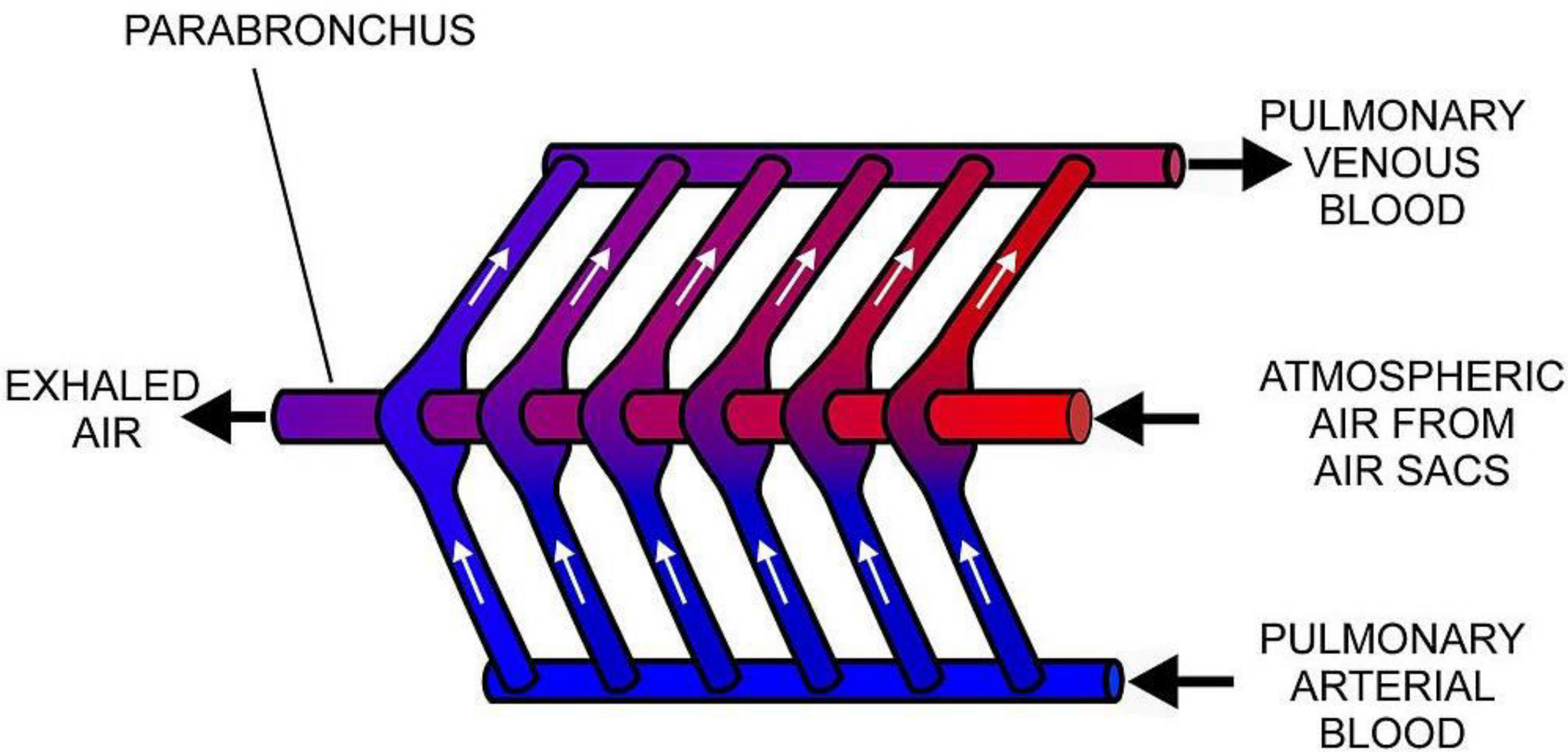
Module-3B: Power Plant Draft system



https://en.wikipedia.org/wiki/Respiratory_system

Estimation of amount of air/gases to be handled in a 500 MW coal power plant

- Coal consumption ≈ **0.5 kg/kWh** (for a very high quality coal)
- For 500 MW, amount of **coal to be burned** ≈ 0.5 x 500 x 1000 = 2,50,000 kg/h ≈ **69.5 kg/s**
- Amount of air required ≈ 69.5 x 12 ≈ 834 kg/s (assuming excellent combustion) ≈ 750 m^3/s ≈ **7,50,000 l/s**!
- This **huge amount of air/gases** has to **flow** through a **different types of components** overcoming resistance to flow and **finally be dispersed** in the environment in a safe way so that **it is sufficiently diluted** before it mixes with air that is breathed by the living beings!
- The system whose job is to ensure the above is called as the **Draft System**

The Draft System

- In **fossil fuel** based power plants, a **draft system (also called as draught system)** is used to:

1. **supply** the **required quantity of air for combustion,** and
2. **remove** the **products of combustion** from the combustion chamber and **discharge** it **into the atmosphere**

- The **draft system** has to **generate** a pressure rise (ΔP_{rise}) that **matches** with the pressure drop (ΔP_{drop}) as air and flue gases flow through the system beginning with preheater and ending with the chimney outlet
- The **draft system of a power plant** may be likened to **the respiratory system of a living being!**

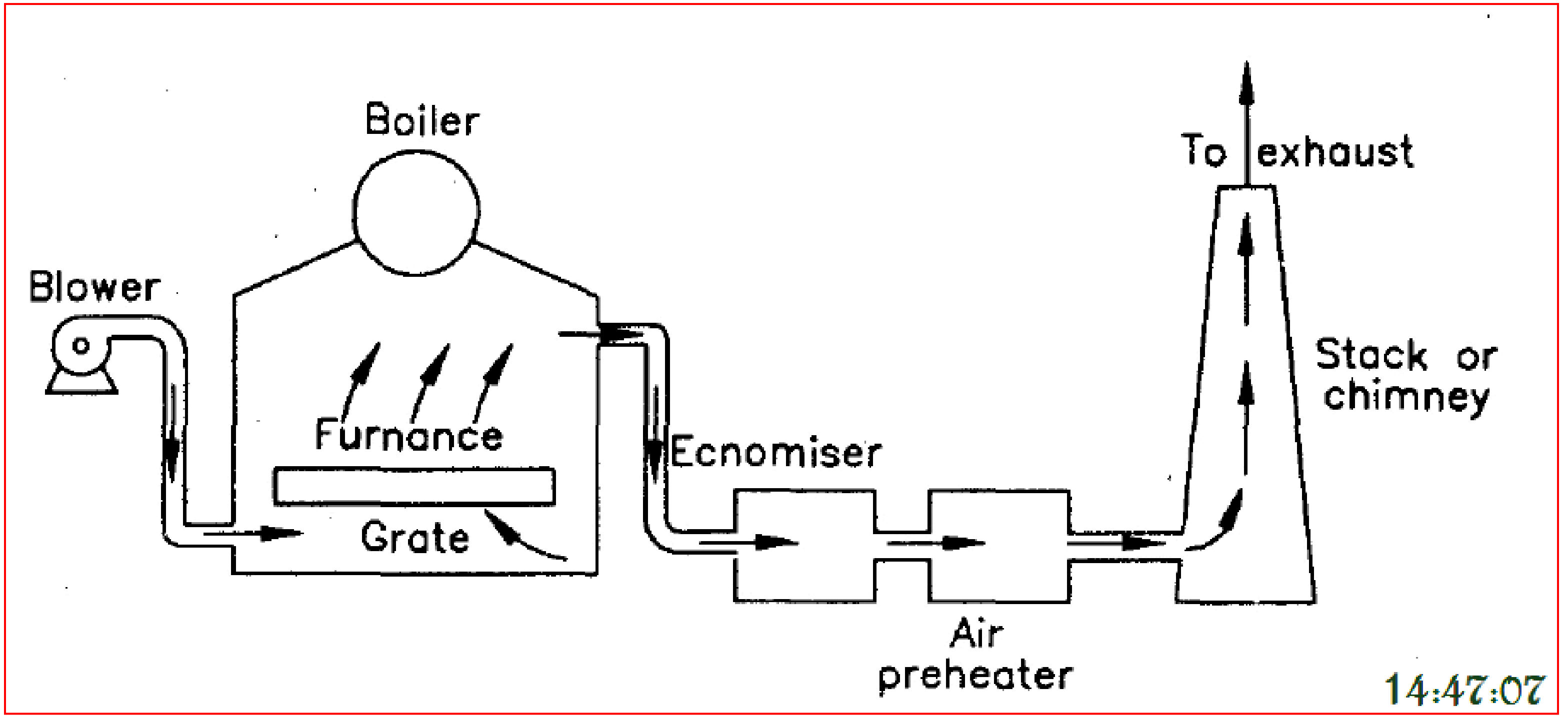
The Draft System (contd.)

- The **draft system** used in power plants can be **classified into**:

1. **Natural draft**, in which the **buoyancy effect** produced by the stack or **chimney** moves air and flue gases
2. **Mechanical draft**, a **fan** or **fans** move air and flue gases. Final dispersion is from a chimney

- **Older plants** with lower capacities and **fewer components** relied on **natural draft only**
- However, all **moderns plants** with high rates of combustion and **large number of components** invariably use **mechanical draft**
  - Mechanical draft systems also **utilize partly** the **buoyancy** effect of the chimney

Typical power plant draft system

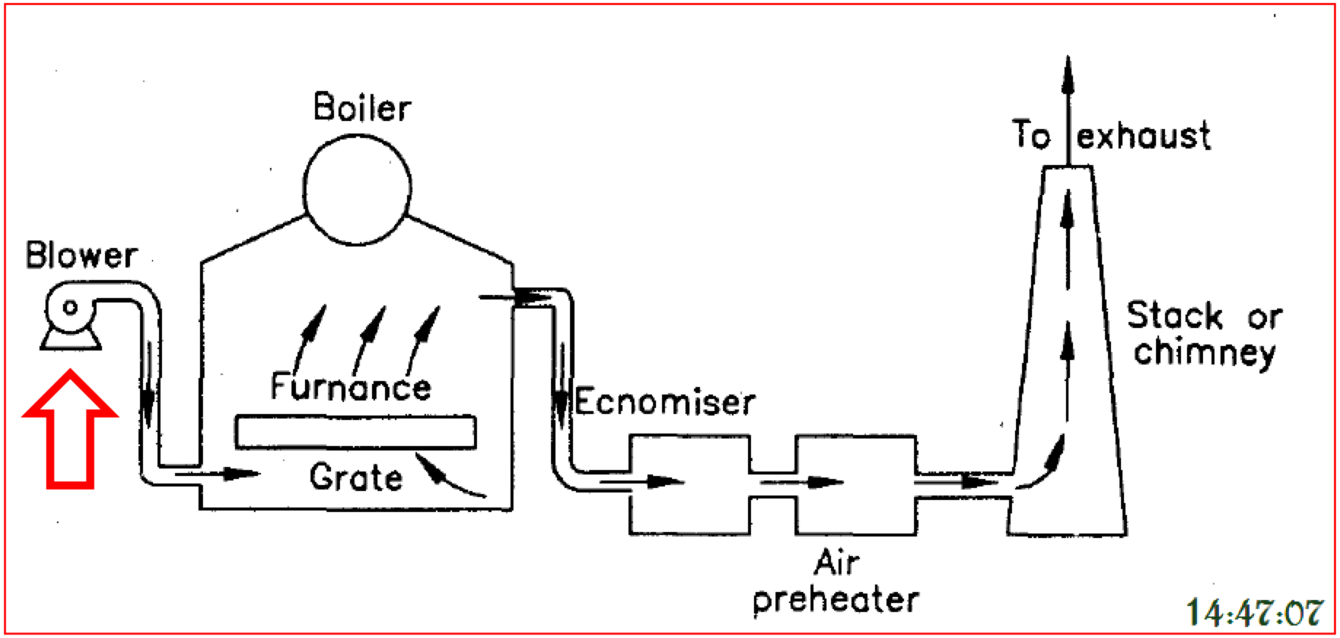


The **combined pressure rise** produced by the **mechanical blower/fan** and the buoyancy driven **chimney** must overcome the **resistance offered** by:

