A Review of Nighttime Boundary Layer and Concentration Models under Calm Conditions
INTRODUCTION

The use of dispersion models in the field of air pollution has increased tremendously after the passage of 1990 Clean Air Act (CAA). A significant amount of the regulatory and compliance work carried out by the government agencies, industries and consulting companies in support of CAA uses these dispersion models. However, there is no single model that can be used for analyzing all the scenarios encountered in real life. Nighttime boundary layer and dispersion of a plume under calm conditions are some of the real time situations that are not considered in most of the dispersion models available in the field.

The purpose of this case study is to review the literature on methods (equations) available for computing nighttime boundary layer height and equations and models available to determine concentrations and plume rise under calm conditions. The literature review covered journals, conference proceedings and U.S. Environmental Protection Agency reports. During the review it was found that very little information is available on nighttime boundary layer and calm condition issues. This study provides the definition of boundary layer, variation of boundary layer with time of day, equations for boundary layer heights and equations for determining concentrations and plume rise under calm conditions.

NIGHTTIME BOUNDARY LAYER

Theory

The boundary layer is defined as that part of the troposphere that is directly influenced by the presence of the earth’s surface, and responds to surface forces with a time scale of about an hour or less. Surface forcing’s include frictional drag, evaporation and transpiration, heat transfer, pollutant emission, and terrain induced flow modification. The boundary layer thickness is quite variable in time and space, ranging from hundreds of meters to a few kilometers.

The general nature of the boundary layer is to be thinner in high-pressure regions than in low-pressure regions (Fig. 1). Over land surfaces in high-pressure regions the boundary layer has a well-defined structure that evolves with the diurnal cycle (Fig. 2). One can distinguish this structure into three major components: mixed layer (ML), the residual layer, and the stable boundary layer (SBL). Further when clouds are present in the mixed layer, they are subdivided into a cloud layer and a subcloud layer. The bottom 10% of the boundary layer is called the surface layer, which is the region at the bottom of the boundary layer where turbulent fluxes and stress vary by less than 10% of their magnitude, regardless of whether it is part of a mixed layer or stable boundary layer.

As the night progresses, the bottom portion of the residual layer is transformed by its contact with the ground into a stable boundary layer. This stable boundary layer often forms at night over land, where it is known as a nocturnal boundary layer (NBL). It can also form by advection of warmer air over a cooler surface.

The stable air tends to suppress turbulence, while the developing nocturnal jet enhances wind shears that tend to generate turbulence. As a result, turbulence sometimes occurs in relatively short bursts that can cause mixing throughout the SBL. During the non-turbulent periods, the flow becomes essentially decoupled from the surface.

Unlike the daytime mixed layer, which has a clearly defined top, the SBL has a poorly defined top that smoothly blends into the residual layer above (Figs. 3 and 4). The base of
the stable layer defines the ML, while the top of the stable layer or the height where turbulence intensity is a small fraction of its surface value define the SBL top.

It is observed that the pollutants emitted into the stable layer disperse relatively little in the vertical. They disperse more rapidly, or “fan out”, in the horizontal. This behavior is called fanning, and is sketched as the bottom smoke plume in Fig. 3. At night when winds are lighter, the effluent meanders left and right as it drifts downwind.

**Literature Review**

According to Randerson at night, a stable stratified boundary layer is generated by the radioactive cooling of the ground and of the air in contact and is usually referred to as nocturnal boundary layer (NBL) in meteorological literature.

There are relatively few relationships for predicting the nocturnal surface inversion height when compared to predicting daytime mixing-layer height. This is mainly due to the fact that the dynamical description of the convective boundary layer can be considerably simplified, since the velocity profiles for both wind and potential temperature become almost uniform due to strong turbulent mixing. No such simplification is justified for the nocturnal boundary layer.

The stable stratification in the NBL implies that solely mechanical processes such as create turbulence by wind shear and by the disturbance of the mean wind flow over surface obstacles. Sometimes these nocturnal turbulence processes are sporadic and nonuniform in the vertical, making a deterministic solution of the mean conservation equations difficult to achieve in practice.

