td>
</tr>
<tr>
<td>Neutral</td>
<td>$-0.22 \leq \frac{\partial T}{\partial z} \leq 0.85 \text{ K/100 m}$</td>
</tr>
<tr>
<td>Unstable</td>
<td>$\frac{\partial T}{\partial z} \leq -0.22 \text{ K/100 m}$</td>
</tr>
</tbody>
</table>

Because $H_{ABL}$ value is one of the key parameter of the safety report as well as in the prediction of concentration profiles of pollutants in the atmosphere, that released from the facility and scaling of turbulence. The aim of this work is to establish a relatively simple procedure to calculate ($H_{ABL}$) in unstable conditions from theoretical model aspect.
2. The HABL in stable conditions

Figure (1) depicts the temporal profiles of $H_{ABL}$ calculated from meteorological data and particle dispersion model by [13]. From figure (1) the unstable mixing layer is characterized by a deep and the stable mixing layer is shallower and steeper vertical gradients in wind speed and potential temperature [14]. The curve has, until certain limits, a universal form for $H_{ABL}(t) = H(t)$ in stable atmospheric conditions. As it can be observed in $H(t)$ versus $t$ line shape reported in literature [15-18]. In order to fit the $H$ experimental data, we used a Boltzmann function:

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

(1)

Where, $B$ represents the afternoon value of ABL height, $A$ is the subtraction between the early morning and the late afternoon $H_{ABL}$ values, $t_1$ is the curve width, and $t_o$ is the curve center. Fig. (1) shows a good fit ($R^2 = 0.99022$) of Boltzmann function with the curve of experimental [13] data, with $B = 2761 \text{ m}$, $A = -2533 \text{ m}$, $t_1 = 0.70 \text{ h}$, and $t_o = 13.13 \text{ h}$, where $t$ is daytime in hour ($\text{h}$).

3. 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 i.e., 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. The 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.
4. Methodology and Theoretical Background

The height of mechanical atmospheric boundary layer \( H_{\text{mech}} \) was calculated by [19, 20]. A computer program was developed using this model to estimate this layer. We have used data gathered from the National Ocean Atmospheric Administration [21] such as wind speed and stability class throughout year 2012 for the northwestern part of Egypt and the user selected the data concerning unstable stability class, which is classified into A–Extremely unstable, B–Moderately unstable and C–Slightly unstable [22].

The day-time \( (H_{\text{mech}})_{\text{mech.}} \) was determined by applying the following equations [19, 23, 24] for neutral and stable class, respectively:

\[
(H_{\text{mech}})_{\text{mech.}} = \frac{0.133 \cdot V_f}{f} \tag{2}
\]

\[
(H_{\text{mech}})_{\text{mech.}} = \frac{0.125 \cdot V_f}{f} \tag{3}
\]

Where, \( (H_{\text{mech}})_{\text{mech.}} \) is day time height of mechanical atmospheric boundary layer, \( f \) is the Coriolis Parameter \( f = 2\Omega \sin(\varphi) \),

\( \Omega \) is Earth’s rotation rate \( \Omega = 7.29 \times 10^{-5} \, \text{rad/s} \),

\( \varphi \) is latitude \( \varphi = 31°:04' \).

The friction velocity \( V_f \) is given by the following equation [5, 25], we proposed the following formula:

\[
V_f = \frac{k \cdot V_{\text{ref}}}{\ln \left( \frac{Z_{\text{ref}}}{Z_o} \right) - \Phi_m \left( \frac{Z_{\text{ref}}}{L} \right) + \Phi_m \left( \frac{Z_o}{L} \right)} \tag{4}
\]

Where,

\( V_f \) is the friction velocity,

\( k \) is Von Karman's constant = 0.42,

\( V_{\text{ref}} \) is the wind velocity at \( z_{\text{ref}} \),

\( Z_{\text{ref}} \) is the reference height at 30 m,

\( Z_o \) is roughness height = 0.03m [26],

\( \Phi_m \) is a function depends on \( Z_{\text{ref}} \) and \( L \) the Monin – Obukhov length, for neutral and stable \( \Phi_m = \left( 1 + 5 \cdot \frac{Z_{\text{ref}}}{L} \right) \),

\( L \) is the Monin – Obukhov length calculated using the following equation [27].
\[ \frac{1}{L} = a \ z_o^b \]  

(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 unstable and neutral conditions are given in Table (2).