1. Furnace bed
2. Boiler tubes
3. Economizer
4. Air preheater, and
5. All connections, dampers, bends etc

The mechanical draft can be classified into:

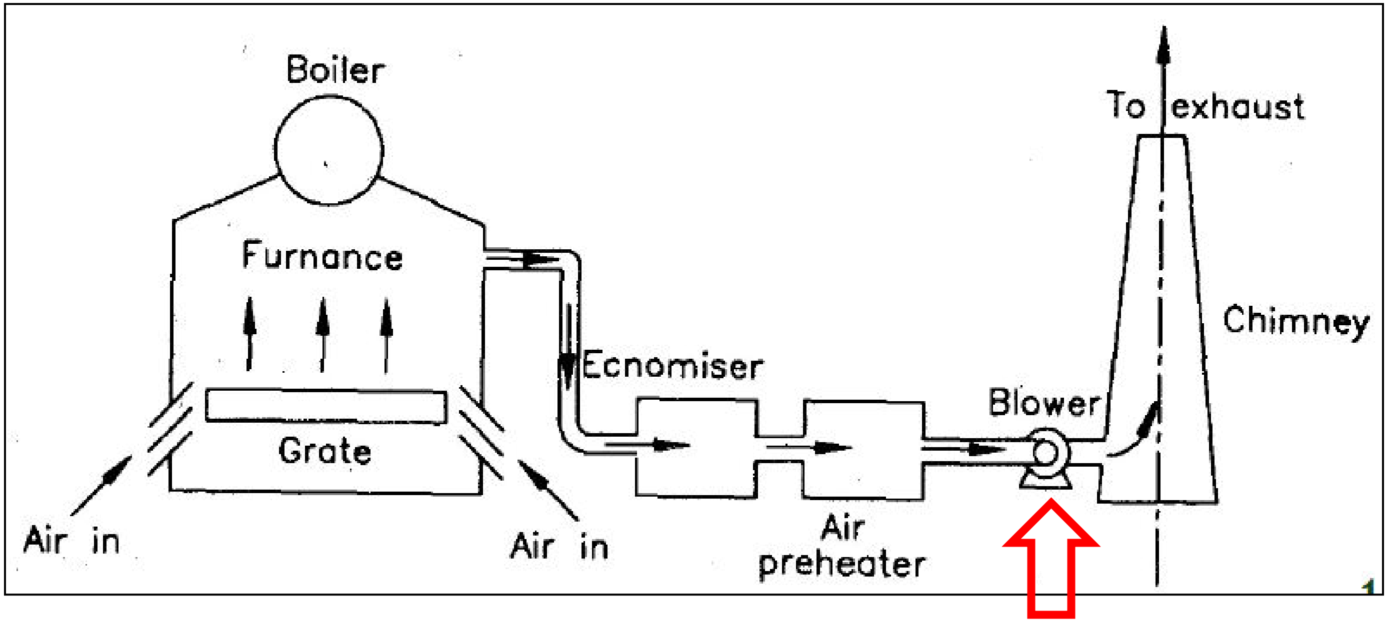
1. Forced draft (F-D)



Forced Draft System:

1. Combustion chamber is at **positive pressure**
   1. Outward structural load on the furnace walls
   2. **Leakage of furnace gases into atmosphere**
2. As the **fan handles cold air** – **it is more efficient and long lasting**

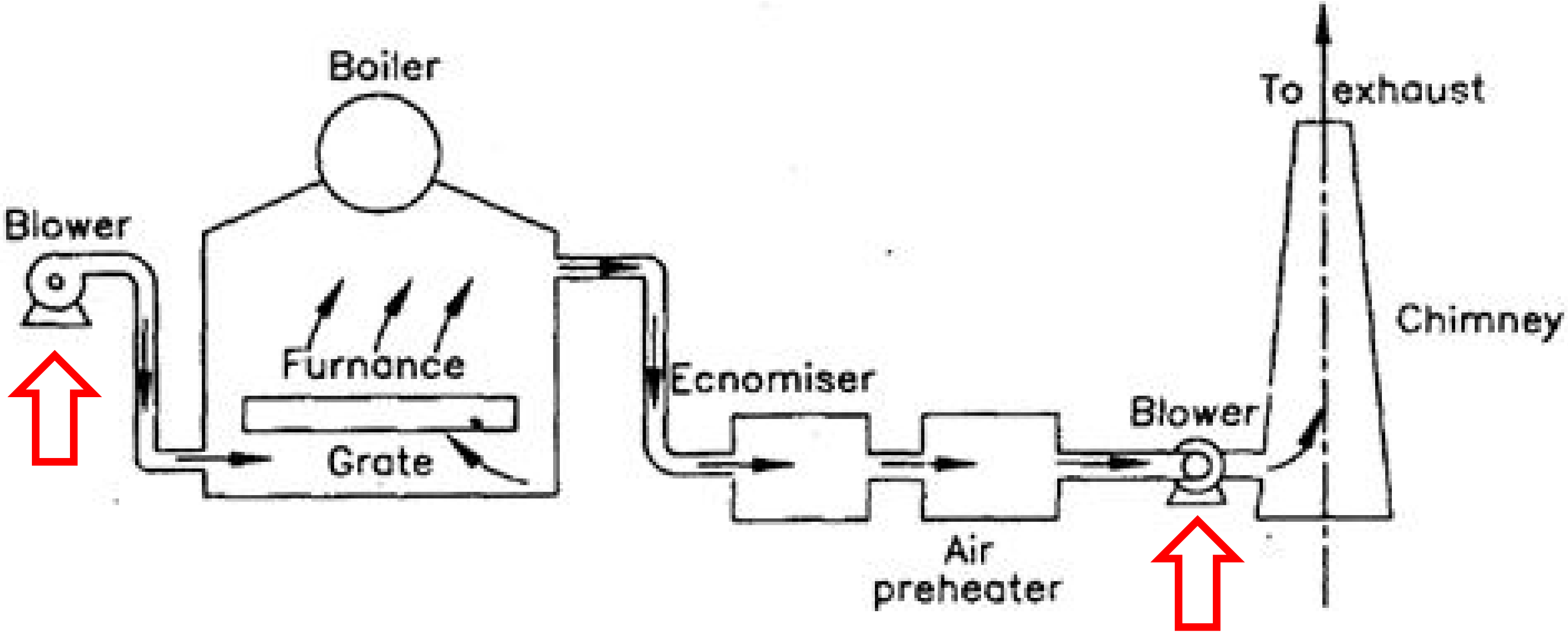
2. Induced draft (I-D)



Induced Draft System:

1. Combustion chamber is under **negative pressure**
    1. **Inward structural load on the furnace walls**
    2. Leakage of atmospheric air into furnace
2. As the fan handles hot products of combustion – shorter life & higher power input - Normally **placed after Electro Static Precipitator** (ESP) to minimize handling of solid particles

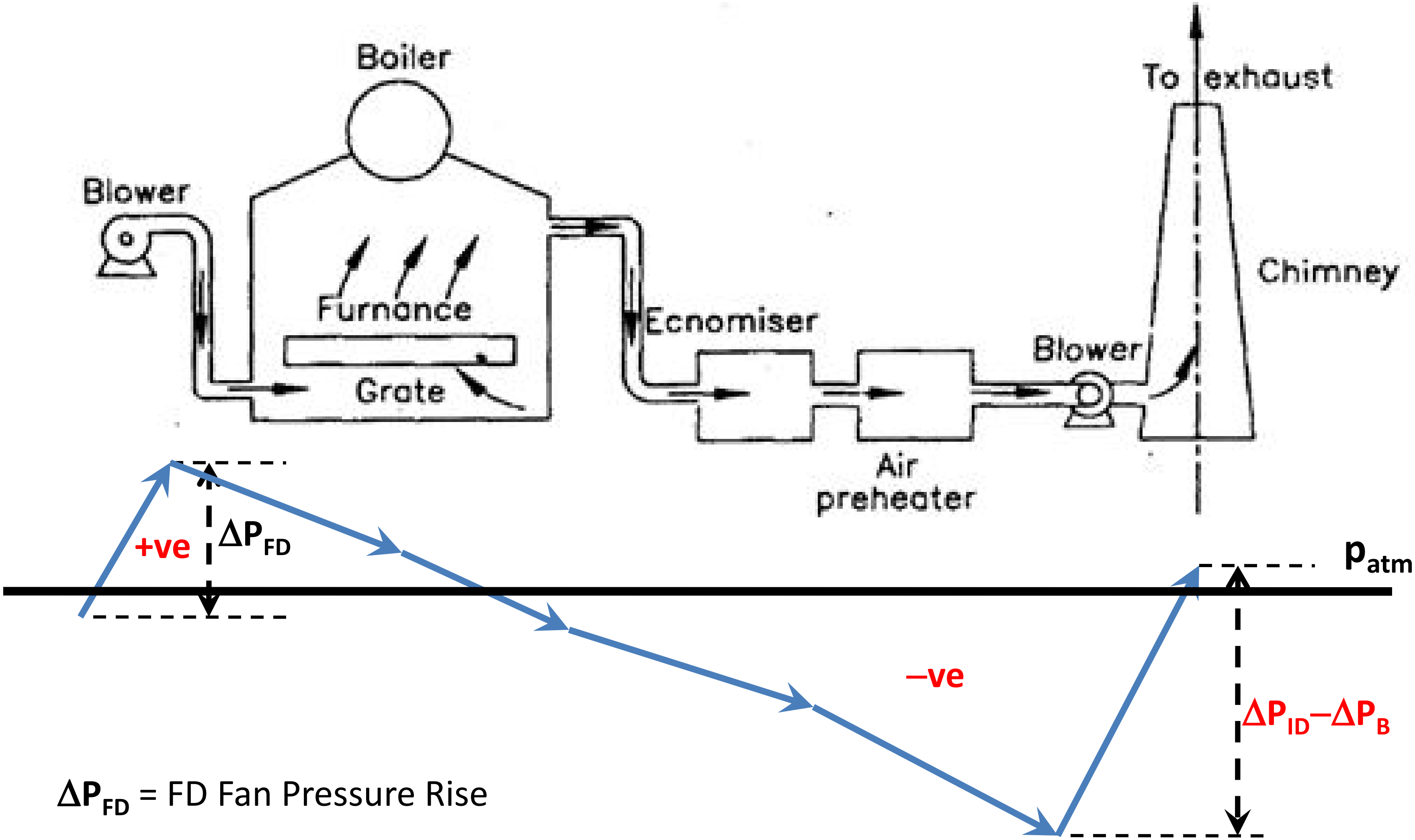
3. Balanced draft (F-D + I-D)



1. **F-D fan pushes air** into the furnace through air pre-heaters, dampers etc
2. **I-D fan pulls the air** from the furnace through the superheaters, reheaters etc.
3. **Furnace** is maintained essentially at **atmospheric or slightly negative pressure**