However, it should be possible to describe the NBL evolution in terms of the imposed external forces. Stull identified a suitable depth scale for the NBL. Based on an empirical and dimensional development he determined a relationship between the imposed forces and the resulting NBL temperature profiles. Further, he developed an equation capable of forecasting the depth and strength of the nocturnal temperature inversion as a function of external forces. He approximated the top of the NBL to be \( h=5H \) (heat flux length scale) based on the similarity form

\[
\frac{\Delta \theta}{\Delta \theta_s} = \exp(-azH^{-1})
\]

where, \( \Delta \theta \) is the temperature change at height \( z \), \( a \) is an empirical constant \( a=0.77 \) which is related to the fraction of cooling of air that is not directly caused by radiation divergence in the air itself and \( H \) is a heat-flux-history length scale.

He obtained a forecast equation for NBL depth, which appears as

\[
h^2 = \left( \frac{Q_H}{Q_H^G} \left( \frac{U_G}{U_G^G} \right) \left( \frac{f U_G}{U_G^G} Z_s \right)^{3/2} \right) g^{-1}
\]

As a special case when the external forces are constant during the night, the term in square brackets goes to unity, leaving.

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* The nomenclature for symbols is given in Appendix A
The larger value of $Z_s$ corresponds to a faster growth of $h$.

Yamada defined the nocturnal surface inversion height $n_h$ for the ideal horizontally homogeneous atmosphere as the lowest height where the temperature lapse rate changes to the dry adiabatic.\(^3\) For less ideal conditions $n_h$ is determined as the height to which significant cooling had extended.

He finally obtained an expression for the variation of NBL with time as follows.

$$\frac{dh_n}{dt} = \frac{-1}{\theta_h - \Theta_s} \left\{ 2Ch_n \frac{\partial \Theta_s}{\partial t} - h_n \left( \frac{\partial \Theta_s}{\partial t} + \frac{\partial \Theta_n}{\partial t} \right) + 4 \left[ \overline{W\Theta} - (\overline{W\Theta})_n \right] \right\}. \quad (1.4)$$

where $C=1$ (constant introduced to conveniently identify the radiative cooling term in the later analyses).

Many researchers (eg. Monin and Clarke) speculate that based on similarity theory the stable boundary layer height $h$ may be determined by a dimensional scale height parameter:

$$h \propto \frac{ku_*}{f} \quad (1.5)$$

where, $u_*$ is surface friction velocity and $k$ the von Kármán constant.\(^4\)^\(^5\)

Deardorff suggested an empirical formula for determining $h$, i.e.,

$$h = \left( \frac{1}{30L} + \frac{f}{0.35u_*} + \frac{1}{H_T} \right)^{-1} \quad (1.6)$$

where $L$ is the surface Monin-Obukhov length and $H_T$ the height of the tropopause.\(^6\)

Businger and Arya deduced a formula through a theoretical steady-state model.\(^7\)

$$h \propto (u_*L/f)^{1/2} \quad (1.7)$$

The above three equations 1.5, 1.6, 1.7 are diagnostic in nature. The nocturnal boundary layer height determined will be independent of time under the conditions $u_*$ and $L$ being nearly constant. However, observations by Blackadar and Izumi and Barad indicate that $h$ typically increases with time during the night.\(^8\)^\(^9\)

Deardorff developed a rate equation for the growth of the nocturnal boundary layer\(^10\):
\[
\frac{\partial h}{\partial t} = 0.025u_*[1 - h/(0.35u_* / f)]
\]  

(1.8)

Melgarejo and Deardorff in their work computed the dimensional scale height parameters based on the equations 1.7 and 1.8 and compared them with the observed values of nocturnal boundary layer heights, \(h_\theta\) and \(h_u\) respectively. They defined \(h_\theta\) to be the height to which significant cooling had extended, as judged both from individual potential temperature profiles and their evolution in time, and \(h_u\) is defined as the height of the lowest definite maximum in the wind profiles.\(^{11}\)

Considering the similarity theory, Zilitinkevich and Monin obtained a rate equation\(^{12}\)

\[
\frac{\partial h}{\partial t} \propto ku_L / h
\]  

(1.9)

If the initial stable boundary layer height is known, the last two prognostic rate equations (1.8,1.9) will give the evolution of nocturnal boundary layer.

The U.S. EPA models contain some description of nighttime boundary layer. In complex terrain dispersion model (CTDM) the nocturnal boundary layer case features a “mixed” layer above the surface layer with super geostrophic wind speeds—the well-known low-level nocturnal jet phenomenon. At night, the downward heat flux into the ground is a function of the surface wind speed and cloud cover. Estimates of \(u_*\) and \(L\) in stable conditions are then used to calculate the height of the stable surface layer.

