

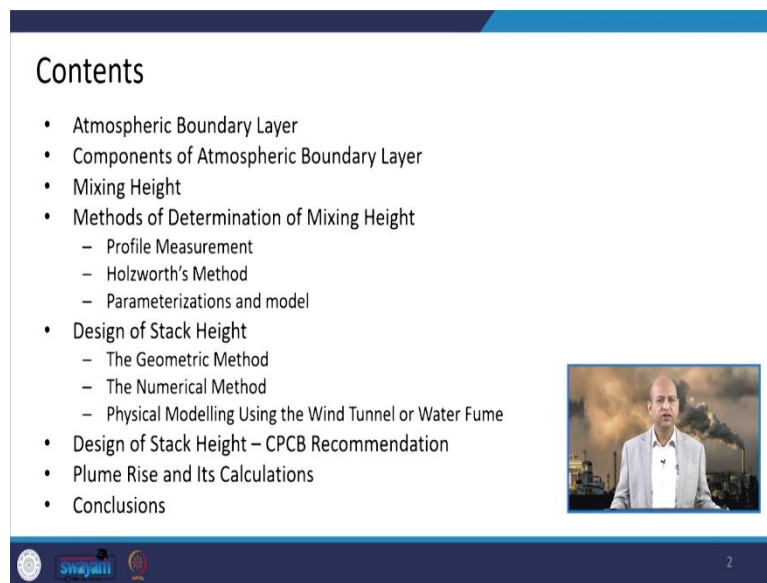
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**Lecture 12**

**Boundary Layer, Mixing Height, Stack Height and Plume Rise**


Hello friends, today we will discuss about Boundary Layer, Atmospheric Boundary Layer and its Mixing Height, Stack Height and Plume Rise because they are interrelated to each other, when we talk about dispersion of pollutants or dilution of the pollutants when it is emitted from a particular stack or point source.

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**Contents**

- Atmospheric Boundary Layer
- Components of Atmospheric Boundary Layer
- Mixing Height
- Methods of Determination of Mixing Height
  - Profile Measurement
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  - Parameterizations and model
- Design of Stack Height
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  - The Numerical Method
  - Physical Modelling Using the Wind Tunnel or Water Fume
- Design of Stack Height – CPCB Recommendation
- Plume Rise and Its Calculations
- Conclusions



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So, the contents of today's lecture is like first of all we will discuss atmospheric boundary layer what is the boundary layer, how it is defined how it is approximated then different components of the boundary layer and then the concept of mixing height and methods of determination of mixing height by different methods like Profile measurement, Holdsworth method is there and Parameterizations and model based calculations are also there.

Then we would talk about the stack height design. So, again there are different methods to design the stack height like geometric method, numerical methods or even by physical modelling in the wind tunnel or water fumes and some recommended, equations or relationships are there by CPCB (Central Pollution Control Board) some minimum heights maxima might those kinds of things are there.

And then the plume rise and its calculations we will discuss because plume rise is also important in the sense because it is added into the physical stack height when we calculate

effectively stack height. So, that is also very important when we talk about stack height and then we will conclude.

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### Atmospheric Boundary Layer (ABL)

The diagram shows a cross-section of the atmosphere above the Earth's surface. The Earth is represented by a green dome. Above it is the Boundary Layer, shaded in pink, extending up to a height of approximately 2 km. Above the Boundary Layer is the Capping Inversion, shown as a dashed line. Above the Capping Inversion is the Free Atmosphere, which includes the Troposphere extending up to approximately 11 km. The x-axis represents the horizontal distance, and the z-axis represents the vertical height.

- Atmospheric Boundary Layer (ABL) is the bottom layer of the troposphere (about 1 -2 km) that is in contact with the surface of the earth.

Source: (Stull, R. B., 1988)    Image Source: (<https://www.eoas.ubc.ca>)

So, when we discuss about atmospheric boundary layer basically it is nothing but the bottom layer of the troposphere. You can assume like 1 to 2 kilometre from the Earth's surface and because topography varies it is not overall smooth somewhere it is mountains or hilly areas, undulations, water bodies etc, so the height is not constant it can vary from 1 to 2 kilometre depending upon the surface nature of the Earth's surface nature of the Earth's surface.

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### Components of Atmospheric Boundary Layer (ABL) (1/5)

➤ The major components of Atmospheric Boundary Layer are:

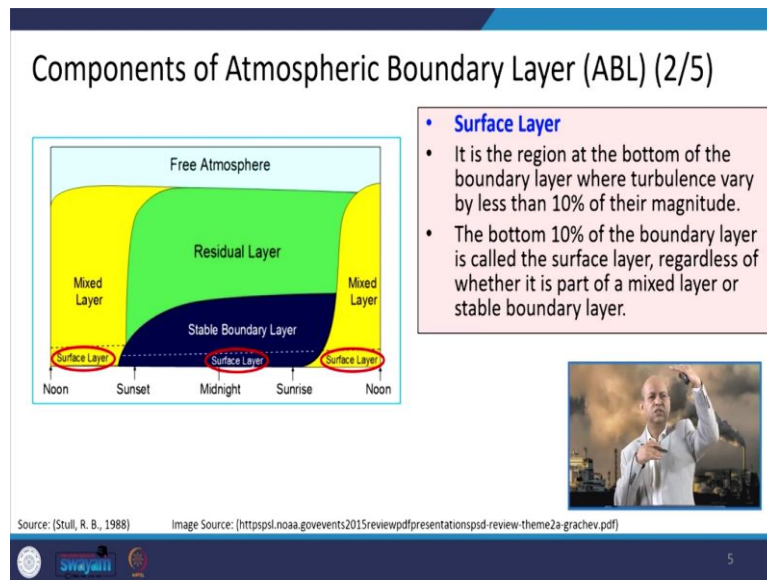
- Surface layer
- Mixed layer (also known as the Convective Boundary Layer)
- Residual layer
- Stable boundary layer

The diagram illustrates the vertical structure of the ABL over a 24-hour period. The x-axis shows the time of day: Noon, Sunset, Midnight, Sunrise, and Noon. The y-axis represents height. The ABL is divided into four layers: Surface Layer (bottom, dark blue), Mixed Layer (yellow), Residual Layer (green), and Stable Boundary Layer (dark blue, which is thicker at night). The Free Atmosphere is shown above the ABL. The diagram shows that during the day, the Mixed Layer and Surface Layer are well-mixed, while at night, the Stable Boundary Layer forms, trapping pollutants near the surface.

Source: (Stull, R. B., 1988)    Image Source: (<https://www.cradle-cfd.com/media/column/a91>)

Well the different components of the boundary layer or atmospheric boundary layer are you know defined or they are given some nomenclature like surface layer or mixed layer then residual layer and stable boundary layer those kinds of names are there and how they are defined let us see.

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So, the surface layer is basically nothing but the, this is the region at the bottom of the boundary layer you can see here this is the surface layer very thin layer within the boundary layer or the troposphere the lowest one the nearer to the Earth's surface. So, this is the region at the bottom of the boundary layer where turbulence you know varies by less than 10 percent of their magnitude, we will see the turbulence what is turbulence basically.

And the bottom 10 percent of the boundary layer if you assume 100 units you know height of the boundary layer, then the bottom 10 percent of the boundary layer is called the surface layer regardless whether it is part of the mixed layer or the stable boundary layer, because there are other components also the boundary layer but means the bottom part the 10 percent of the total boundary layer or height of the atmospheric boundary we consider as the surface layer.

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### Components of Atmospheric Boundary Layer (ABL) (3/5)

- **Mixed Layer**
- It is a layer where turbulence is predominant causing uniform mixing primarily in vertical direction.
- The turbulence in the mixed layer is due to solar heating; a nearly well-mixed layer can form in regions of strong winds.
- Maximum height is reached during late afternoon during summer season.

Source: (Stull, R. B., 1988) Image Source: (<https://psl.noaa.gov/events2015/reviewpdf/presentationspsd-review-theme2a-grachev.pdf>)

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Then when we talk about the mixed layer basically it is the layer where turbulence is predominant. Again, as I said we will see what is the turbulence it is you know churning of the air lot of mixing takes place. So, this causes uniform mixing primarily in vertical direction because of turbulence, in the mixed layer is due to solar heating nearly well mixed layer can form in the regions very strong winds are also occurring. So, maximum height is reached during the late afternoon during summer seasons because of high solar insolation and these high Eddies or turbulence this happens.