- **Most commonly used in large power plants**

3. Pressure variation in balanced draft (F-D + I-D)

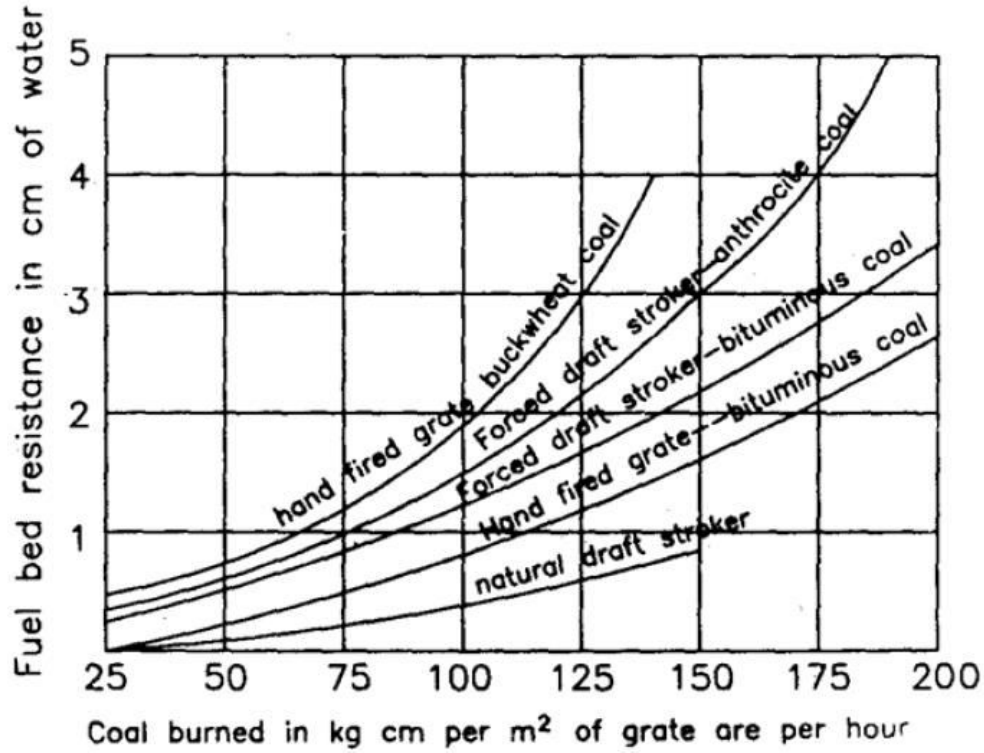


ΔP_{FD} = FD Fan Pressure Rise

ΔP_{ID} = ID Fan Pressure Rise

ΔP_B = Pressure Rise due to Buoyancy

- Large number of **correlations**, **tables**, **charts** etc. are developed to estimate the pressure loss through **heat exchangers**, **furnaces**, **ash handling units** etc.
- **Estimation of pressure losses** is a must in the proper selection of blower/fan and in the design of the chimney (or stack)



Typical Pressure drop in ash collectors			
Type	Velocity of air	Collection efficiency	Pressure drop
Cyclone	15 to 20 m/s	70 to 90 %	500 to 1000 Pa
ESP	1 to 2 m/s	99 %	100 to 200 Pa

Fan Power Consumption

Forced Draft (FD) Fan:

$$W_{FD} = \frac{m_a \Delta P_{FD}}{\rho_a \eta_{FD}} = \frac{m_f \left(\frac{A}{F}\right) \Delta P_{FD}}{\rho_a \eta_{FD}}$$

Induced Draft (ID) Fan:

$$W_{ID} = \frac{m_f \left(1 + \frac{A}{F}\right) \Delta P_{ID}}{\rho_{fg} \eta_{ID}}$$

- m_a = mass flow rate of air, kg/s
- m_f = mass flow rate of fuel, kg/s
- A/F = Air-to-Fuel ratio, kg of air/kg of fuel
- ρ_a = density of air, kg/m^3
- ρ_{fg} = density of flue gases, kg/m^3
- η_{FD}, η_{ID} = Efficiency of FD and ID fans, respectively

Example 1

- A **600 MW** power plant with a thermal efficiency of **40 %** (based on HHV), uses a forced draft (**FD**) fan. The fan has to generate a pressure head of **250 mm WG** to overcome the resistance offered by the steam generator. Air enters the FD fan at **101 kPa** & **30°C**. The FD fan has an **efficiency** of **75 %**. Find the power input to the FD fan, if combustion takes place with **30 % excess air**. The chemical formula of coal is: $CH_{0.808}N_{0.013}S_{0.013}O_{0.057}$. Use Dulong formula for estimating HHV of coal.

HHV (in kJ/kg) = 33960(C) + 144212(H – O/8) + 9420(S)

Ans.: 1621 kW

Example 2

- For the power plant described in **Example 1**; what will be the power consumption, if instead of using a single FD fan, a **balanced draft with an FD fan and an ID fan are used**. Assume that **the pressure rise is equal across the fans**, and the **efficiency of ID fan** is **65%**. The **temperature of flue gases** at the inlet to the ID fan is **180^oC**. Assume that the gas constant of flue gases is approximately same as that of air.

Ans.: W_{FD} = 810.5 kW, W_{ID} = 1500 kW & W_{total} = 2310.5 kW

Power plant stacks

The role of stack in power plants

- The **fly ash** in the products of combustion is **removed** effectively by **mechanical collectors** and **electrostatic precipitators**
- The gaseous products of combustion (**flue gases**) have to be taken care by **suitably designed chimneys**
- In power plants **a few tall and wide chimneys** (stacks) are installed to take the flue gases as high into the atmosphere as possible
- The **required stack height** is **guided** mainly by the control of **air pollution** near the ground level
- However, reverse flow of flue gases towards the ground, called as **downwash** may occur when the wind velocity is high
- Due to downwash, the products of combustion may reenter into the power plant!
- A **minimum chimney height** is required to **minimize downwash**

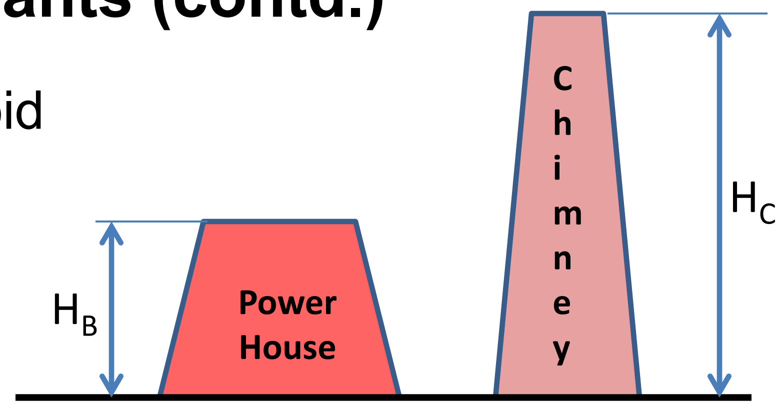
The role of stack in power plants (contd.)

- A general thumb rule to avoid downwash is:

$$H_C \geq 2.5\ H_B$$

- **Other considerations are**:

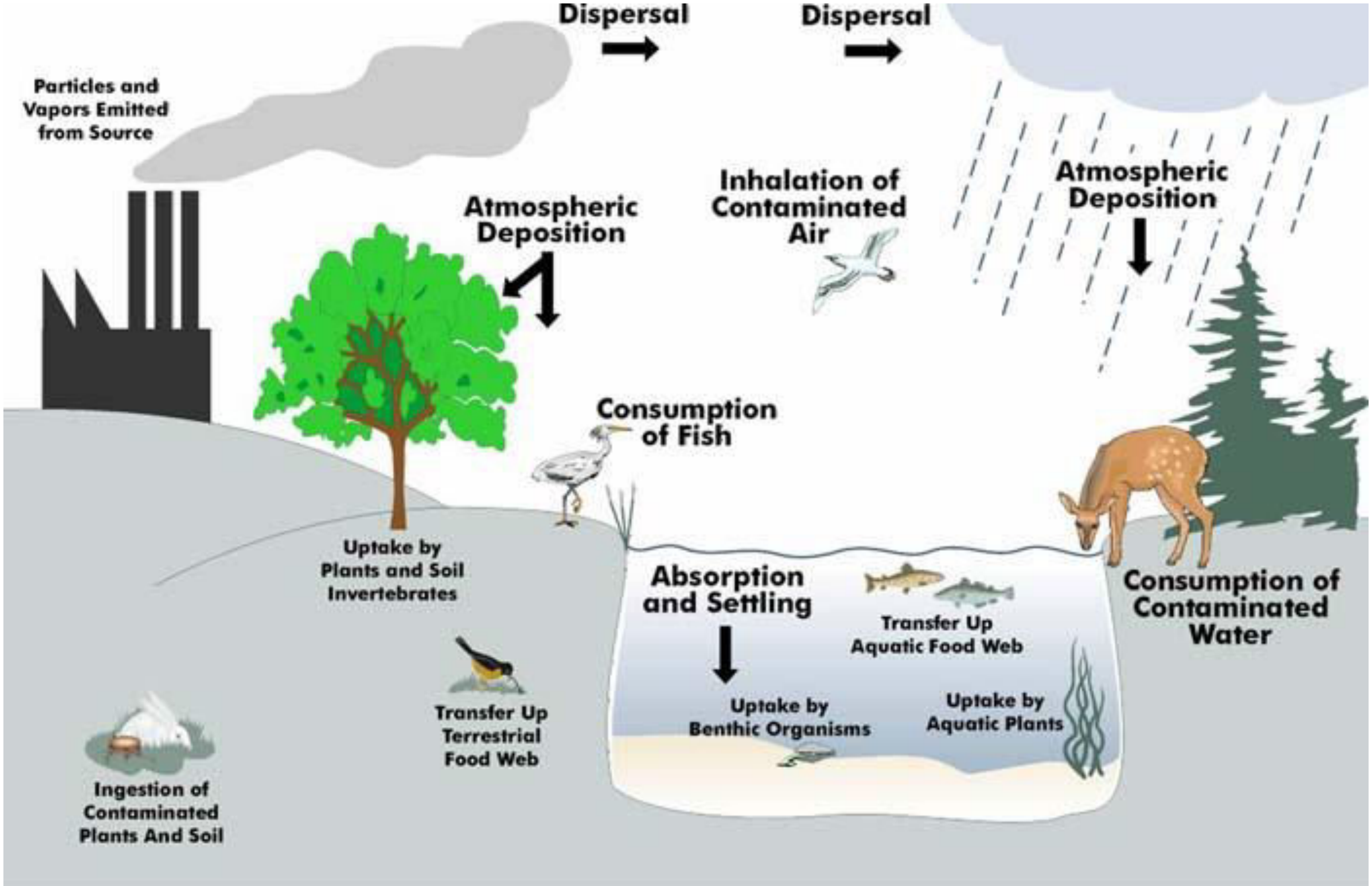
1. Number and separation of stacks
2. Heat and SO_2 emission rates
3. Population density around the plant
4. Topography and terrain
5. General and micrometerology
6. Surrounding land use and forest cover



H_C = Chimney Height

H_B = Max. height of the Power House

Flue gas dispersion



Example: Dilution required from stack

- For the power plant discussed in Example 2, find the **dilution ratio** required for the flue gases so that after dilution the concentration of **CO_2** and **SO_2** are within acceptable limits. Use the data given below obtained from combustion analysis of **coal considered in Example 2**
- **Mol fraction of CO_2** in flue gases = 0.15 (approx) = **1,50,000 ppm**
- **Mol fraction of SO_2** in flue gases = 0.0.0022 (approx) = **2200 ppm**
- **Allowable CO_2 concentration** after dilution = **1000 ppm**
- **Allowable SO_2 concentration** after dilution = **5 ppm**
- **CO_2 concentration** in atmosphere = **350 ppm**
- **SO_2 concentration** in atmosphere = **0 ppm**
- Flow rate of flue gases = 795 m^3/s