Zilitinkevich developed an expression, which is valid for very stable conditions\(^{13}\):

\[
h = 0.4\left(\frac{u_* L}{f}\right)^{3/2}
\]  

(1.10)

This expression was used in modeling the nocturnal boundary layer height. Where \(h\) is the height of the stationary nocturnal boundary layer, \(f\) is the Coriolis parameter, \(9.374 \times 10^{-5}\) s\(^{-1}\).

Later Nieuwstadt developed an interpolation scheme, which extends Zilitinkevich’s formula to nearly neutral case:

\[
\frac{h}{L} = \frac{0.3u_*}{fL} \frac{1 + 1.9h/L}{1 + 1.9h/L}
\]  

(1.11)

where, \(L\) is the Monin-Obukhov length.\(^{14,13}\)

The solution for \(h\) obtained by this formula approaches Zilitinkevich’s stable case equation for small \(L\) and approaches \(0.3\ u_*/f\) for large \(L\).\(^{13}\)
Applications

To compare and review the above equations, some sample calculations are done which are shown in Table 1.1. The calculations are made for three different wind speeds that are usually prevalent under nighttime conditions. The nighttime boundary layer height (mixing height) is found to be in the range of 120 to 750 for 2m/s wind speed, 340 to 1500 for 4 m/s wind speed, and 630 to 2250 for 6m/s wind speed. Equations 1.6, 1.7 and 1.9 are atmospheric stability dependent. The mixing heights given in Table 1 will change if atmospheric stability changes.

MODELS UNDER CALM CONDITIONS

Literature Review

It is observed (Bierly and Hewson, Irwin and Cope, Ventakram) that under daytime convective conditions with moderate to weak winds for tall industrial stacks and/or buoyant effluents mean ground level concentrations (glc) are usually high. The glc is found to be much higher under zero mean wind speed. These cases were studied by Deardorff by modeling a continuous succession of mean circular puffs emanating from a point source, with each spreading puff having a standard deviation of spread, $\sigma_R$, prescribed by

$$\sigma_R^2 = \left(\frac{\sigma_R}{Z_i}\right)^2 = \frac{(0.6T)^2}{(1 + 2T)} + \sigma_{Ro}^2$$  \hspace{1cm} (2.1)

where: $T = (W^*/Z_i)t$ and $t$ is the puff travel time.

$W^*$ is the convective velocity scale within the convective boundary layer, $Z_i$ is the boundary layer height,

$\sigma_{Ro}$ is the initial puff spread about equal to the stack radius, and $r$ is the radius centered on a drifting expanding mean puff.\(^{18}\)

Deardorff obtained a mean incremental concentration, $dc$, as a function of time $t'$ after release by considering a single puff spreading outwards from a nearly point source in accordance with Eq. (2.1) and well mixed in the region $0 < Z < Z_i$ as follows:

$$dc = dM\left[2\pi Z_i, \sigma_R^2(t')\right]^{-1} \exp[-r^2/(2\sigma_R^2(t'))]$$  \hspace{1cm} (2.2)

where, $dM$ is the net contaminant mass of the individual puff.\(^{18}\)

He modeled a continuous source by considering a steady succession of puffs, and arrived at the mean concentration by integration

$$\overline{C}(t) = \int_0^{t} dc = \int_0^{t} Q\left[2\pi Z_i, \sigma_R^2(t')\right]^{-1} \exp[-r^2/(2\sigma_R^2(t'))]dt'$$  \hspace{1cm} (2.3)

where,

$$Q = dM/dt'$$
is the source emission rate, assumed constant after emissions commence at time t=0.

According to Briggs, “calm” means that the plume rises essentially vertically, although it may bend over at stratification level. For most industrial plants minimum ground level concentrations of effluent are likely to occur at fumigation after a calm night with a steep ground inversion.

It is observed that, the concentration is inversely proportional to the height of plume rise through the nighttime inversion. This is because fumigation occurring after sunrise due to convection of ground heating builds up to the level of stratified smoke, mixing it evenly down to the ground.

Briggs, applying dimensional analysis, reached to the relation

\[
C_{\text{max}} \propto \frac{Q}{F_b^{1/2} s^{-1/4} (h_s + 4.7 F_b^{1/4} s^{-3/8})}
\]

(2.4)

where, \(C_{\text{max}}\) is maximum ground concentration
\(h_s\) is the stack height.

He estimated a value of the order of 0.05 for the constant of proportionality based on limited field data.