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### Components of Atmospheric Boundary Layer (ABL) (4/5)

- **Residual Layer**
- About half an hour before sunset the thermals cease to form allowing turbulence to decay in the formerly well-mixed layer. The resulting layer of air is called the residual layer.

Source: (Stull, R. B., 1988) Image Source: (<https://psl.noaa.gov/events2015/reviewpdf/presentationspsd-review-theme2a-grachev.pdf>, Stull, R. B., 1988)

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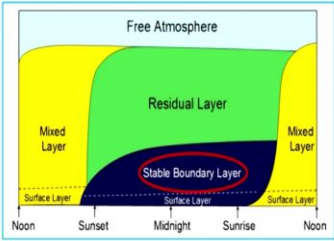
Well, when we talk about the Residual Layer, mixed layer was this one and it could go up to the boundary layer. So, the residual layer is the upper part you can see this is nothing but

about the layer which is like about half an hour before the sunset when thermals cease to exist. And they allow like turbulence to decay slows down in the formerly well next layer.


So, the well mixed layer like this one reduces into these kind of two parts, stable layer the residual layer. So, the residual layer is the upper part because this is kind of you know the difference between the stable boundary layer where stability classification will be applied the concept of instability classification. So, the remaining layer above the stable layer is basically the residual layer.

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### Components of Atmospheric Boundary Layer (ABL) (5/5)



- **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 is characterized by stable air with weaker, sporadic turbulence.



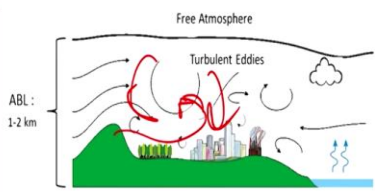
Source: (Stull, R. B., 1988) Image Source: (<https://psl.noaa.gov/events/2015/review/pdf/presentations/psd-review-theme2a-grachev.pdf>, Stull, R. B., 1988)

And what is the stable layer? When we talk about this then this is like when evening occurs and night progresses, then the bottom part of the residual layer is transformed into in the contact of the ground and it becomes like a stable boundary layer because of certain instability classification related temperature profile. So, this is characterised by a stable air with weaker or sporadic turbulence very less very negligible kind of thing.

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## Turbulence (1/2)

- **Turbulence**, the gustiness (a sudden strong rush of wind) superimposed on the mean wind, can be visualized as consisting of irregular swirls of motion called *eddies*.
- Turbulence consists of many different size eddies superimposed on each other.



The diagram illustrates the atmospheric boundary layer (ABL) extending from the ground to approximately 1-2 km. It shows a green landscape with buildings and trees. Red, irregular swirls represent turbulent eddies. Horizontal arrows indicate the mean wind direction. The top of the diagram is labeled 'Free Atmosphere'. A small inset photo shows a man in a white shirt speaking.

Source: (Stull, R. B., 1988) Image: (Chaudhari, A., K., 2014)

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When we talk about the turbulence basically you see the air does not move in a very smooth single direction. It goes up and down depending upon churning and the solar insulation, topographical undulations all those. So, here goes like this it will go up, then come down mixing takes place those kinds of things occur.

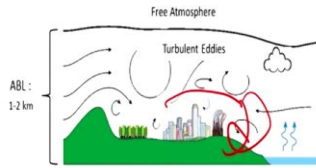
So, this is the gustiness a certain strong rush of the wind superimposed on the mean wind direction and you can visualise it as a consistent of regular swirls of the motion which are called as Eddies. So, the turbulence consists of many different sized Eddies smaller, larger those kinds of and they are superimposed on each other. So, lot of mixing takes place in a mixture also you takes a lot of currents go, on one direction other direction those kinds of things happen.

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## Turbulence (2/2)

The boundary layer turbulence is generated by forces from the ground. For example,

- **Solar heating** of the ground causes thermals of warmer air to rise which forms large eddies causing turbulence.
- **Frictional drag** on the air flowing over the ground causes **wind shears** to develop, which causes turbulence.
- **Obstacles** like trees and buildings deflect the flow, causing **turbulent wakes** adjacent to and downwind of the obstacle.



The diagram illustrates the atmospheric boundary layer (ABL) extending from the ground to a height of 1-2 km. It shows air flow over a terrain with trees and buildings. Turbulent eddies are depicted as swirling air masses. The top of the diagram is labeled 'Free Atmosphere'. Source: (Stull, R. B., 1988) Image: (Chaudhari, A., K., 2014)



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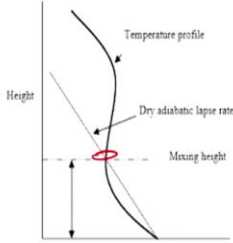
Well, so the boundary layer the turbulence which is generated by forces from the ground in the bottom part of the like solar heating of the ground causes thermals of the warmer air which rises from the ground and it forms large Eddies causing a lot of turbulence. Then there are frictional drag because air is flowing it is touching with the ground lot of friction is there. So, this wind shears develop, which causes the turbulence also because of this drag force.

Then, obstacle also like trees or buildings or undulated the terrain is there that also causes turbulence some weeks, because building is there, then some wake formation occurs. So, again it will be forced like air will come down. So, that is why you know, neither buildings we do not want stacks because when plume comes then there is tendency that it will go down because of this wake formation, those are issues maybe we will discuss later on also in detail.

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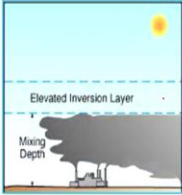
## Mixing Height

- It is the height of the layer in which pollutants, or any constituents emitted or entrained into it are vertically dispersed due to turbulence.
- It determines the volume of atmosphere available for the dispersion of pollutants.




Temperature profile  
Height  
Dry adiabatic lapse rate  
Mixing height

- Mixing Height is involved in:
  - many predictive and diagnostic methods
  - models to assess pollutant concentrations
  - atmospheric flow models.



Temperature  
Source: Ahmed, A., 2018



Source: (P. Seibert et al., 2002) Image Source: ([https://www.nrcs.usda.gov/Internet/FSE\\_DOCUMENTS/stelprdb1046311.pdf](https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1046311.pdf))

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Well, the mixing height basically when we talk about in the boundary layer up to what height a lot of mixing will take place. So, that is also defined because of atmospheric characteristics, and normally we, get it by intersection of adiabatic lapse rate from the maximum temperature at the surface and whatever temperature profile is there like this one and then this intersection occur so, this is the mixing height.

But in theory you can see like, this is the height of the layer in which a lot of pollutants or any constituents of the atmosphere vertically disperses due to turbulence, vertical dispersion occurs, because of this, within this mixing height. So, larger mixing height, lot of volume is available for mixing, dilution of the pollutants, and if it is lower than higher concentration, we will be there because volume will be low.


Mixing height is involved in like many predictive and diagnostic methods which are related to air pollution, then models to assess the pollutant concentration at a particular place or atmospheric plume model. So, this is mixing is very important concept like you can see the whole this mixing height is there where all the pollutants disperse. The more mixing height, more dilution, more dispersion those kinds of things, then how to determine?



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## Methods of Determination of Mixing Height

1. Determination of Mixing Height from **Profile Measurement**
  - Radiosoundings
    - o Subjective Methods
    - o Objective Methods
  - Remote Sounding System
2. Determination of Mixing Height from **parameterizations and model**
  - Neutral Conditions
  - Unstable Conditions
  - Stable Conditions




Source: (P. Seibert et al., 2002)

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So, there are methods to determine the mixing height, like because your profile measurement you can measure it like radiosounding or subjective methods within the radiosounding objective methods, subjective methods or their, remote sounding system is also there, then you can determine mixing height by parameterization and model which are again divided like neutral conditions, what will happen to mixing height or there are empirical equations also, which uses these kinds of conditions or unstable condition, stable condition those kinds of things are there.


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## Mixing Height Determination from Profile Measurement



### Radiosoundings

- A radiosonde equipped with various measuring devices is carried up to high altitudes by a balloon filled with hydrogen or helium.
- The balloon rises at a constant speed and carried away by the wind flow.
- GPS equipped system (position, altitude, wind speed and wind direction)
- Every second, the radiosonde transmits its measurements by radio to the station on the ground.