Ans.: a) Dilution ratio = $(V_{air}/V_{flue\ gases})$ = **230** (**1,82,238 m^3/s of air**) from **CO_2 limit**

b) Dilution ratio = $(V_{air}/V_{flue\ gases})$ = **439** (3**,49,005 m^3/s of air**) from **SO_2 limit**

The above example implies that **stack design** should be **based on SO_2 concentration**

Stack calculations

- Almost **all fossil fuel** based **power plants** use a **stack or chimney** for dispersing the flue gases
- **Dispersal of flue gases** may be **entirely due to** the **buoyancy effect** created by the stack **or** due to a **combination of stack and a fan**

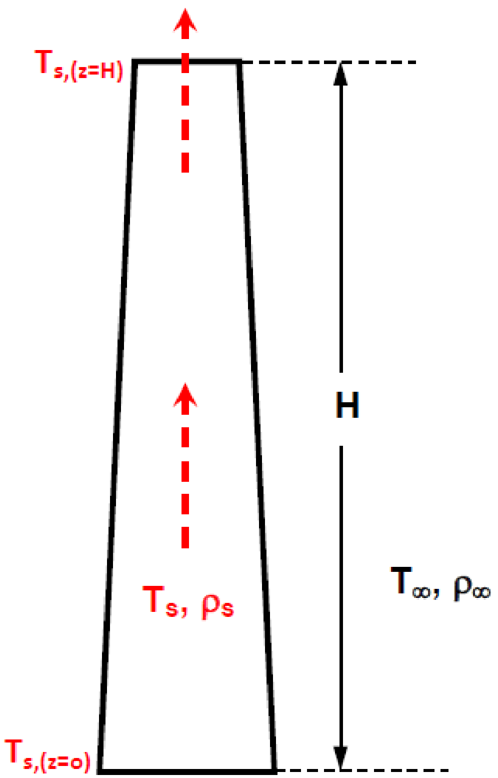
$$\boxed{\text{Driving Buoyancy pressure}, \Delta P_{stack} = (\rho_\infty - \bar{\rho}_s) g H}$$

where:

ρ_∞ = Ambient air density

$\bar{\rho}_s$ = Average density of stack gas

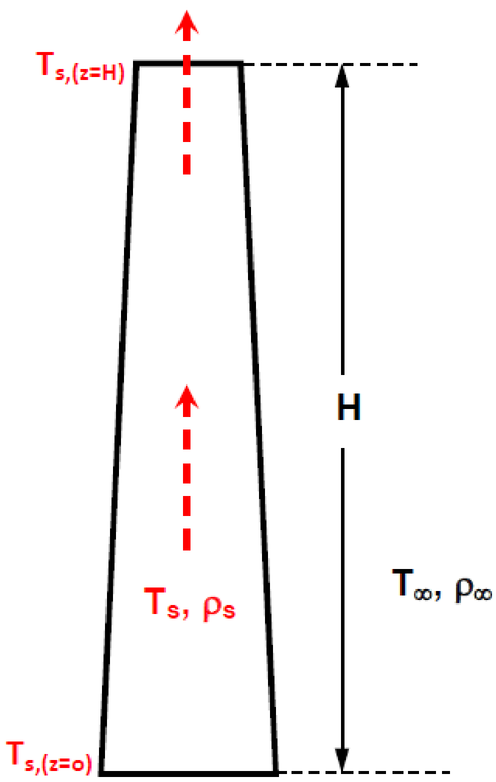
H = Height of the stack



The stack (chimney) – contd.

Assuming ideal gas behavior for both ambient air stack gases,

$$\boxed{\Delta P_{stack} = (\rho_{\infty} - \bar{\rho}_s)gH = \left(\frac{P_{\infty}}{R_a T_{\infty}} - \frac{P_s}{R_s \bar{T}_s}\right)gH}$$



where:

P_{∞}, P_s = Absolute pressure of ambient air and stack gas

R_a, R_s = Gas constant of ambient air and stack gas

T_{∞} = Absolute temperature of ambient air

$\bar{T}_s$= Average absolute temperature of stack gas

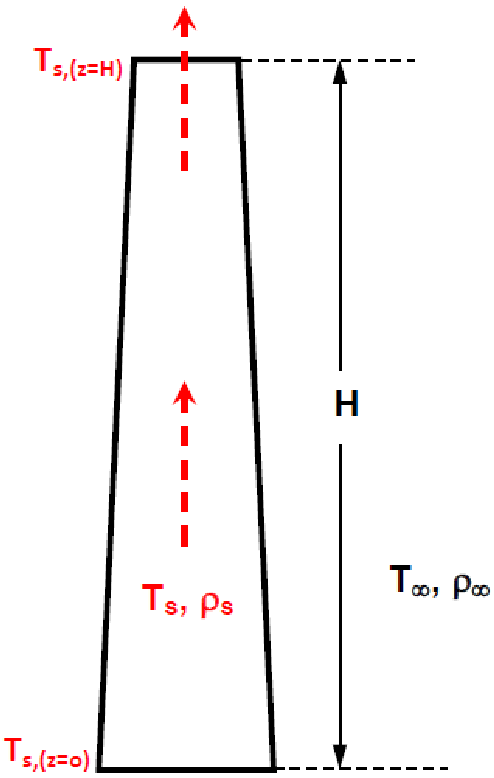
The stack (chimney) – contd.

P_∞ and P_s are almost equal and vary with altitude

The **gas constant** of the **stack gas depends** upon the composition of the stack gases, which in turn depend upon the composition of the fuel

If we **assume** that the **stack gas molecular weight** is approximately **equal to** molecular weight of **air**, then

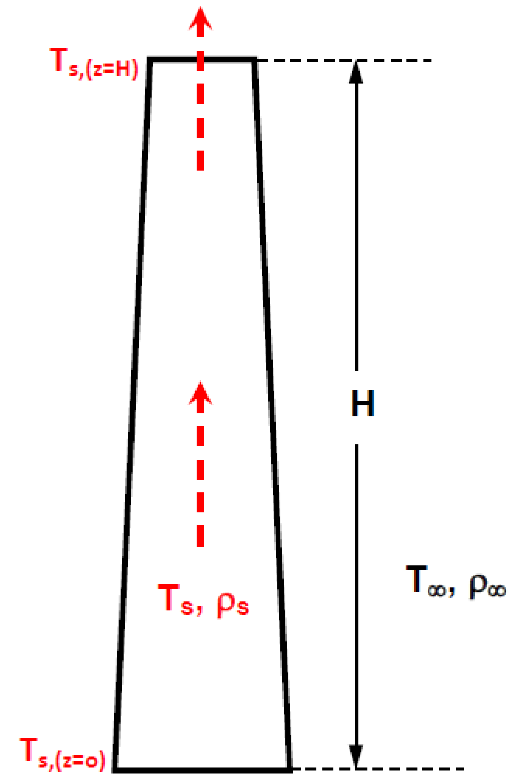
$$\therefore \Delta P_{stack} \cong \frac{P_\infty}{R_a}\left(\frac{1}{T_\infty} - \frac{1}{\bar{\bar{T}}_s}\right) gH$$



The stack (chimney)-contd.

$$\therefore \Delta P_{stack} \cong \frac{P_\infty}{R_a}\left(\frac{1}{T_\infty} - \frac{1}{\bar{\bar{T}}_s}\right) gH$$

The average temperature of stack gas has to be obtained by integration of local stack temperature, i.e.,



$$\bar{T}_s = \frac{1}{H}\int_0^H T_{s(z)} dz$$

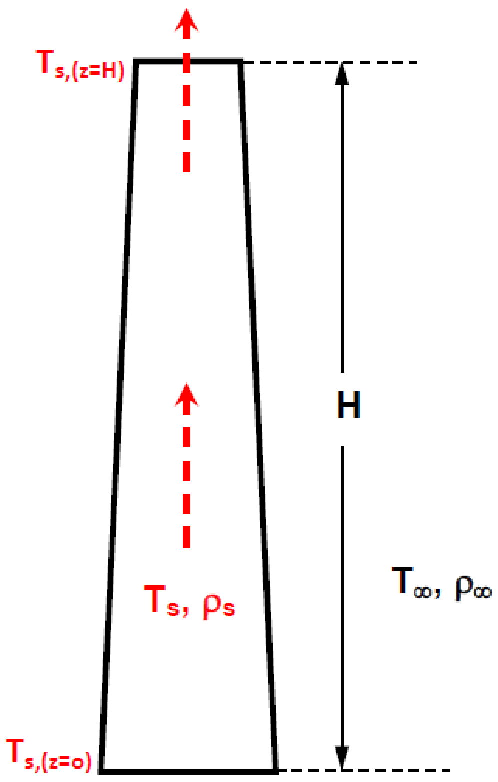
However, as an **approximation** one can use the **arithmetic average** temperature, i.e,

$$\bar{T}_s \cong \frac{\left(T_{s,(z=0)} + T_{s,(z=H)}\right)}{2}$$

The stack (chimney)-contd.

For a given stack gas inlet temperature, $T_{s,(z=0)}$, the stack gas exit temperature $T_{s,(z=H)}$ depends on the stack height, stack diameter, ambient air temperature and wind velocity

The **exit stack temperature decreases** as the stack height increases and/or ambient temperature decreases and/or wind velocity increases

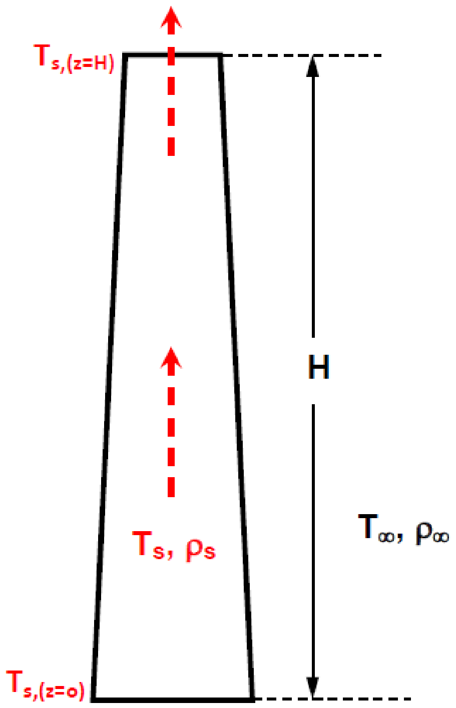


Normally the **frictional and dynamic pressure losses** introduced by the stack itself is **negligible compared** to the pressure head created by the stack