It is observed that under atmospheric conditions of little or no wind there is no bending of the plume and it rises to some height where the bouyancy force is completely dissipated. Briggs recommends using a relation developed by Morton et al., which is

\[
\Delta h = 5.0 F_b^{1/4} / s^{3/8}
\]

(2.5)

where, \(\Delta h\) is the plume rise above stack.

Morton predicted heights of forced plumes generated when smoke or other effluent is discharged vertically into a stably stratified atmosphere under calm conditions. In order to model for these forced plumes, he assumed that profiles of mean vertical velocity and excess temperature (or bouyancy) at all heights in the plume are of similar form, and, that the rate of entrainment at the edge of the plume is proportional to the mean vertical velocity on the axis.

Using the conservation of volume, momentum and heat Morton obtained a solution for height \(H_v\) of the plume-top above a virtual source in a stably stratified atmosphere under calm conditions as given below

\[
H_v = 2^{-5/8} \alpha^{-1/2} \lambda^{-1/4} \left| R_o^2 w_o g \frac{\rho_{ao} - \rho_o}{\rho_{ao}} \right|^{1/4} \left( - \frac{g}{\rho_{ao}} \frac{dp_a}{dz} \right)^{-3/8} H_1(\tau_d)
\]

(2.6)

where,

\[
\left| R_o^2 w_o g \frac{\rho_{ao} - \rho_o}{\rho_{ao}} \right|^{1/4} \left( - \frac{g}{\rho_{ao}} \frac{dp_a}{dz} \right)^{-3/8}
\]

is the scale length formed from the given physical parameters, and \(H_1(\tau_d)\) is the form of the dimensionless height which depends on the source conditions \(\tau_d\) is a non-dimensional constant which will be representative of the behavior of the plume, and hence the heights of plume-tops
above a variety of sources in stratified atmospheres will depend only on $\tau_d$.\textsuperscript{21}

From the results of this study Morton inferred that for calm weather conditions the discharge of smoke by pumping at increased speeds from short chimneys cannot be as effective in dispersing the smoke as normal discharge from taller chimneys.\textsuperscript{21} The EPA developed a RVD 2.0 model to provide short-term ambient concentration estimates for screening pollutant sources emitting denser-than-air gases through vertical releases\textsuperscript{22}. The empirical equations developed by Hoot et al based on the wind tunnel tests formed the basis for this model\textsuperscript{23}.

In this model the plume rise from the stack top ($\Delta h$) under quiescent (calm) atmospheric conditions is calculated by using the following equation

$$\Delta h = 2.96(Fr)d$$

where, $Fr$ is the vertical densimetric Froude number defined by

$$Fr = \frac{v_s}{\sqrt{gd}} \left( \frac{1 - \rho_a}{\rho_o} \right)^{1/2}$$

In this model the cloud radius is obtained by numerical integration with respect to time of the rate equation:

$$dR_c/dt = U_f$$

where $R_c$ is the cloud radius

$U_f$ is the frontal velocity derived from the numerical integration of an equation $dU/dt$, obtained from the radial momentum budget of the cloud. Further, in the model, the time rate of change of the cloud volume is modeled as

$$\frac{dV_c}{dt} = \pi R_c^2 V_c$$

During the review of literature it is found that only limited work has been published during the last three decades on elevated releases under calm conditions. Therefore, we extended our review to ground level releases. A few more studies that have been published on ground level releases under calm conditions were found.

A. P. Van Ulden analyzed the heavy gas mixing process for Thorney Island experimental conditions and for the laboratory experiments in still air by Havens and Spicer.\textsuperscript{24,25} Based on the observations and the laboratory experiments he developed a dynamic integral model to describe the processes involved.

Van Ulden\textsuperscript{26} has described the model for the spreading and mixing of a dense cloud in still air in detail.
where, \( V_c \) is the cloud volume.

The cloud height is obtained as

\[
\bar{H}_c = \frac{V_c}{\pi R^2}
\]  

(2.11)

and then the cloud averaged concentrations by volume is defined as

\[
\frac{- \bar{c}}{c} = \frac{V_o}{V_c}
\]

(2.12)

Matthias described a simple analytical semi-empirical model, that describes the concentration field in a collapsing gas cloud of cylindrical shape under no atmospheric effects, i.e., no wind or ambient turbulence. The model examines the two distinct bodies of the cloud, a leading torus and a trailing disk, as shown by the experimental results.