Source: (Radio soundings, 2002) Image Source: (<https://www.tropos.de/en/research/projects/infrastructures-technology/technology-at-tropos/remote-sensing/radiosounding>)

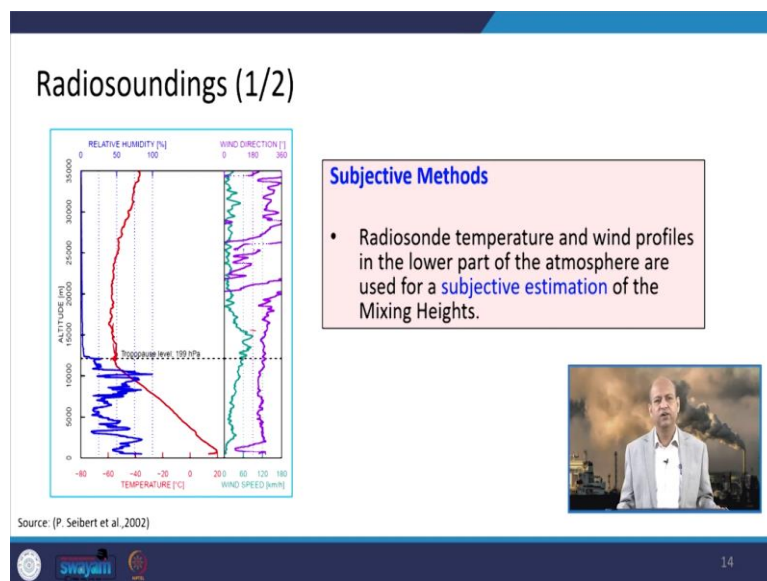
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So, when we talk about radio sounding you use, we use the balloons and some instruments are hanging to that, when you know balloon rises, then at different heights, those sensor

based equipment's, give us the reading. So, GPS equipped system is there which gives the position and the altitude and wind speed, wind direction all those data are collected at the ground level that system and every second this radio sound transmits its measurements by radio to the station on the ground.

So, but as this balloon goes wherever depending upon the wind direction flew etc, those data we get, it is not of our choice that we wanted this particular vertical column that is not possible in this that case.

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Then, within that subjective method is there because we have the profile we have temperature profile all those wind velocity etc. So, depending upon the expertise when wherever you know this profile is changing like this you can see the variation with the altitude this temperature decreases and at this height, temperature then rather than decrease it remains almost constant.

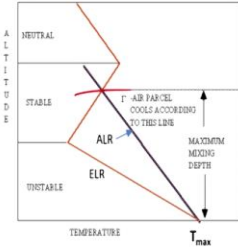
So, up to this one can expert can say, this is the mixing height after that this mixing it stops to work. So, through the subjective method you can get the because of this relationship with the wind profile also you can see it changes here up to this, increases the wind speed and then you know it start decreasing. So, the combination of these wind direction wind profile, temperature profile and expert can easily find out where up to which height the mixing it is there. So, this is known as the subjective method.

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### Radiosoundings(2/2)

#### Objective Methods

- Simplify and homogenize the estimation of the Mixing Height
- Follow the **dry adiabatic** starting at the surface with **max. temperature** up to its intersection with the temperature profile from the most recent radiosounding.
- It determines the **Mixing Height as the equilibrium level of a hypothetical rising parcel of air**. This method strongly depends on the surface temperature.



The diagram shows a vertical cross-section of the atmosphere with layers labeled: NEUTRAL, STABLE, and UNSTABLE. A temperature profile is plotted against altitude. A red line represents a dry adiabatic parcel rising from the surface. The intersection of this parcel with the temperature profile is labeled 'MAXIMUM MIXING DEPTH'. The area below this intersection is labeled 'ELR' (Equilibrium Level Region), and the area above is labeled 'ALR' (Adiabatic Lapse Rate). The surface temperature is marked as  $T_{max}$ . A note says 'AIR PARCEL COOLS ACCORDING TO THE LINE'.



Source: [P. Seibert et al., 2002] Image Source: www.euromotor.org

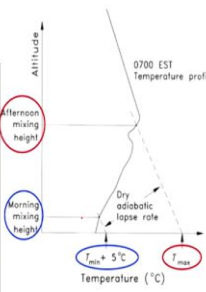
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Objective method is also there, where you plot the profile as well as you know, see what is the maximum temperature during that observation and from there you know intersect this adiabatic lapse rate. So, wherever this is intersecting up to that, the mixing height or maximum mixing height is known. So, that is also one method this is objective, because, some value will come because of these plots and also.


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### Holzworth's Method (Objective Method)

- Mixing depth has been determined by Holzworth of the **U.S. Environmental Protection Agency** in reference to the morning and afternoon.
- The **morning mixing height** is calculated as the height above ground at which the dry adiabatic extension of the **morning minimum surface temperature plus 5°C** intersects the **vertical temperature profile** observed at 12:00 Greenwich Mean Time.
- The **afternoon mixing height** is calculated in the same way except that the **maximum surface temperature observed between 12:00 and 16:00 local standard time** intersects the **vertical temperature profile**.



The diagram shows a vertical cross-section of the atmosphere with 'Altitude' on the y-axis and 'Temperature (°C)' on the x-axis. A vertical temperature profile is shown for '0700 EST'. A dashed line represents a 'Dry adiabatic lapse rate'. Two horizontal lines represent surface temperatures:  $T_{min} + 5^{\circ}C$  and  $T_{max}$ . The intersection of the  $T_{min} + 5^{\circ}C$  line with the temperature profile is labeled 'Morning mixing height'. The intersection of the  $T_{max}$  line with the temperature profile is labeled 'Afternoon mixing height'.



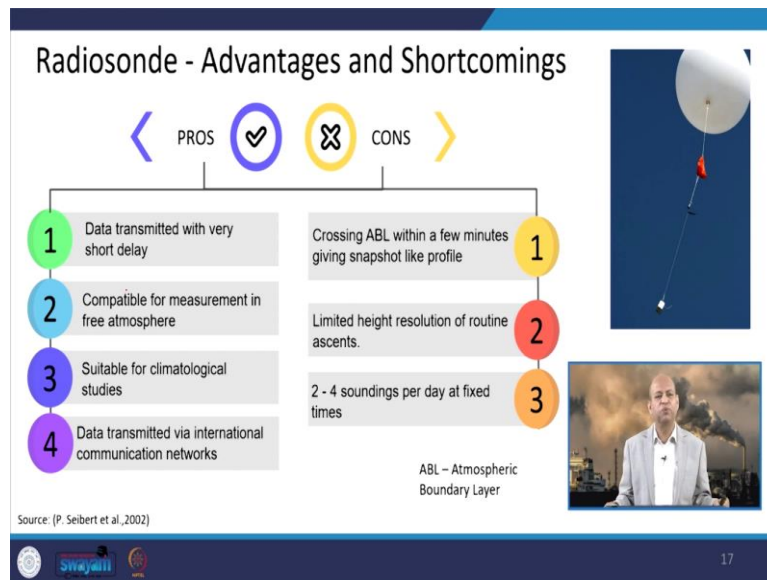
Source: [Karl B. Schnelle, 2003] Image Source: [Source: Hemond and Fechner, 2015]

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Then, there are other methods like this Holzworth's method which is the again objective method which gives readings about like morning mixing height or afternoon mixing height depending upon the time of the day. So, like this morning mixing height the minimum the minimum temperature at the plus 5 percent, there you can have this dry adiabatic lapse rate.

Then from T maximum you have the dry adiabatic lapse rate that gives the afternoon mixing height and the morning mixing height is known when we plot the adiabatic lapse rate from the T minimum plus 5 degrees Celsius. So, those methods are there and you can easily calculate those mixing heights.

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Then there are certain plus or minus, pros and cons depending upon their nature by when we are knowing these data from different methods. So, the reduced sound advantage and shortcomings are also there like you know data transmitted with very short delay so, this is good point for that it is compatible for measurement in the free atmosphere. And then, the suitable for climatological studies, because it needs lot of data then data transmitted via international communication networks.

So, you have huge amount of data and you can play with those to get different kinds of insights about the atmosphere mixing etc. But there are shortcomings also like, there are limitations you can't go beyond 2-4 soundings per day at mixed limited height is their resolution depending upon this wind and the crossing of the atmospheric boundary layer within a few minutes given this snapshot kind of profile. So, there are these shortcomings you can see.