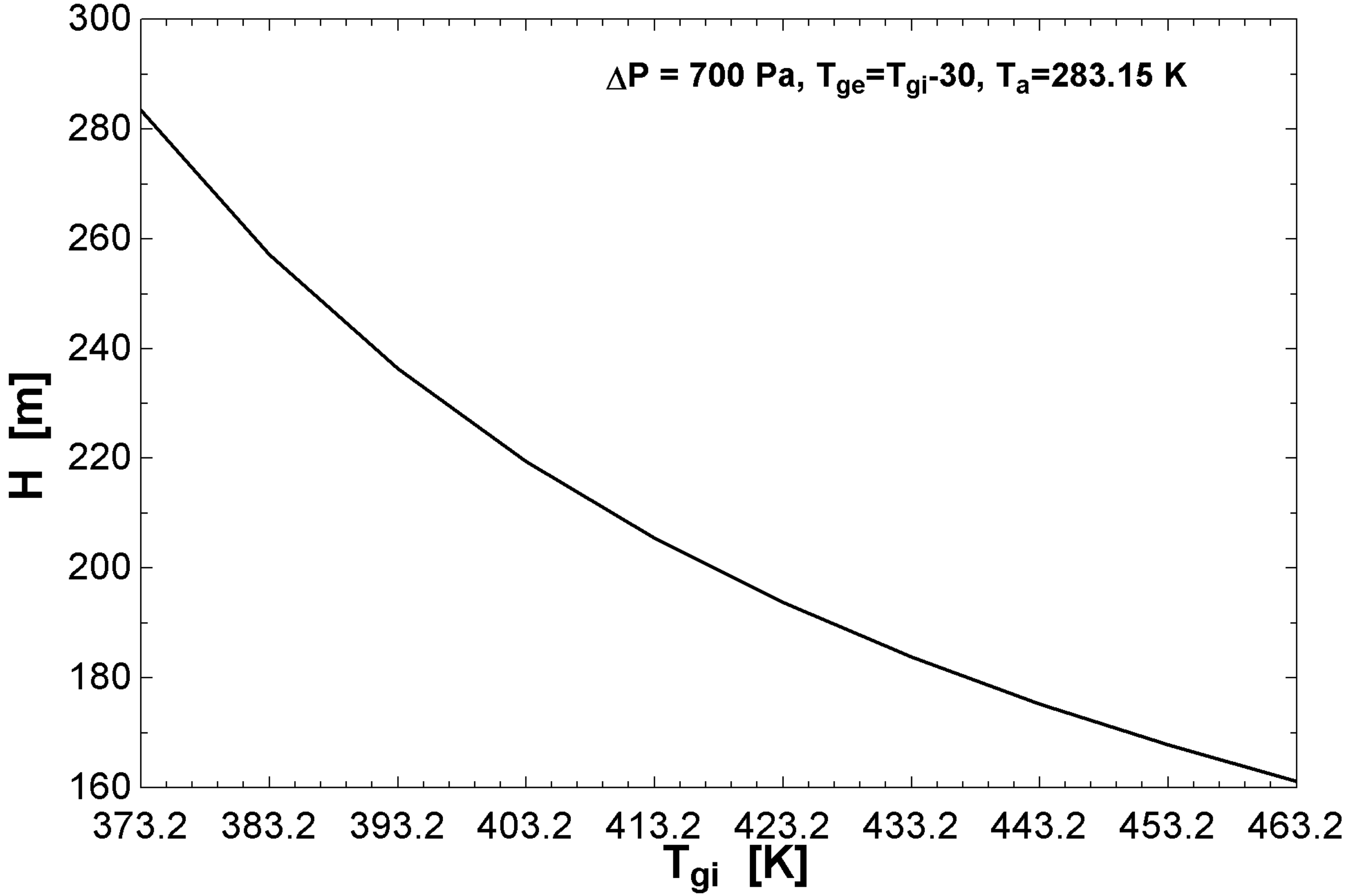
Example 3

- A power plant is situated at an altitude of **300 m** (p_∞ = 0.977 bar). Flue gases enter the stack at a temperature of **140°C** and leave at a temperature of **110°C**. Find the height of stack if the stack has to develop a pressure of **0.7 kPa**. Assume the ambient temperature to be **10°C.**

Ans.: H = **205.5 m**



Effect of flue gas temperature



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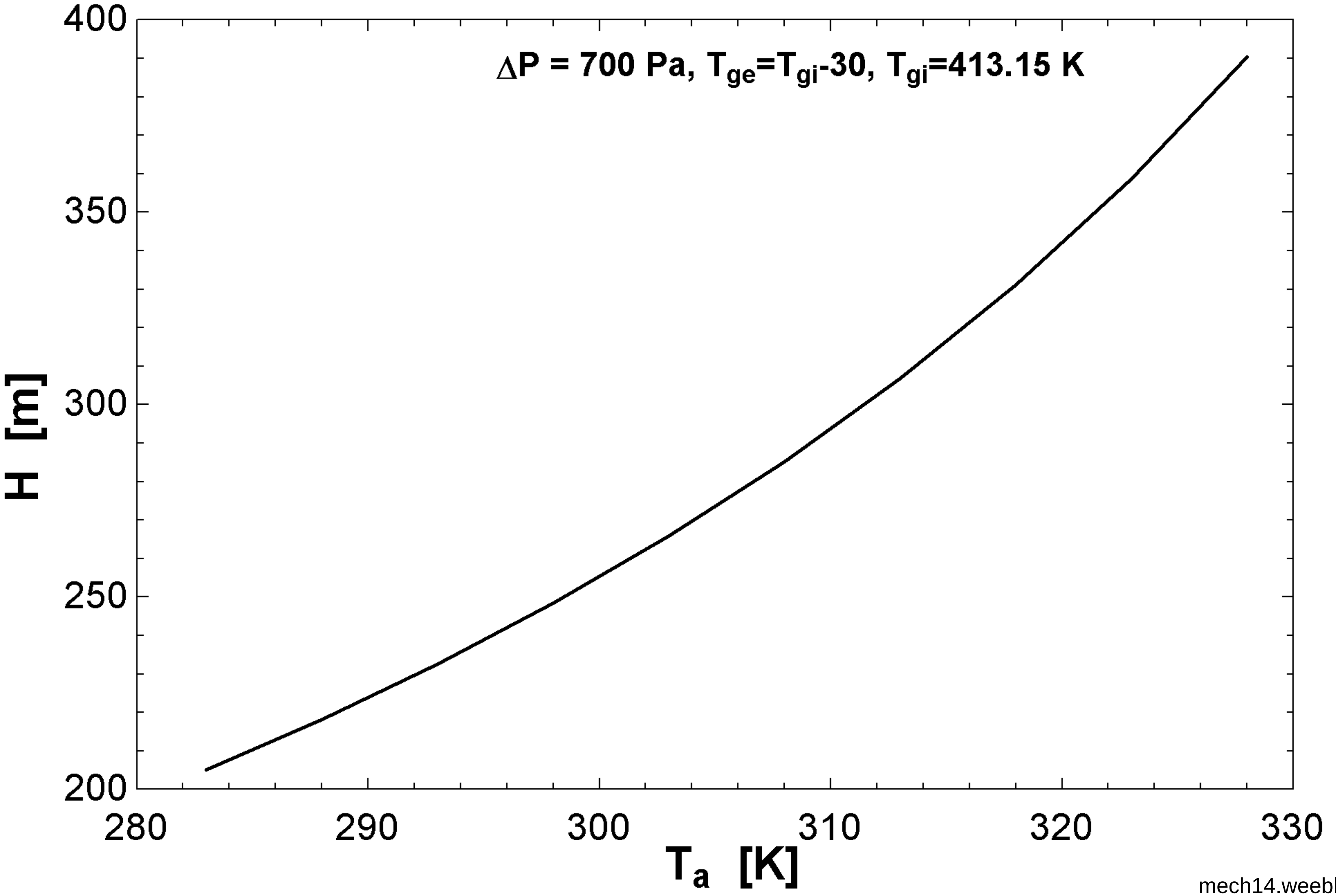
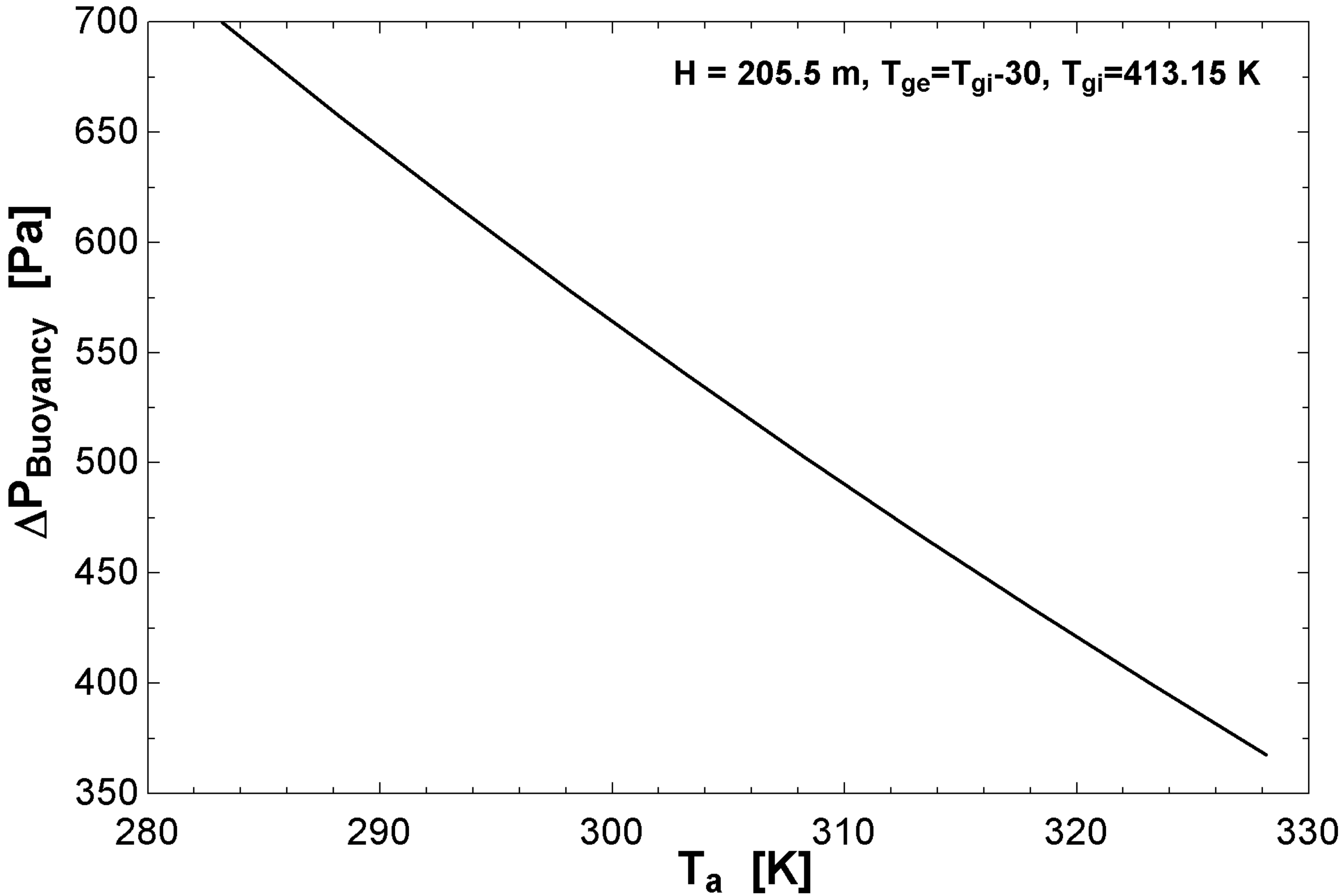
Effect of ambient air temperature



Effect of ambient temperature on buoyancy



Pressure Drop through Stack

Pressure drop through the stack is due to both **fluid friction** and **dynamic losses**

$$\Delta P_{stack} = \left(\frac{f H_{st}}{D} + K_c\right)\frac{\rho u_c^2}{2}$$

where	Δp_{stack}	= stack pressure drop, Pa
	f	= friction factor
	H_{st}	= height of the chimney, m
	D	= diameter of the chimney , m
	K_c	= Dynamic exit loss factor $\cong$ **1.0**
	ρ	= gas density in the stack, kg/m^3
	u_c	= gas velocity at the chimney outlet, m/s