**Table (2). The values of \( a \) and \( b \) for different stability classes**

<table>
<thead>
<tr>
<th>Parameter value</th>
<th>Stability Classes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( A )</td>
</tr>
<tr>
<td>( a )</td>
<td>-0.0875</td>
</tr>
<tr>
<td>( b )</td>
<td>-0.1029</td>
</tr>
</tbody>
</table>

Table (3) presents a summary of the data sources, subdivided according to atmospheric stability classification. The criterion for stability classification is done according to the temperature gradient as elucidated in table (3). Two sets of measurements were based on those obtained from the National Ocean Atmospheric Administration [21] are the sources of data upon which this investigation was based. 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, wing 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**

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

5. Results and Discussion

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

![Figure (2). The height of mechanical atmospheric boundary layer \((H_{ABL})_{mech}\) during the period from the begin of year 2012 until the end of year 2012](image)

The height at neutral class shows that the model by [23] related to equation (2) gives the best repeated results. These results occur when the wind speed is greater than or equal to 4 m/s, where mixed layer was observed reaching depths of up to 2338 m on May 22nd \(ws = 23 \text{ m/s}\) due to monsoon winds, while the model by [24]. According to equation (2) gives the highest result when the wind speed is less than 6 m/s, where mixed layer was observed reaching depths of up to 1931 m on April 18th \(ws = 19 \text{ m/s}\). In the case of neutral and stable classes the model
suggested by [23] 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 June 14th at ws = 6 m/s and from 1423 m on June 20th at ws = 14 m/s, up to 1624 m on October 10th 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 [23] 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 23rd at ws = 15 m/s. This results correlate with that obtained by [1, 28, 29]. A general equation which takes into accounts both buoyancy and momentum components is:

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

where, $H_{PR}$ is the calculated plume rise (meters),
$p_1, p_2, \ldots, p_5$ 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 [12].

$$H_{PR} = 1.5 \cdot d \frac{V_C}{Q_h} + 0.44 \frac{Q_h}{W_S}$$

In this work, another formula is suggested as:

$$H_{PR} = p_1 + p_2 \cdot d + p_3 \cdot \log \left( \frac{V_C}{Q_h} \right) + p_4 \cdot \log \left( \frac{Q_h}{W_S} \right) + p_5 \cdot \log (W_S)$$

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, found that 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 [12, 20, 30].
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Table (4). The range of proposed meteorological and chimney parameters prevails during data acquisition period

<table>
<thead>
<tr>
<th>Wind Speed (m/s)</th>
<th>Wind Velocity (m/s)</th>
<th>Heat Emission Rate (kcal/sec)</th>
<th>Observed Plume Rise range (m)</th>
<th>Chimney Diameter (m)</th>
<th>Observed Chimney Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-4</td>
<td>350-500</td>
<td>4.5</td>
<td>2.0-12.0</td>
<td>0.44</td>
<td>34</td>
</tr>
<tr>
<td>4-5</td>
<td>500-650</td>
<td>6.7</td>
<td>3.0-30.0</td>
<td>0.77</td>
<td>51.22</td>
</tr>
<tr>
<td>5-6</td>
<td>650-800</td>
<td>8.9</td>
<td>70-200</td>
<td>1.76</td>
<td>58.67</td>
</tr>
<tr>
<td>6-7</td>
<td>800-950</td>
<td>5.6</td>
<td>400-600</td>
<td>2.42</td>
<td>71.66</td>
</tr>
<tr>
<td>7-8</td>
<td>950-1100</td>
<td>7.8</td>
<td>800-1000</td>
<td>2.75</td>
<td>77.66</td>
</tr>
<tr>
<td>8-9</td>
<td>1100-1250</td>
<td>9.10</td>
<td>2000-4x10^3</td>
<td>3.08</td>
<td>82.43</td>
</tr>
<tr>
<td>9-10</td>
<td>1250-1400</td>
<td>11.12</td>
<td>6x10^2-8x10^3</td>
<td>4.73</td>
<td>123.25</td>
</tr>
<tr>
<td>10-11</td>
<td>1400-1550</td>
<td>13.14</td>
<td>1-2 x 10^4</td>
<td>6.38</td>
<td>156.45</td>
</tr>
<tr>
<td>11-12</td>
<td>1550-1700</td>
<td>15.20</td>
<td>3-4 x 10^4</td>
<td>7.04</td>
<td>169.08</td>
</tr>
<tr>
<td>12-13</td>
<td>1700-1850</td>
<td>21.25</td>
<td>5-6 x 10^4</td>
<td>8.03</td>
<td>187.83</td>
</tr>
</tbody>
</table>