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### In-situ Measurement of Mixing Height

- Tethered Balloon**
  - Tethered balloons are open balloons that are only a little pressurized, the excess gas being vented through a valve.
  - Balloons are attached with rope and are tied to the ground station.
- Mast**
  - Meteorological masts and towers have been employed for measurements in the (lower) atmospheric boundary layer (ABL). They allow to conduct continuous profile measurements at high vertical.



Source: <https://asr.science.energy.gov/news/program-news/post/9035>



Source: (Pommereau, J.P., 2015, [https://www.dwd.de/EN/research/observing\\_atmosphere/lindenberg\\_column/boundary\\_layer/profilmasten.html](https://www.dwd.de/EN/research/observing_atmosphere/lindenberg_column/boundary_layer/profilmasten.html)) Nov. 2<sup>nd</sup>, 2021



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Then, we go for in-situ measurements of the mixing height where you can have this kind of balloon tied with a rope. So, up to certain height you can have the those profile related measurements. Then you can have the mast where you can have this kind of tower very tall and you can install different instruments at different heights and you can have these observations related to wind velocity temperature profile everything. So, you can have the data in the column.

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### Tethered Balloon - Advantages and Shortcomings

PROS	CONS
1 Desired ascent velocity according to the desired vertical resolution	1 Trained personnel required for operation
2 Turbulence and trace gas concentration measurements possible	2 Limited to 500 m
	3 Not possible during high wind speed or strong convection.



Source: (P. Seibert et al., 2002) Image Source: (<https://asr.science.energy.gov/news/program-news/post/9035>)

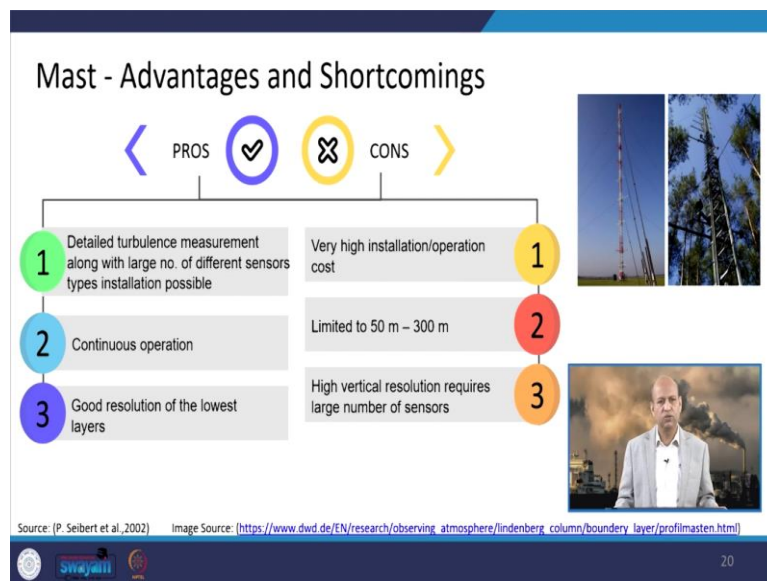
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Well again, there are some pros and cons like there are this tethered balloon where it is tied to the rope. So, plus point is like desired ascent velocity according to the desired vertical

resolution that we can maintain. Then the turbulence and trace gases concentration measurements are possible in this particular way.

But it requires a lot of skill, skilled person required to handle it, and then it can't go beyond 500 metres. So, that is the limitation and it is not possible during very high wind speed or during strong convection where a lot of vertical movements happen. So, it can be damaged because of those high winds etc we cannot have better results.

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Similarly, in Mast also there are certain plus point like it can give detailed turbulence measurements along with the large number of different sensors which are installed on the tower this installation. Then continuous operation is possible good resolution of the lowest layer is very much possible you can do whatever height, you want to install those instruments, but it is very high installation cost is needed because of this infrastructure which are needed.

Then limitation like 50 to 300 metre only beyond that, it is not cost effective and high vertical resolution requires large number of sensors. So, again it adds into the cons. So, operational cost also increases.

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### Remote Sounding Systems

- The process of detecting and monitoring the physical characteristics of an area by measuring its reflected and emitted radiation from a distance.
- Basic advantages
  - continuous operation and
  - they do not cause any modification of the investigated flow.

GNSS – Global Navigation Satellite System

Image Source: (Wulfmeyer, V., et al., 2015)

Source: (P. Seibert et al., 2002, <https://www.usgs.gov/>) Nov. 2<sup>nd</sup>, 2021

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When we talk about remote sounding systems, then from the distance you can have some observations. So, basic advantages are like continuous operation can be maintained, and they do not cause any modifications of the investigated flow because whenever you are having a tower or balloon, so it is a little bit changing that particular location related flow metrics, but in this this is sensor based on some raise. So, there are no obstacles at all in this particular method.

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### Types of Remote Sounding Systems (1/3)

- Lidars (Light Detection and Ranging)
- Sodars (Sound Detection and Ranging)
- Wind profiling radars
- RASS (Radio-acoustic sounding systems)

GNSS – Global Navigation Satellite System

Image Source: (Wulfmeyer, V., et al., 2015)

Source: (P. Seibert et al., 2002)

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Well types of remote sensing sounding systems or there like light detection and ranging, which is known as LIDARS, then sound detection and ranging or SODARS, then when profile radars are also there, then Radio Acoustic Sounding Systems (RASS) is also there.

And the Global Navigation Satellite System (GNSS) can easily be used for these kinds of measurements.

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### Types of Remote Sounding Systems (2/3)




Image 1: Lidars

**Lidars** (Light Detection and Ranging): It allows the measurement of aerosol or trace gas concentration profiles and may therefore be considered to provide direct measurements of the Mixing Height.





Image 2: Sodars

**Sodars** (Sound Detection and Ranging): simpler and less expensive remote sounding systems operational in lower troposphere, making it well suited for routine operation.



Source: (P. Seibert et al.,2002; Clifford et al.,1994) Image Source: 1(csl.noaa.gov)2 (www.i-igm.net)

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Well, these LIDARS you can use for measurements of the aerosols and trace gases concentration also. So, this is very much considered to provide direct measurement of the mixing height. And then, the SODAR is also very simple, less expensive, remote sounding system and operational in lower troposphere, which can make, very much suited for routine operations in that sense.

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### Types of Remote Sounding Systems (3/3)

**Wind profiling radars:** for direct and continuous measurement of the Mixing Height in deep Convective Boundary Layer.

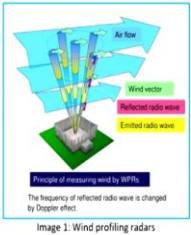


Image 1: Wind profiling radars





Image 2: RASS

**RASS** (Radio-acoustic sounding systems): extensions of either sodars or wind profiling radars, providing virtual potential temperature profiles in addition to wind and acoustic refractive index ( $C_n^2$ ) profiles.



Source: (P. Seibert et al.,2002; Clifford et al.,1994); Image Source: ([1]) Jenn Dias, Wind Profiler Radars (2) www.eol.ucar.edu)

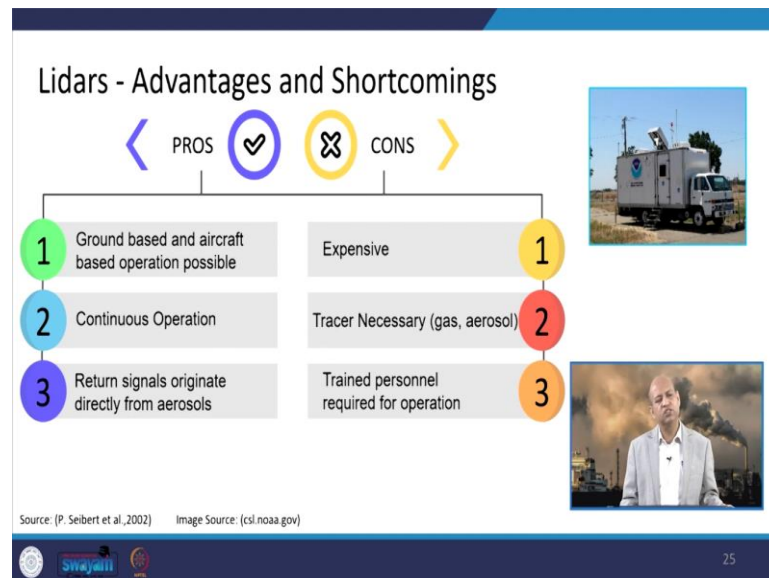
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Then wind profile radars are also there, which are for direct continuous measurements of the mixing height in deep convective boundary layer, otherwise other systems may not give



realistic data. And then when we talk about RASS Radio Acoustic Sounding System so, this is an extension of either SODARs or wind profile and it provides virtual potential temperature provide in addition to the wind and acoustic related these refractive indices profiles.