Example 4

- For the **stack described in Example 3**, find the number of stacks required, if the **frictional and dynamic pressure loss** through the chimney is not to exceed **50%** of the **buoyancy head** and **the exit diameter of the stack is less than 5 m**? The flue gas mass flow rate is **600 kg/s.** Use the following property values for flue gases:
- At mean temperature: ρ **= 0.855 kg/m^3**, μ = **22.84 x 10^{-6} kg/m.s**
- At exit temperature: ρ = **0.855 kg/m^3**
- Use the following equation for estimating friction factor:

$$f = \frac{0.079}{Re_d^{0.25}}$$

Ans.: No. of stacks required = **3**, exit diameter of stack = **4.947 m**

Dispersion of flue gases through the stack

A flue gas stack at GRES-2 Power Station in Ekibastuz, Kazakhstan, the tallest stack in the world (420 meters)[wikipedia]

Power generation capacity	Stack Height, H in m
Less than 200/210 MW	$H = 14(Q)^{0.3}$ Where Q is SO_2 emission in kg/hr
More than 200/210 MW & less than 500 MW	220
500 MW or above	275

Environmental guidelines for proper dispersion of SO_2 from coal based thermal power plants (CEA)

Dispersion of flue gases from power plants

Dispersion of flue gases from power plants

- **Fossil fuel based power plants** discharge **huge amounts of obnoxious flue gases** into atmosphere **through chimneys**
- **Atmosphere** has **great capacity for dispersing** and **absorbing** these obnoxious gases, **provided** the **conditions** for dispersal are **favourable**
- As the flue gases leave the chimney they form **a plume**

Plume: "A long cloud of smoke or vapour resembling a feather as it spreads from its point of origin"

Dispesrion of flue gases from power plants

- Under **favourable weather conditions**, the **plume** from the chimney **rises gradually** as it **flows downwind** and the **gases disperse** until their **concentration** in the atmosphere **becomes negligible**

Dispersion of flue gases from power plants

- However, when **conditions are unfavourable**, the **plume is brought down to the ground** within a **distance of less than a kilometer** from the chimney
- This is termed as "**downwash**"

Unsatisfactory dispersion may give rise to:

1. **High concentration** of the flue gases at ground level **for short periods** of time, or
2. **Low concentration** of the flue gases at ground level **for long periods** of time

Both of these could be **equally dangerous**

Path followed by flue gases is not same for all chimneys

Factors affecting flue gas dispersal

1. **Height and number of chimneys**
2. **Velocity of flue gases at the exit of the chimney**
3. **Temperature of flue gases** at the exit of the chimney
4. **Aerodynamic factors**
    1. Buildings and other structures in the vicinity of the chimney
5. **Terrain in which the power plant is located**
6. **Meteorologic conditions**
    1. Atmospheric temperature
    2. Wind

Dispersion of flue gases through the stack

- For **effective dispersion of pollutants**, dynamic mixing of flue gases with the **ambient air** should **be delayed** as much as possible
- Among other things, the **dynamic mixing depends** upon the **velocity** of the flue gases at the **exit** of the **stack**
- If the **velocity** is **too low**, then dispersion will be **ineffective** in the presence of **external winds** and heat transfer
- If the **exit velocity** is **too high**, then mixing of flue gases with ambient air gets accelerated due to turbulence, leading to **ineffective dispersion**
- Also, **higher stack gas velocities** calls for use of **mechanical draft**, which calls for higher initial and operating costs
- **Conventionally** the exit velocities are in the range of **18 to 20 m/s**
- However, if the stack height is to be constrained due to legal or other issues, then there is no other alternative for dispersion, but the use of high exit velocities and mechanical draft

Dispersion of flue gases through the stack

- **Particle size** from **power plant chimney** is in the range of **0.1 to 10 µm**
- The **stack gases** from the chimney **carry** these **particles** as long as they have **sufficient velocity** to carry the particles
- However, due to **turbulence** and **mixing** with surrounding air, the **flue gases slow down**, and when this happens the **particles** start getting **separated** from the flue gases **due to gravity** and start **settling down**
- **Size** of particulate matter in the flue gases **influence** their **settling**
- Particles **larger than 20 µm** are affected strongly by gravity and tend to **settle down within few minutes** of their release into the environment, thus affecting the immediate surroundings
- Particles in the size range of **few microns** travel **several kilometers** before they settle down
- **Very small particles** may travel **thousands of kilometers** before they settle

The dispersal of flue gases from the stack

The flue gases are dispersed vertically and horizontally and diluted by mixing with the ambient air

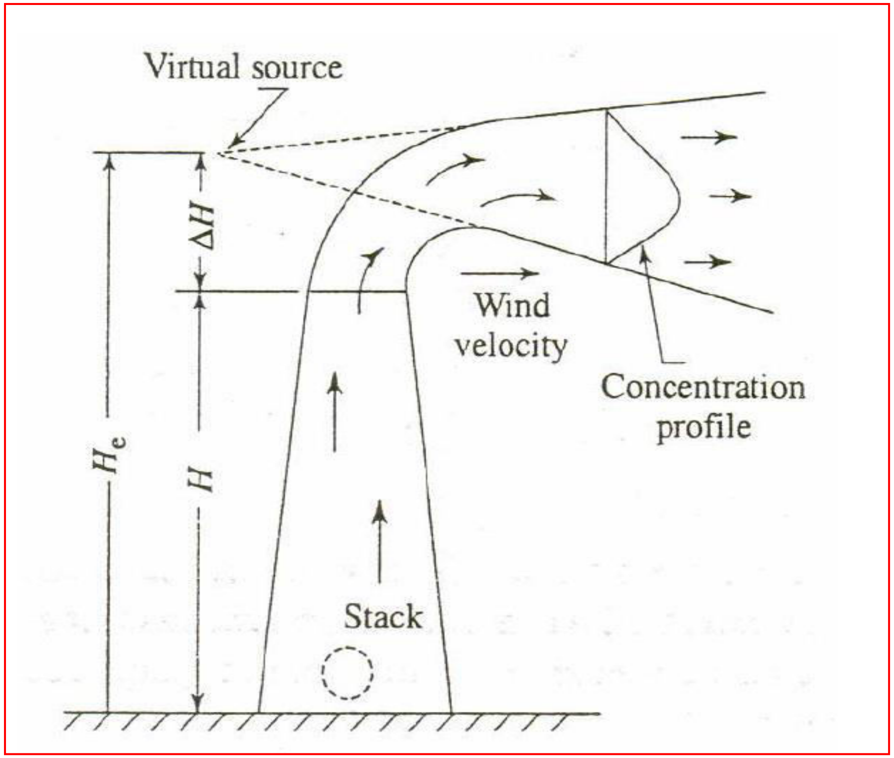
The **horizontal motion** of the stack gases is **due to** the prevailing **wind**, while the **vertical motion** is **due to** the **buoyancy** and momentum at the exit of the stack

The dispersal of flue gases from the stack

Due to exit velocity of the stack gases, a **plume** is formed, which is **equivalent to a virtual pollution source** that is at a height **ΔH** above the stack

The effective stack height, $H_e = H + \Delta H$

Several analytical and empirical methods are used to estimate **ΔH**



Plume height is required for predicting the dispersion of pollutants from the stack

Estimation of plume height

- Carson & Moses Equation:

$$\Delta H \text{ (in m)} = -0.029 \frac{V_s D}{V_w} + \frac{2.62 (Q_e)^{0.5}}{V_w}$$

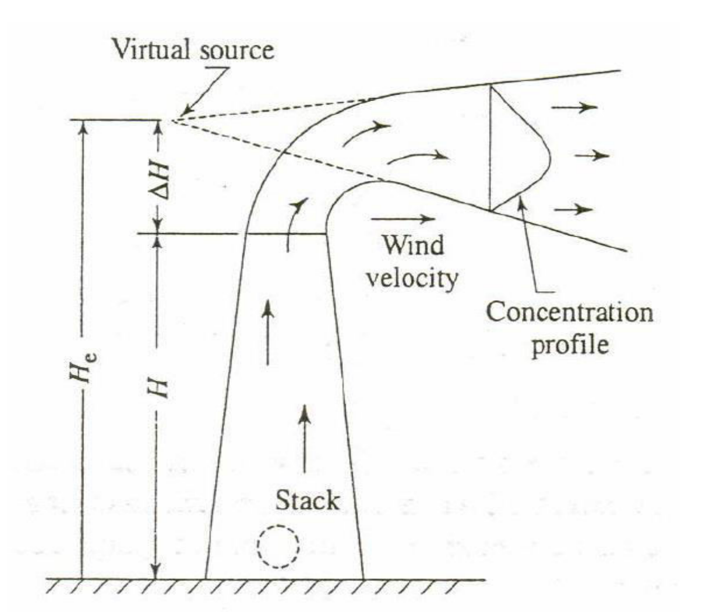
Where:

V_s = stack gas exit velocity (m/s)

D = Diameter of the stack (m)

V_w = Wind velocity at stack exit (m/s)

$Q_e = m_s c_p (T_{s,(z=H)} - T_\infty)$ = Heat emission rate (kW)



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Example 5

- In a power plant located at sea level, flue gases at a flow rate of **200 kg/s** enter a **5 m** diameter stack at a temperature of **140°C** and leave the stack at **110°C**, ambient air temperature = **25°C**. The stack is designed for a driving pressure of **700 Pa**. The wind velocity is **25 km/h**. Using the Carson & Moses Correlation, find:

  a) Chimney height, H

  b) Plume height, ΔH

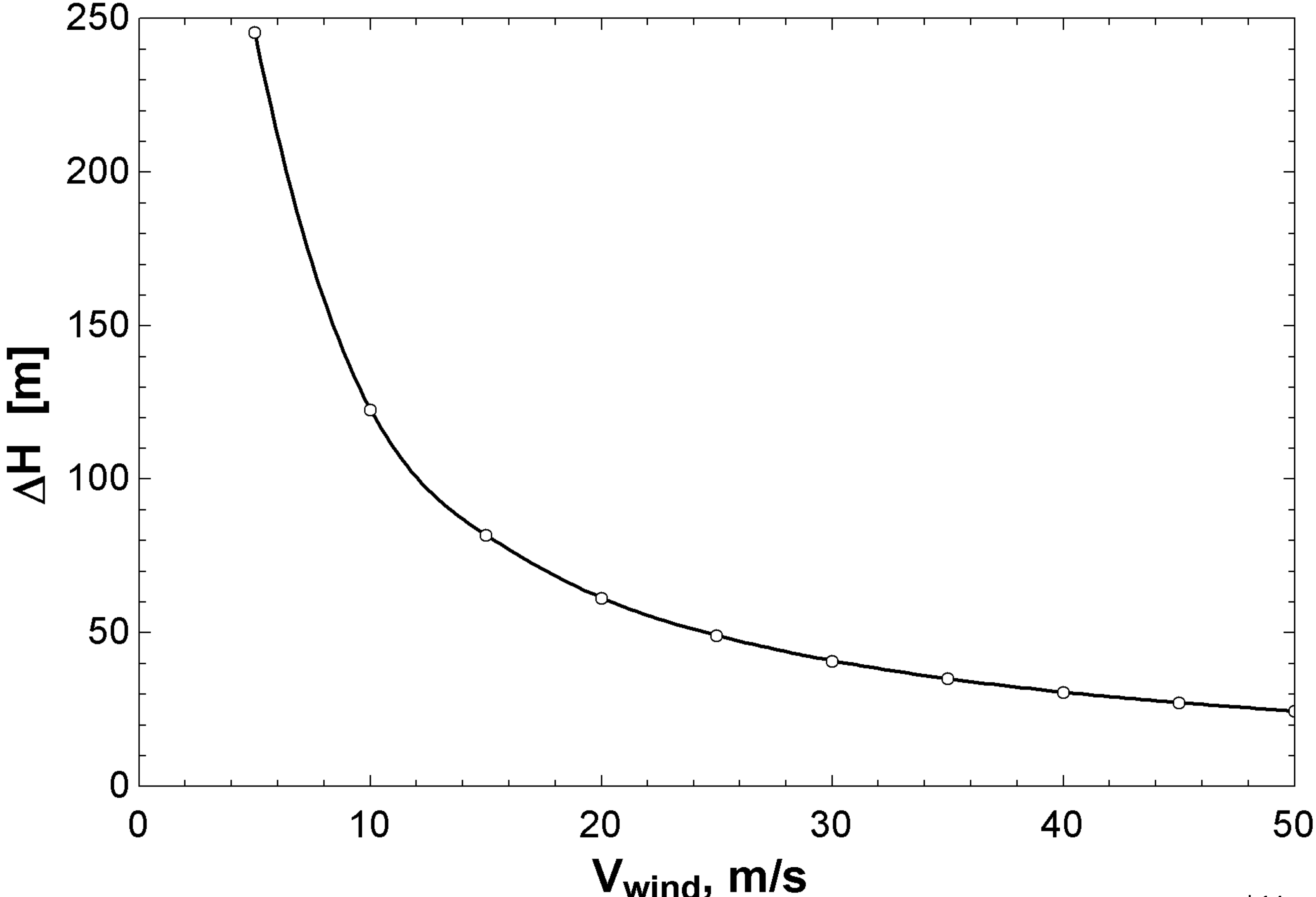
  c) Effective height, H_e

Given: c_p = **1.005 kJ/kg**.K. Assume flue gases to behave as dry air.