The data were 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. With our single equation based on all data, thus only one equation would be necessary.

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

<table>
<thead>
<tr>
<th>Data from Neutral and Stable Classes</th>
<th>$P_1$</th>
<th>$P_2$</th>
<th>$P_3$</th>
<th>$P_4$</th>
<th>$P_5$</th>
<th>Sample size $N$</th>
<th>Standard deviation</th>
<th>Correlation Coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chimney height</td>
<td>1.67E+01</td>
<td>1.92E+01</td>
<td>-6.26E+00</td>
<td>6.38E+00</td>
<td>4.82E+00</td>
<td>297</td>
<td>1.31</td>
<td>0.9997</td>
</tr>
<tr>
<td>plume rise</td>
<td>-1.49E+02</td>
<td>2.87E+02</td>
<td>2.60E+00</td>
<td>-1.00E+01</td>
<td>1.00E+01</td>
<td>297</td>
<td>2.51</td>
<td>0.9999</td>
</tr>
</tbody>
</table>

6. Conclusions

From the standpoint 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 nor 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 $p_2$ and $p_5$ could change. Further, the recommended value of $p_2$ and $p_5$ may also be adjusted as 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 varying between 50 m to 2338 m with a neutral to stable classes, covering the period of summer, autumn, 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 January 22nd with wind speed 23 m/s in winter season. 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, stepwise 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.

References


احيائيات الأمان في المدافع الصناعية والمنشآت النووية باستخدام النموذج الإحصائي

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(قدم في 5/10/2013م - وقـب في ١٣/١٢/٢٠١٤م)

ملخص البحث
ارتفاع طبقة الخلط الميكانيكي هو أحدى عوامل تطبيق مراقبة الأمان لأي منشأة نووية وذلك
لعلاقته بعمول التشذيب للملوثات. ويمكن أن يؤدي الى معلومات حول التشذيب في طبقات الغلاف الجوي الدنيا،
والتي تستخدم لدراسة الملوثات المطلقة من المنشآت النووية وتحليل المخاطر وخطط الطوارئ. من الصعوبة
قياس ارتفاع طبقة الخلط وذلك ادخرت طرق رياضية حساب ارتفاع تلك الطبقة. وللمطور العديد من البرامج
لحساب (Monin–Obukhov length) وكذلك دالة الاستقرار العالمي وسرعة الاحتكاك وكل تلك العوامل
تستخدم في حساب ارتفاع طبقة الخلط الميكانيكي. نجح النتائج أظهر تغير في الارتفاع إثارة إلى درجات عدم
الاستقرار في الغلاف الجوي وسرعات الرياح حيث بلغ الارتفاع 2433 م عند رياح سرعتها 1.45 م/ث
و 1952 م عند 1.45 م/ث و 1700 م عند 1.3 م/ث والغرض من هذا العمل هو حساب ارتفاع طبقة الخلط
الميكانيكي باستخدام نماذج في حالات الاستقرار وعدم الاستقرار حيث يمكن استخلاص منها توقعات حول
تركيز الملوثات المطلقة وتقدير العائد منها بالغلاف الجوي من أي منشأة نووية.
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