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So, these are again pros and cons like for LIDARs, then ground based and aircraft based operation possible in case of LIDARs and the continuous operation is also possible then, return signal this originated directly from the aerosols. And but it is expensive the negative part or shortcoming. And the tracer necessary like gas or aerosol, some tracer must be there, because without that, it is difficult, to take those readings and then the trained personnel required for the operation. So, a skilled person is required.

(Refer Slide Time: 18:03)

## Sodars - Advantages and Shortcomings

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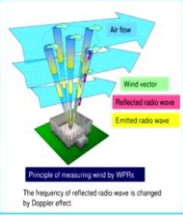
<div style="display: flex; justify-content: space-between;"> <div style="width: 45%;"> <ol style="list-style-type: none"> <li style="margin-bottom: 10px;"><span style="background-color: #90EE90; border-radius: 50%; padding: 2px 5px; display: inline-block; width: 15px; height: 15px; line-height: 15px;">1</span> Relatively simple operation</li> <li style="margin-bottom: 10px;"><span style="background-color: #ADD8E6; border-radius: 50%; padding: 2px 5px; display: inline-block; width: 15px; height: 15px; line-height: 15px;">2</span> Not very expensive</li> <li style="margin-bottom: 10px;"><span style="background-color: #4169E1; border-radius: 50%; padding: 2px 5px; display: inline-block; width: 15px; height: 15px; line-height: 15px;">3</span> Suited for unmanned long-term operation</li> </ol> </div> <div style="width: 45%;"> <ol style="list-style-type: none"> <li style="margin-bottom: 10px;"><span style="background-color: #FFD700; border-radius: 50%; padding: 2px 5px; display: inline-block; width: 15px; height: 15px; line-height: 15px;">1</span> Limited Range (500-1000m)</li> <li style="margin-bottom: 10px;"><span style="background-color: #FF4500; border-radius: 50%; padding: 2px 5px; display: inline-block; width: 15px; height: 15px; line-height: 15px;">2</span> Sensitive to environmental noise</li> </ol> </div> </div>	
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Source: (P. Seibert et al., 2002) Image Source: (www.i-igm.net)


26

## Wind Profiling Radar - Advantages and Shortcomings

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<div style="display: flex; justify-content: space-between;"> <div style="width: 45%;"> <ol style="list-style-type: none"> <li style="margin-bottom: 10px;"><span style="background-color: #90EE90; border-radius: 50%; padding: 2px 5px; display: inline-block; width: 15px; height: 15px; line-height: 15px;">1</span> Ground based and aircraft based operation possible</li> <li style="margin-bottom: 10px;"><span style="background-color: #ADD8E6; border-radius: 50%; padding: 2px 5px; display: inline-block; width: 15px; height: 15px; line-height: 15px;">2</span> Continuous Operation</li> </ol> </div> <div style="width: 45%;"> <ol style="list-style-type: none"> <li style="margin-bottom: 10px;"><span style="background-color: #FFD700; border-radius: 50%; padding: 2px 5px; display: inline-block; width: 15px; height: 15px; line-height: 15px;">1</span> Not suitable below 200m</li> <li style="margin-bottom: 10px;"><span style="background-color: #FF4500; border-radius: 50%; padding: 2px 5px; display: inline-block; width: 15px; height: 15px; line-height: 15px;">2</span> Expensive</li> <li style="margin-bottom: 10px;"><span style="background-color: #FF8C00; border-radius: 50%; padding: 2px 5px; display: inline-block; width: 15px; height: 15px; line-height: 15px;">3</span> Do not work well in clean air</li> </ol> </div> </div>	 <p style="font-size: 0.7em; margin-top: 5px;">Principle of measuring wind by WPRs The frequency of reflected radio wave is changed by Doppler effect.</p>
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Source: (P. Seibert et al., 2002) Image Source: (Jenn Dias, Wind Profiler Radars)


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When we talk about the SODARs. So, the good point is like relatively simple operation, not very expensive and it is suited for even unmanned long term operation automatic operations are also possible, but then the range is limited. So, the shortcoming is like 500 to 1000 metre only this gives the reading good reading and sensitive to the environmental noise, then readings may be disturbed, so, that we have to again process after you know observations.

So, when we talk about wind profiling radar, so again good points like continuous operation is possible, ground based and aircraft-based operation possible. But you know shortcomings are like not stable below 200 metre, only beyond 200 metre, it is good and expensive it does not work well in clean air. So, again there are limitations of this particular issue.

(Refer Slide Time: 18:57)

## Mixing Height Determination from parameterizations and models(1/4)

### Neutral Conditions

- Under neutral conditions, the depth of the mixed layer should be proportional to the **surface friction velocity**  $u_*$  and the **Coriolis parameter**  $f$ ,

$$u_* = \sqrt{\frac{\tau}{\rho}}$$

$$f = 2 \Omega \sin \phi$$

where  $\tau$  is surface stress,  $\rho$  air density,  $\phi$  latitude, and  $\Omega = 7.29 \times 10^{-5} \text{sec}^{-1}$ , the rate of the earth's rotation.

- The thickness can then be estimated as

$$h \approx 0.2 \frac{u_*}{f}$$

Since  $u_*$  increases with wind speed and surface roughness,  $h$  increases with these two parameters as well.



Source: (Karl B. Schnelle, 2003)



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Then when we talk about mixing high determination, so depending upon stability classification neutral condition those kinds of different equations you can use to, these are the empirical relationships which can you use for determination of the mixing height.

(Refer Slide Time: 19:12)

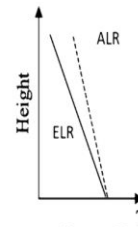
## Mixing Height Determination from parameterizations and models(2/4)

### Unstable Conditions

- During the day, the depth of the mixed layer grows as a function of the surface heat flux  $H$  (heat energy per unit area per unit time). If the initial daytime surface temperature is  $T_0$  and the temperature at time  $t$  is  $T$  after an adiabatic temperature profile has been established, then conservation of heat energy requires:

$$\int_{t_0}^t H dt = \frac{C_p \rho h (T - T_0)}{2}$$

where  $C_p$  is the specific heat of air.



Source: (Karl B. Schnelle, 2003)



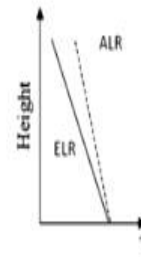
29

## Mixing Height Determination from parameterizations and models(3/4)

- From this we can calculate the depth of the mixed layer noting that the ratio  $\frac{(T-T_0)}{h}$  is equivalent to  $\lambda - dT/dz$  :

$$h = \left[ \frac{2 \int_0^t H dt}{C_p \rho (\lambda - \frac{dT}{dz})} \right]^{1/2}$$

$\lambda$  is dry adiabatic lapse rate.



This equation is a simplified expression which can be affected by atmospheric phenomena that cause the inversion layer to change.



source: (Karl & Schnelle, 2003)

Well, this environmental lapse rate they are used and unstable conditions when we are talking about them another equation or relationship is there. And when we talk about these like calculation of mixing height by parameterization and models, then again there are certain empirical relationships, where these temperature differences is there and gradient of the environmental lapse rate, they all these things are used and dry adiabatic lapse rate is also used for calculation.

(Refer Slide Time: 19:44)

### Mixing Height Determination from parameterizations and models(4/4)

**Stable Conditions**

- The thickness of the lowest continuously mixed turbulent layer can be estimated from

$$h \approx 0.4 \sqrt{\frac{u_*}{f}} L$$

- Monin-Obukhov length,  $L = \frac{\rho C_p T u_*^3}{k g H}$ , where k is the von Karman constant and with upward heat flux H taken as positive.