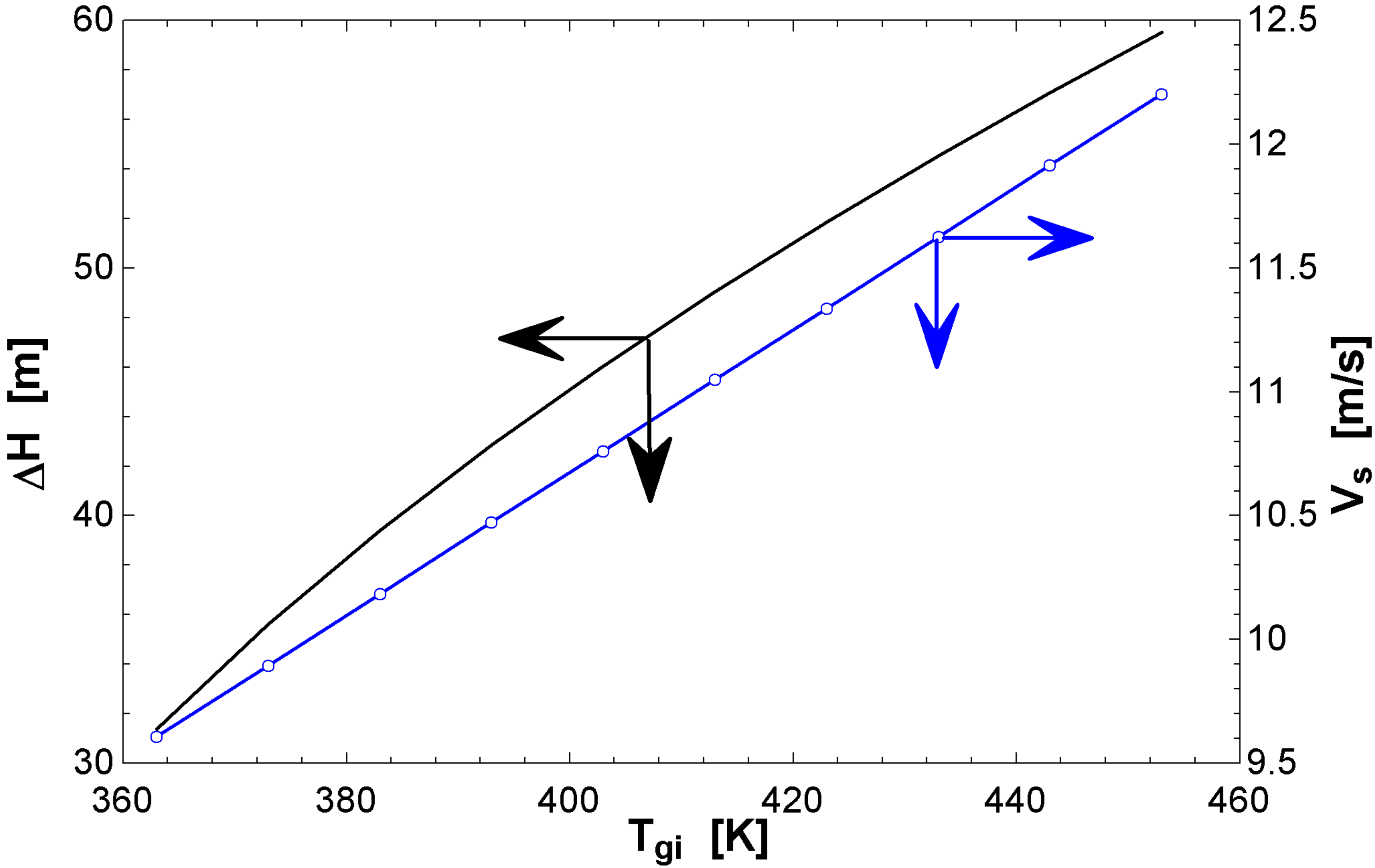
$$\Delta H\ (\text{in m}) = -0.029\frac{V_s D}{V_w} + \frac{2.62(Q_e)^{0.5}}{V_w}$$

Ans.: a) 239.9 m; b) 49.08 m; c) 289 m

Effect of wind velocity on plume height



Effect of stack gas temperature on plume height



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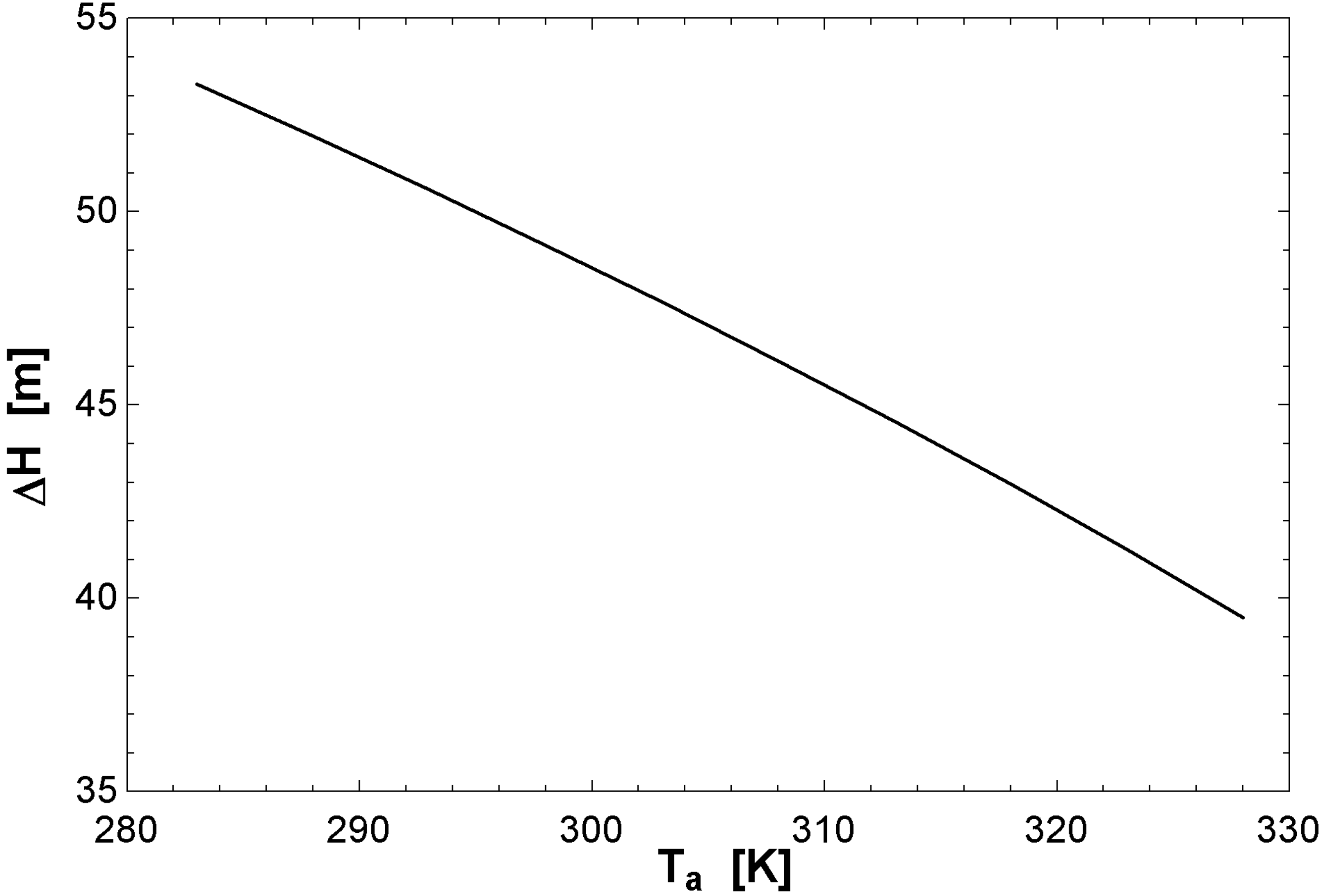
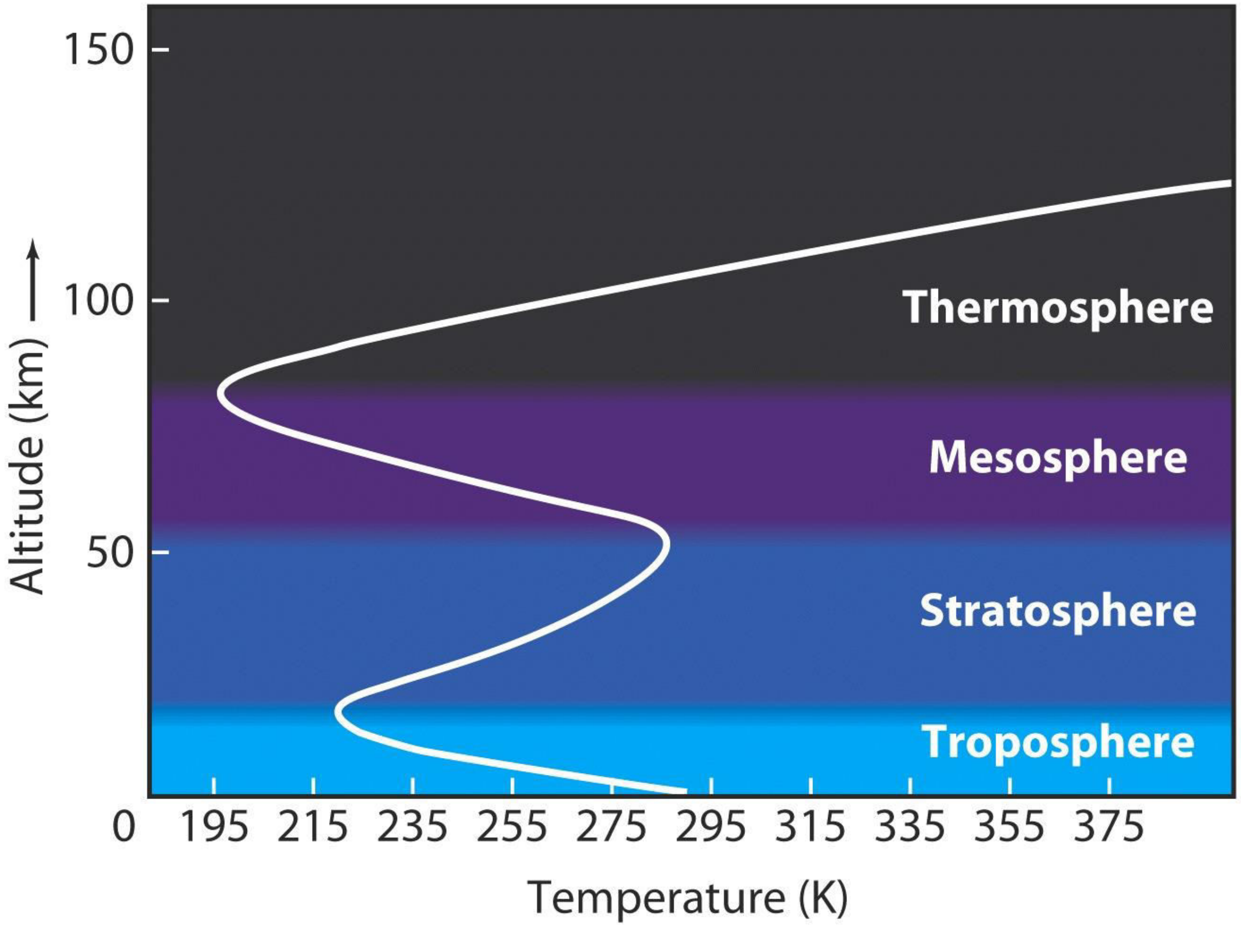
Effect of ambient temperature on plume height