The radial growth of a uniform cylinder is obtained as

\[
R_c^2 = R_{co}^2 + 2a_4 b_o^{1/2} t
\]

(2.13)

where, \( R_c \) is the radius of the cloud

\( R_{co} \) is the initial radius of the cylindrical cloud

\( a_4 \) is the proportionality constant, and

\( b_o \) is the initial buoyancy given by

\[
b_o = g V_o \Delta_o / \pi
\]

(2.14)

\( \Delta_0 \) being the relative density excess initially,

\( V_0 \) is the initial volume of the cylindrical cloud, and

\( g \) is the acceleration due to gravity.

Matthias developed a general expression for the location of the frontal radius (\( R_f \)) of the leading or frontal edge of the cloud, as follows:

\[
\frac{\bar{R}^2}{R_i^2} = \frac{R_o^{-2}}{} = \frac{2a_4 a t^{-2}}{2a_4 + a_3 \pi^{1/2} t}
\]

(2.15)

where, \( a_4 = 1.16 \) a constant of proportionality

\( a_4 = 0.35 \) acceleration parameter

\[
\frac{\bar{R}_o}{R} \cdot \frac{R_{co}}{1}
\]

(2.16)
\[
\bar{R}_f = \frac{R_f}{l} \tag{2.17}
\]

\[
\bar{t} = \frac{t}{\tau} \tag{2.18}
\]

where,

\[
1 = V_o^{1.5} \tag{2.19}
\]

\[
\tau = \left(\frac{\Delta u}{g}\right)^{\frac{1}{2}} \tag{2.20}
\]

**Applications**

During the review it is found that most of the equations available for heavy gas releases are for ground level releases and provide radius and height of the cloud which are then used in computing concentrations averaged over the volume. It is also found that there is one model (RVD 2.0) by EPA for vertical releases which give the plume rise using densimetric Froude number as shown in equation 2.8.

After looking at the various model equations available, it is found that Equations 2.3 and 2.4 can be utilized in the computations for concentrations under calm conditions due to elevated passive releases. However, Equation 23 requires integration techniques to solve for concentration. Hence, Equation 2.4 is used in our sample calculations which are shown in Table 2. The choice of the equation is tentative and should be verified with field data. The maximum concentrations shown in Table 2 will occur very close to the stack.

**CONCLUSIONS**

During a literature review nine equations were found to compute nighttime boundary height. Sample calculations were done for three equations which can be easily applied for dispersion work. Wide variations were seen in computing nighttime boundary height using these equations.

Most of the equations for concentration calculations under calm conditions are for ground level heavy gas releases. There are two equations available for elevated passive releases. Sample results are given for one equation.

**REFERENCES**

27. Matthias, C. S., "Dispersion of a dense cylindrical cloud in calm air," *J. Hazardous
APPENDIX A - Nomenclature

- $a_1$: Proportionality constants
- $a_4$: Acceleration parameter
- $b_0$: Initial buoyancy
- $c$: Cloud averaged concentration by volume
- $C_{\text{max}}$: Maximum ground level concentration (MGLC)
- $d$: Diameter of the stack
- $d_c$: Mean incremental concentration
- $dM$: Net contaminant mass of the individual puff
- $f$: Coriolis parameter
- $F_b$: Buoyancy flux
- $Fr$: Vertical densimetric Froude number
- $g$: Acceleration due to gravity
- $H$: Heat-flux-history length scale
- $h$: Height of the Nocturnal Boundary Layer (NBL)
- $H_c$: Cloud height
- $h_n$: Nocturnal surface inversion height
- $h_s$: Stack height
- $H_t$: Height of the tropopause
- $k$: Von-Karman constant
- $L$: Monin-Obukhov length
- $Q$: Emission rate
- $Q_H$: Surface heat flux into the air
- $Q_{\text{av}}$: Average surface heat flux into the air
- $r$: Radius centered on a drifting expanding mean puff
- $R_c$: Initial radius of the cylindrical cloud
- $R_f$: Frontal radius
- $R_f$: Average frontal radius
- $R_0$: Mean radius of the “top-hat” profile at the source
- $t$: Time
- $t'$: Time
- $T$: Nondimensional time, $= (W^*/Z_i) \cdot t$
- $u*$: Surface friction velocity
- $U_f$: Frontal velocity
- $U_G$: Geostrophic wind vector
- $\bar{U}_G$: Average geostrophic wind
- $V_c$: Cloud volume
- $V_e$: Entrainment velocity
- $V_0$: Initial volume of the cylindrical cloud
- $V_s$: Exit velocity
- $w_0$: Vertical velocity of stack gasses
\[\langle w'\theta' \rangle_h\] Turbulent heat flux at NBL
\[\langle w'\theta' \rangle_s\] Turbulent heat flux at surface

\[z\] Mean plume rise from the stack top
\[Z_1\] Boundary layer height
\[Z_s\] Empirical roughness parameter