This equation has had relatively little success in correlating measured values.

Source: [Karl B. Schnelle, 2003]

Similarly, in this case also like strongly stable when so, maximum mixing depth in stable conditions you can get here, see the adiabatic lapse rate is crossing even inversion is there. So, mixing is possible. So, I mean to say like when we talk about inversion, we say that it acts like the cap, but because of this relationship a little bit, it can go inside even inversion layer sometimes. Then maximum mixing depth is calculated in weekly stable atmosphere and this is strongly stable. So, again wherever this intersection is there, so, that kind of mixing depth can be calculated.

(Refer Slide Time: 20:24)

### Critical Assessment of different methods to determine MH

	Continuous Data Output	Range covered well			Determination of turbulence parameters
		10-100 m (low SBL)	100-500m (SBL/CBL)	0.5-3km (CBL)	
<b>In-situ measurements</b>					
Radiosonde	-	-	✓	✓	-
Tethered Balloon	-	✓	✓	-	(✓)
Mast	✓	✓	-	-	✓
<b>Remote Sounding</b>					
Mini-sodar	✓	✓	-	-	✓
Sodar	✓	-	-	-	✓
Radar	✓	-	(✓)	✓	✓
RASS	(✓)	-	(✓)	(✓)	(✓)
Lidar	✓	-	(✓)	✓	✓
<b>Numerical Models</b>	(✓)	(✓)	-	✓	✓
<b>Note:</b>					
	✓	means fulfilled			
	(✓)	partly fulfilled			
	-	not fulfilled			

It clearly appears that none of the systems meets all the requirements. Reliable MH determination under all conditions is therefore still an unsolved problem. The best approach is to use a combination of systems.

MH – Mixing Height  
SBL – Stable Boundary Layer  
CBL – Convective Boundary Layer


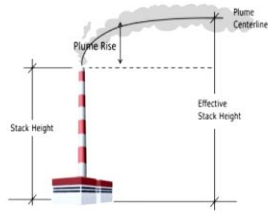
Source: [P. Seibert et al., 2002]

When we talk about critical assessment of different methods to determine mixing height. So, if we go for different methodologies, no single methodology is perfect. So, the combination of different ways we need to go for determining a good assessment.

(Refer Slide Time: 20:40)

### Design of Stack Height (1/2)

- The stack must reach high enough to ensure that the exhaust plume is sufficiently diluted when it reaches sensitive areas downstream (building air intakes, entrances, operable windows, and outdoor plazas)
- The appropriate stack height is a function of:
  - The plume (rise) height for the exhaust system
  - The subsequent dispersion, or concentration levels at downwind location.


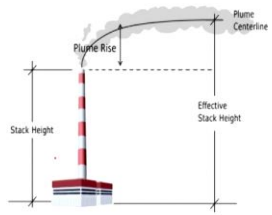


Source: [L. J. DiBerardinis, 2013] Image Source: [https://www.pca.state.mn.us/sites/default/files/aaq\_ppt5-11.pdf]

33

### Design of Stack Height (2/2)

- Stack Design Methods for small or laboratory buildings are:
  - The Geometric Method
  - The Numerical Method
  - Physical Modelling Using the Wind Tunnel or Water Fume



Source: [L. J. DiBerardinis, 2013] Image Source: [https://www.pca.state.mn.us/sites/default/files/aaq\_ppt5-11.pdf]



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When we talk about design of a stack height. So, again there are many empirical relationships to design the stack height like geometric method is there numerical method is there, physical modelling can also be therefore for determining the stack height.

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### Stack Design - Geometric Method(1/3)

- The geometric method is designed for isolated rectangular buildings that do not have taller buildings, dense taller trees, or taller hills close to the stack.
- Also, air intakes on the emitting building shouldn't be higher than the top of the physical exhaust stack opening.



Source: (L. J. DiBerardinis, 2013; Image: <https://www.em-solutions.co.uk/services/stack-emission-monitoring/>)

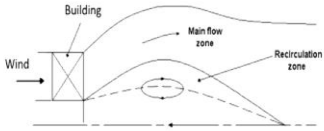
35

So, you can see like geometric method has certain parameters for isolated rectangular buildings that do not have taller buildings or dense taller trees, those kinds of conditions we have to see before calculation.


(Refer Slide Time: 21:12)

### Stack Design - Geometric Method(2/3)

- Calculate the length of the recirculation zone (R) downwind of the building for each of the four basic approach wind directions.

$$R = (B_{small})^{0.67} (B_{large})^{0.33}$$


- where  $B_{small}$  is the smaller of the building height and width, and  $B_{large}$  is the larger of the two. As used here, the recirculation zone height is the height of the emitting building.



Source: (L. J. DiBerardinis, 2013)

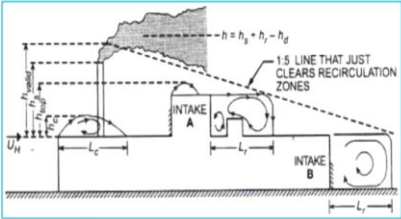
36

So, these are the you know relationships which gives us the particular parameters which are used for designing the stack.

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### Stack Design - Geometric Method(3/3)

- The geometric method, specifies that the bottom of an exhaust plume should clear the emitting building, including penthouses, and the recirculation zone downwind of the building.
- The bottom of the plume extends downward at a 5 : 1 slope (5 units horizontal and 1 unit downward) from the effective stack height (physical height plus added plume rise).
- This should be done for all four of the basic approach wind directions.



Source: (L. J. DiBerardinis, 2013) Image Source: (<http://www.irsst.qc.ca/media/documents/pubirsst/R-392-Chap-1-2-3.pdf>)

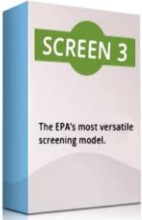
37

So, you can see here you know this plume is going this side so, the bottom of the plume extend downwind like 5 to 1, 5 horizontal 1 vertical. So, we have to take care that this should not come into the height where wind is intake in the buildings, the wind is going inside the buildings or some wave formation is there that is should be avoided. So, those things are to be observed and it should be ensured that the height of the stack must be sufficient so that plume does not come in this particular range.

(Refer Slide Time: 21:52)

### Stack Design – Numerical Method

- Applicable if air intakes is below the stack top.
- Adopted if the stack heights or flowrates are too large for the geometric method.
- It also accounts for dilution within the plumes.
- The EPA screening dispersion model, SCREEN3 can be used.



Source: (L. J. DiBerardinis, 2013) Image Source: (<https://www.providencecoris.com/product/screen3-for-windows/>)

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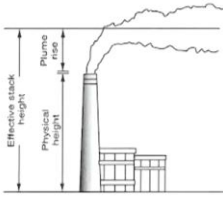
When we talk about numerical methods. So, you see different models are also available like EPA has designed one SCREEN3 model which can give the stack height related calculations.



(Refer Slide Time: 22:05)

### Stack Design – Physical Modelling using Wind Tunnel or Water Fume

- Adopted if the above two methods can't determine the stack height.
- It provides **more accurate**, and typically less conservative, predictions than the numerical or geometric methods.
- It is the **safest method** to determine stack heights in new buildings or in buildings being retrofitted.



Source: (L. J. DiBerardinis, 2013; Image: Guevara et al., 2014)


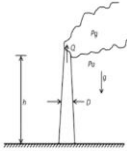
39

You can see here stack design based on physical modelling for by using wind tunnel or water fume. So, that is very accurate kind of method, but again it requires a lot of skilled manpower and some infrastructure which is very kind of sophisticated. So, that we also you can calculate by studying in those models.

(Refer Slide Time: 22:28)

### Design of Stack Height – CPCB Recommendation(1/5)

- For Chimney emitting **particulate matter(PM)**  
$$h = 74 (Q_p)^{0.27}$$
  
• h = height of chimney in meters  
•  $Q_p$  = particulate matter emission (tones/hr.)
- For Chimney emitting **SO<sub>2</sub>**  
$$h = 14 (Q_s)^{1/3}$$
  
• h = height of chimney in meters  
•  $Q_s$  = SO<sub>2</sub> emission (kg/hr.)



Source: (A method to determine the minimum stack height, CPCB, 1984-85)


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Then there are some empirical relationships like you can have this for particulate matter, central pollution control board is it recommended certain heights, similarly SO<sub>2</sub> related some estimated height can be taken from this particular relationship. So, these are empirical relationships, you calculate and then you take the maximum one.

(Refer Slide Time: 22:49)

### Design of Stack Height – CPCB Recommendation(2/5)

- **Minimum Values**
- The Board has further recommended that the height of the chimney calculated based on particulate matter and  $SO_2$  emissions by the above two equations should be subjected to the following minimum values:
  - For chimney adopted for industries in general (except thermal power plants) – 30m
  - For thermal power plants above 200MW and below 500MW capacity – 220m
  - For thermal power plants having greater than 500MW capacity – 275m



Source: (A method to determine the minimum stack height, CPCB, 1984-85)


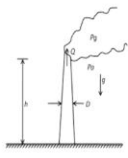
41

And then the minimum values are also recommended that whatever calculation is there it should not be less than 30 metre in case of this chimney which is in industries accepting thermal power plants, for thermal power plants depending upon their capacity they have recommended like 220 or 275 whether this you know power plant is of 200 megawatt and below 500 megawatt and then beyond 500 megawatt this is the height minimum height that should be taken.

(Refer Slide Time: 23:17)

### Design of Stack Height – CPCB Recommendation(3/5)

- **E.g.:** An Industry utilizes 0.3 ML (Million Liters) of oil fuel per month. It has also been estimated that for every 1 ML of fuel oil burnt in the factory, per year, the quantities of various pollutants emitted are given as:
  - Particulate Matter = 2.9 t/yr.
  - $SO_2$  = 60 t/yr.
  - $NO_x$  = 8 t/yr.
  - HC = 0.4 t/yr.
  - CO = 0.5 t/yr.
- Calculate the height of the chimney required to be provided for safe dispersion of the pollutants.



Source: (S. K. Garg, 2012)

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So, when we go for an example like there are certain input parameters, you take those equations and these values you can use,  $SO_2$  say particulate matter etc.

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### Design of Stack Height – CPCB Recommendation(4/5)

- **Sol: For Particulate Matter emission,**
- Chimney height,  $h = 74 (Q_p)^{0.27}$
- Where,  $Q_p$  is emission of particulate matter in t/hr.
- In given case, the particulate matter emission = 2.9 t/yr./ML of fuel burnt =  $2.9 \times (12 \times 0.3) \text{ t/yr.} = 10.44 \text{ t/yr}$
- Assuming 300 working days in the yr. with 24 hr. working
- $Q_p = \frac{10.44}{300 \times 24} \text{ t/hr.} = 1.45 \times 10^{-3} \text{ t/yr.}$
- Chimney height,  $h = 74 (1.45 \times 10^{-3})^{0.27} \text{ m} = 12.67 \text{ m}$
- **For  $SO_2$  emission,**
- Chimney height,  $h = 14 (Q_s)^{1/3}$
- Where,  $Q_s$  is emission of  $SO_2$  in kg/hr.

Source: [S. K. Garg, 2012]



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And you put in those equations values and you get calculations like for particulate matter the calculation is coming around 13 metre.

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### Design of Stack Height – CPCB Recommendation(5/5)

- $SO_2$  emission = 60 t/yr./ML of oil burnt =  $\frac{60 \times 1000}{300 \times 24} \text{ kg/hr./ML}$  of oil =  $\frac{60 \times 1000}{300 \times 24} \times (12 \times 0.3) \text{ kg/hr.} = 30 \text{ kg/hr.}$
- Chimney height,  $h = 14 (30)^{1/3} \text{ m} = 43.45 \text{ m; say } 43.5 \text{ m}$
- So, chimney height,
  - $h = 12.67 \text{ m}$  (as per PM requirement)
  - $h = 43.5 \text{ m}$  (as per  $SO_2$  requirement)
  - $h = 30 \text{ m}$  (as per minimum CPCB recommendation)
- Hence chimney height adopted is **maximum of all i.e., 43.5m**

Source: [S. K. Garg, 2012]

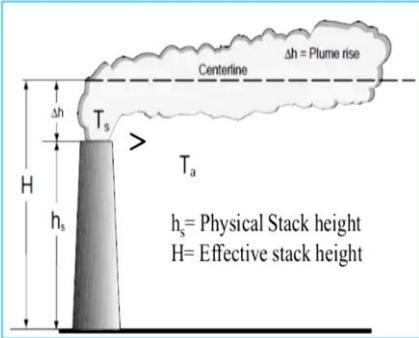


44

For  $SO_2$  is coming around you know this 43.5 or 44 metre. So, you go for the maximum one out of this because this recommended minimum value is also lower than 43.5 it is 30 metre. So, these three values are there and you go for the maximum one.

(Refer Slide Time: 23:57)

### Plume Rise(1/2)



Plume rise ( $\Delta h$ ) is usually defined as the height above the stack orifice that the plume centerline rises due to the momentum and buoyancy of the stack gases.

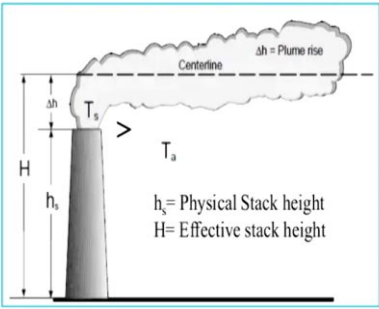
Effective Stack Height(H) =  
Chimney Height( $h_s$ ) + plume rise( $\Delta h$ )

$h_s$  = Physical Stack height  
 $H$  = Effective stack height

Source: (James E. Carson & Harry Moses, 1969) Image Source: (Dr. Shrikant Jahagirdar, AIR POLLUTION CONTROL)

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### Plume Rise(2/2)



Three sets of parameters control the behavior of a smoke plume.

- stack engineering factors (shape and size of stack, height of stack etc.)
- meteorological conditions (ambient temp., wind speed etc.)
- the nature of the effluent itself (temp. of plume)

$h_s$  = Physical Stack height  
 $H$  = Effective stack height

Source: (James E. Carson & Harry Moses, 1969) Image Source: (Dr. Shrikant Jahagirdar, AIR POLLUTION CONTROL)

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When we talk about plume rise because we discussed earlier also like plume rises because of you know momentum and the buoyancy, because of temperature difference, momentum because of exhaust velocity. So, these two components really helped us to get the plume rise. And plume rise this delta h is added into physical stack height to calculate the effective stack height which is used in model calculations when we go for dispersion models etc.

(Refer Slide Time: 24:25)

### Estimation of Plume Rise (1/2)

**Holland's Equation** (valid for Neutral Condition)

- $\Delta h = \frac{v_s D}{u} \left[ 1.5 + 2.68 \times 10^{-3} P D \left( \frac{T_s - T_a}{T_s} \right) \right]$


**Davidson and Bryant Equation** (valid for Neutral Condition)

- $\Delta h = D \left( \frac{v_s}{u} \right)^{1.4} \left( 1 + \frac{T_s - T_a}{T_s} \right)$

Where,

- $\Delta h$  = plume rise above stack(m)
- $v_s$  = plume exit velocity from stack(m/s)
- $D$  = inside exit stack diameter(m)
- $u$  = wind speed at top of stack(m/s)
- $P$  = atmospheric pressure(milli-bars)
- $T_s$  = stack gas temperature(K)
- $T_a$  = air temperature(K)

- For **unstable condition**,  $\Delta h$  = increase by 10 – 20 %
- For **stable condition**,  $\Delta h$  = decrease by 10 – 20 %



Source: (S. K. Garg, 2012) Image Source: (Dr. Shrikant Jahagirdar, AIR POLLUTION CONTROL)

So, you can see here like these are the empirical equations recommended by different researchers like Holland's equation is there. So, they are taking into account this momentum the velocity and the temperature different that is the buoyancy part. So, different combinations are there and different combinations are because of those conditions only unstable condition, stable conditions these are the parameters you can see which are given in these equations.