Greek symbols

\[\alpha, \beta\] Entrainment constants
\[\Delta_o\] Initial relative density excess
\[\Delta h\] Height of the plume rise
\[\Delta \theta\] Temperature change at height \(z\)
\[\Delta \theta_s\] Amount of warming of the air just above the earth’s surface
\[\Delta \rho_o \text{ and } V_o\] Initial values of \(\Delta \rho\) and \(V_c\)
\[\lambda\] Spreading ratio
\[\Theta\] Mean value of potential temperature
\[\Theta_h\] Mean value of potential temperature at NBL
\[\Theta_s\] Mean value of potential temperature at surface
\[\theta\] Fluctuating value of potential temperature
\[\theta_h\] Fluctuating value of potential temperature at NBL
\[\rho_a\] Ambient atmospheric density
\[\rho_{ao}\] Density of ambient air at source
\[\rho_o\] Exhaust gas density
\[\sigma_R\] Standard deviation of spread for mean puff at time \(t\)
\[\sigma_r\] Standard deviation of spread for instantaneous puff
\[\sigma_{Ro}\] Initial puff spread equal to the stack radius
\[\tau\] Dummy of integration
\[ \tau_d \quad \text{Non-dimensional constant} \]

| Table 1. Sample Calculations for Mixing Height Under Nighttime Conditions |
|-------------------------|-----------------|----------------|-----------------|-----------------|
| Wind Speed at 10 m     | Eq. 1.5^2       | Eq. 1.6^3       | Eq. 1.7^2,3     | Eq. 1.10        |
| Height (m/s)^1       |                 |                 |                 |                 |
| 2                      | 746.75          | 457.12          | 306.39          | 122.56          |
| 4                      | 1493.49         | 1052.77         | 866.61          | 346.64          |
| 6                      | 2240.24         | 1609.10         | 1592.06         | 636.82          |

1 Friction velocity is computed according to SCREEN model using wind speed at 10m height.
2 Constant of proportionality of these equations is assumed as 1.
3 Height of the troposphere in this equation is assumed to be 11km = 1 1000m. And also L, the MoninObukhov length, is determined using a single empirical relation propsed by Venkatram: L \( Au^* \), where A under stable conditions is aroximatel 1100 s^2/m.\(^{17}\)

| Table 2. Sample Calculations Using Equation 2.4 for Concentrations Under Calm Conditions |
|-----------------|-------------------|-------------------|-----------------|-----------------|
| Emission Rate   | Stack Height H    | Exit Temp. K      | Exit Stack Vet. V | Stack Buoyancy Diam. Flux F* |
| Q gl/sec m      |                   |                   |                 |                 |
| 9.59            | 38                | 573               | 9               | 2.1             | 46.67            | 4.19E-05        | 41.91           |
| 9.77            | 53                | 733               | 5.3             | 2.4             | 44.39            | 4.17E-05        | 41.72           |
| 14.92           | 38                | 783               | 11              | 1.9             | 60.26            | 5.43E-05        | 54.34           |
| 13.96           | 38                | 811               | 8.9             | 1.8             | 44.69            | 6.29E-05        | 62.92           |
| 47.38           | 31                | 472               | 7.2             | 3               | 58.53            | 0.000181        | 181.01          |
| 279.69          | 76                | 506               | 28.4            | 3               | 257.42           | 0.000325        | 324.57          |
| 978.08          | 61                | 1000              | 20              | 2.3             | 181.97           | 0.001508        | 1507.87         |

Note: In the above calculations the stability parameter is computed using the equation
\[ s = ((dT/dz) + F) \times g/T = 0.0005\text{sec}^2, \text{dT/dz} = 0.5\text{C/100m} \text{and} = 1\text{C/100m} \text{is assumed} \]

- F is obtained by using the equation F= \( (gVs^*(D/2)^2) \times (T_\text{To~})/Tg \)
Maximum height reached by surface-modified air during a one-hour period.

Figure 1 General nature of the boundary layer

Figure 2 Different parts of boundary layer in high pressure regions