(Refer Slide Time: 24:52)

### Estimation of Plume Rise (2/2)

- Alternatively,  $\Delta h = \Delta h$  momentum +  $\Delta h$  buoyancy
- Empirical Formula of Moses and Carson,**
- $\Delta h = C_1 \frac{v_s d}{u} + C_2 \frac{Q_h^{1/2}}{u}$


Where,

- $C_1, C_2$  is plume rise regression coefficient, depends on atmospheric stability (neutral, unstable, stable)
- $\Delta h$  is plume rise(m)
- $v_s$  is Stack exit Velocity(m/s)
- $u$  is speed of wind(m/s)
- $d$  is stack diameter(m)
- $Q_h$  is heat emission rate(kcal/s)

$$\Delta h = C_1 \frac{v_s d}{u} + C_2 \frac{Q_h^{1/2}}{u}$$

Vertical momentum of gas leaving the stack      Buoyancy force of the plume because of heat content

	$C_1$	$C_2$
Stable	-1.04	4.58
Unstable	3.47	10.53
Neutral	0.35	5.41



Source: (M. N. Rao, H. V. N. Rao, 2007; James E. Carson & Harry Moses, 1969)

Then when we talk about like empirical relationship which is given by Moses or Carson. So, momentum and buoyancy factor as I said. This is the momentum related, this is the bouncy

related, these are the different nomenclatures of those parameters which are used for calculation purpose.

(Refer Slide Time: 25:08)

### Estimation of Plume Rise – BIS Suggestion(1/2)


As per BIS (Bureau of Indian Standards) (IS: 8829 - 1978) suggestion, the following Brigg's formula is used.

**A. For hot effluents with heat release of the order of  $10^6$  Cal/s or more**

➤  $\Delta h = 0.84(12.4 + 0.09h) \frac{Q_h^{1/4}}{u}$

Where,

- $\Delta h$  is plume rise(m)
- $Q_h$  is heat emission rate(Cal/s)
- $u$  is speed of wind(m/s)
- $h$  is height of chimney(m)



Source: (S. K. Garg, 2012)

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This Bureau of Indian Standards this recommended the BIS formula for estimating plume rise which is quite popular. So, again this Q part energy part or heat emission this takes care of the buoyancy. So, delta is calculated by this particular formula u is the, this wind speed h is the height of the chimney. So, according to that this plume rise can be calculated.

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### Estimation of Plume Rise – BIS Suggestion(2/2)

**B. For not very hot releases, and which can be counted as momentum sources above**

➤  $\Delta h = \frac{3v_s D}{u}$

Where,

- $\Delta h$  is plume rise(m)
- $v_s$  is stack gas velocity(m/s)
- $u$  is speed of wind(m/s)
- $D$  is inside exit dia. of stack(m)



Source: (S. K. Garg, 2012)

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Then for hot releases then this is the relationship which is by this velocity of the exhaust emissions. So, these are two parts basically A part is heat release related that is the buoyancy

related and this is because of momentum related wind speed is  $u$  but this is the  $V_s$ , is the exhaust velocity that is taken into account for momentum calculations.


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### Estimation of Plume Rise

- **E.g.:** Determine the effective height of a stack, with the following given data:
  - (a) Physical stack is 180m tall with 0.95m inside diameter.
  - (b) Wind velocity is 2.75 m/s
  - (c) Air temperature is 20°C
  - (d) Barometric pressure is 1000 millibars
  - (e) Stack gas velocity is 11.12 m/s
  - (f) Stack gas temperature is 160°C

**Sol.:** Using Holland's Equation

- $\Delta h = \frac{v_s d}{u} \left[ 1.5 + 2.68 * 10^{-3} PD \left( \frac{T_s - T_a}{T_s} \right) \right]$
- $\Delta h = \frac{11.12 * 0.95}{2.75} \left[ 1.5 + 2.68 * 10^{-3} * 1000 * 0.95 * \left( \frac{433 - 293}{433} \right) \right]$
- $\Delta h = 8.92\text{m}$
- Effective Stack height,  $H = h + \Delta h = 180 + 8.92 = 188.92\text{m}$



Source: (S. K. Garg, 2012)


This numerical example is given for practice purpose. So, you can use these empirical relationships you can calculate the plume rise and see which is the maximum one which is the minimum one, why they are coming that way you can go for those simple calculations.

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### Plume Rise: Additional Empirical Equations (1/4)

- **The Stümke Formula**
- $\Delta h = \frac{1}{u} \left[ 1.5 V_s d + 65 d^{3/2} \left( \frac{T_a - T_s}{T_s} \right)^{1/4} \right]$

- $\Delta h$  = plume rise
- $V_s$  = plume exit velocity from stack, m/s
- $d$  = stack diameter, m
- $Q_h$  = heat emission rate, kJ/sec
- $u$  = mean wind speed at top of stack, m/s
- $T_a$  = air temperature, °K
- $T_s$  = stack gas temperature, °K



Source: (James E. Carson & Harry Moses, 1969)

## Plume Rise: Additional Empirical Equations (2/4)

### The Concawe Formula

- $\Delta h = \left[ K \frac{Q_h^x}{u^y} \right]$ , where
- $K, x, y$  were determined empirically by regression techniques, the resulting equation is
- $\Delta h = \left[ 2.58 \frac{Q_h^{0.58}}{u^{0.70}} \right]$

### The Concawe Simplified

- $\Delta h = \left[ K \frac{Q_h^{1/2}}{u^{3/4}} \right]$ , where
- The value of  $K$ , derived from regression techniques, was 5.53 (Brummage, et al.)



Source: (James E. Carson & Harry Moses, 1969)



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Then there are additional empirical relationships by different researchers depending upon what is the stability classification, temperature difference those kinds of things are there.

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## Plume Rise: Additional Empirical Equations (3/4)

### The Lucas-Moore-Spurr Formula

- Neutral condition and modified from Concawe Simplified formula

$$\Delta h = \left[ 135 \frac{Q_h^{1/4}}{u} \right]$$

### The Rauch Formula

$$\Delta h = \left[ 47.2 \frac{Q_h^{1/4}}{u} \right]$$

### The Stone-Clarke Formula

$$\Delta h = \left[ (104.2 + 0.171H_s) \frac{Q_h^{1/4}}{u} \right]$$

- $u$  = mean wind speed at top of stack, m/s
- $u = u_0 \left( \frac{z}{z_0} \right)^p$ , where
- $u$  = speed of wind at height  $z$
- $u_0$  = speed of wind at height  $z_0$
- $p = 1/7$  for normal lapse rate
- $= 1/9$  for large lapse rate
- $= 1/3$  for inversion



Source: (James E. Carson & Harry Moses, 1969)



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So, many researchers have recommended different you know formula or equations for calculating plume rise in different conditions.



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### Plume Rise: Additional Empirical Equations (4/4)

- The Briggs Transitional Case**
  - $\Delta h = \left[ \frac{F^{1/3} L^{2/3}}{u} \right]$ , where
  - F is the buoyancy flux ( $=0.038 Q_h$ )
  - L is the distance downwind from the stack
- Briggs Neutral Windy Formula**
  - $\Delta h = \left[ 400 \frac{F}{u^3} \right]$
- Briggs Windy Stable Formula**
  - $\Delta h = \left[ 2.6 \left( \frac{F}{uS} \right)^{1/3} \right]$
  - S is Stability Parameter
- Csanady Formula**
  - $\Delta h = \left[ 250 \frac{F}{u^3} \right]$



Source: (James E. Carson & Harry Moses, 1969)


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Well, you can see here delta h is being calculated by buoyancy factor or momentum.

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### Conclusions

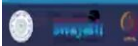
- The more is the mixing height the more is the dispersion and thus dilution of pollutant in the atmosphere.
- Remote Sounding Systems are the preferred methods for the determination of the Mixing Height.
- Of the three methods for the design of stack height, Physical Modelling may give the most accurate results, however appropriate mathematical models can also be used.
- Apart from BIS recommended plume rise calculation, Holland's Equation is frequently used.



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So, in conclusion, we can say that this this mixing height when it is more than more volume is available for dispersion and for dilution of the pollutants and remote sounding systems are preferred methods for determination of the mixing height they give good realistic values. When we talk about like different three methods for the design of the stack height, then physical modelling may give a more accurate result, but it has limitations as I said infrastructure is needed for that all those, but there are mathematical models also we they can also give some values and we can choose out of those different recommended values.

Then, if we talk about like BIS recommended plume rise calculations, then Holland's equation is also popular. And these Briggs formula recommended by BIS is also very much popular. So, this is all for today and these are the references for additional information. So, thank you for your kind attention. See you in the next lecture. Thanks.