Apart from exit flue gas and wind velocities, **the temperature of atmospheric air** into which the flue gases are discharged also **affects** the dispersal of the flue gases

The **temperature** of air **varies** with altitude **in a complicated manner**, however, in the **troposphere**, into which the flue gases are released, the **temperature decreases** with altitude



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Adiabatic lapse rate

The **adiabatic lapse rate** is the **rate** of temperature decrease with altitude for a parcel of dry or unsaturated air rising under **adiabatic** conditions

Adiabatic lapse rate of dry air:

$$T.ds = dh - v.dP = dh - \frac{dP}{\rho} = 0$$

$$dh = c_p.dT$$

$$dP = -\rho g.dZ \rightarrow \frac{dP}{\rho} = -g.dZ$$

$$\therefore \frac{dT}{dZ} = -\frac{g}{c_p} \cong -\frac{9.81}{1005} \cong -0.001 \left(\frac{K}{m}\right)$$

Since **atmospheric air** in the **lower regions** consists of **water vapour**, and c_p value of moist air is higher than that of dry air, the Adiabatic lapse rate of **moist air** is **smaller**

The **actual lapse rate** is around **–0.0066 K/m** or about **6.6 K per kilometer**

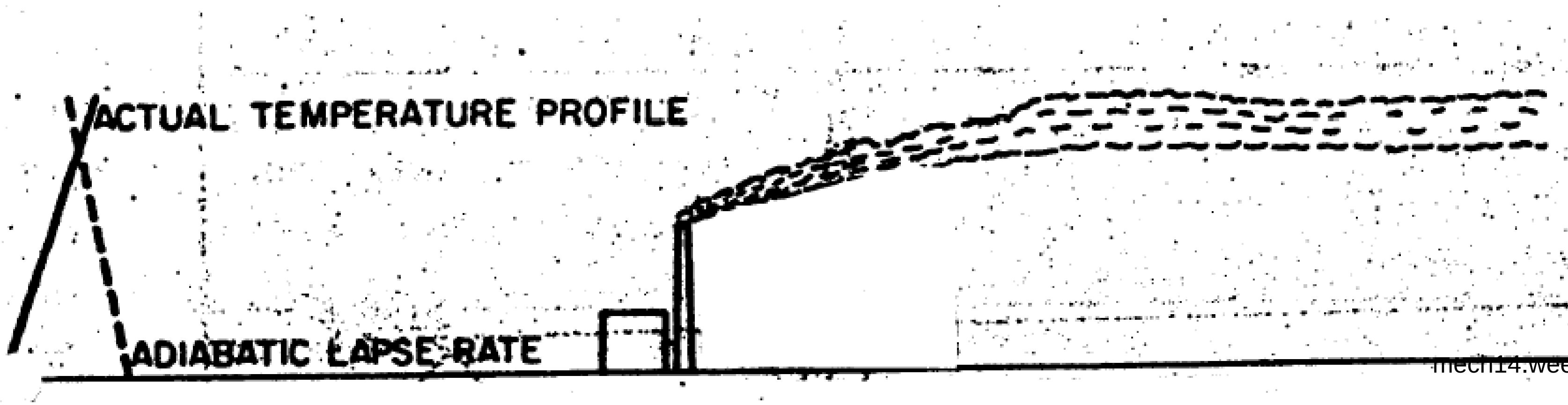
Variation of atmospheric air temperature

Sometimes due to atmospheric inversion, the vertical dispersion of the flue gases is hampered leading to increase in local concentration of flue gases

Atmospheric inversion implies rise in atmospheric air temperature with altitude. (Normally air temperature decreases by about **6.6 K per km**)

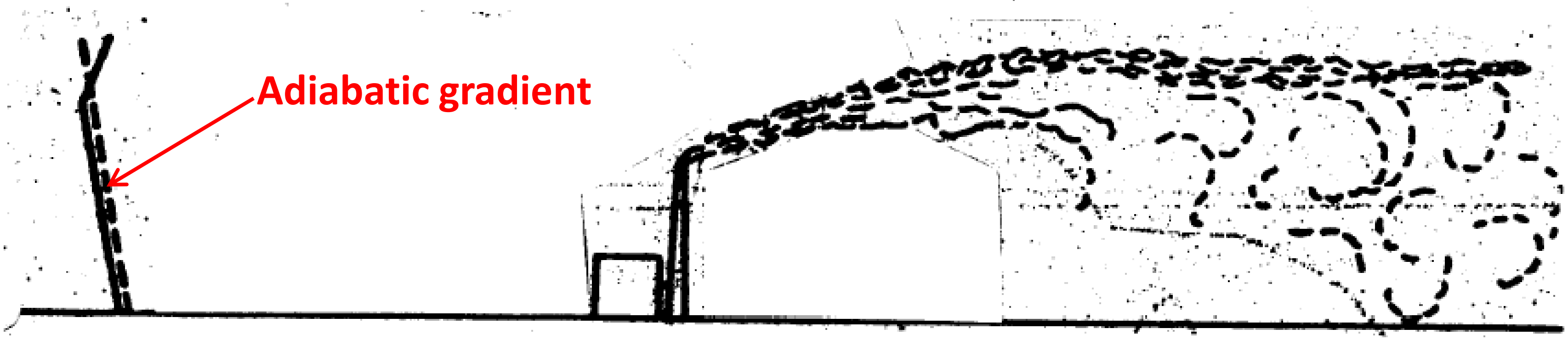
Inversion typically can happen **during clear nights**, when the air near the surface of the earth is cooler due to radiation heat transfer between the ground and the sky

Due to this, a stable layer extending up to several thousands of meters forms near the earth, leading to a **fanning plume**

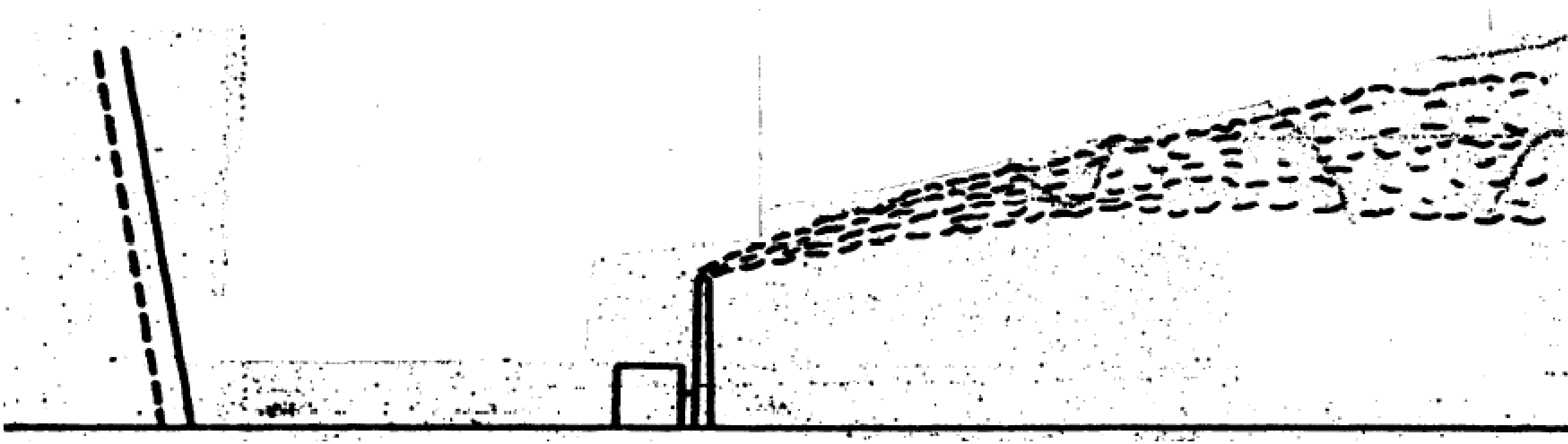


The dispersal of flue gases from the stack (contd.)

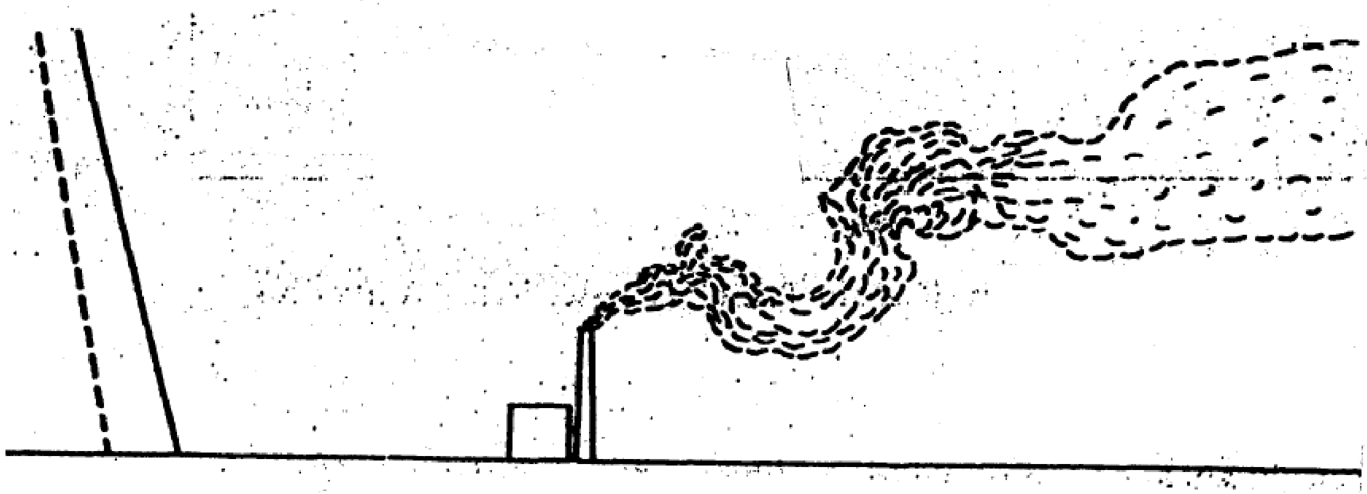
As the sun rises, the air near the ground gradually heats up, leading to formation of eddies, which cause mixing of the plume and resultant high concentration near the surface, called as **fumigation plume**



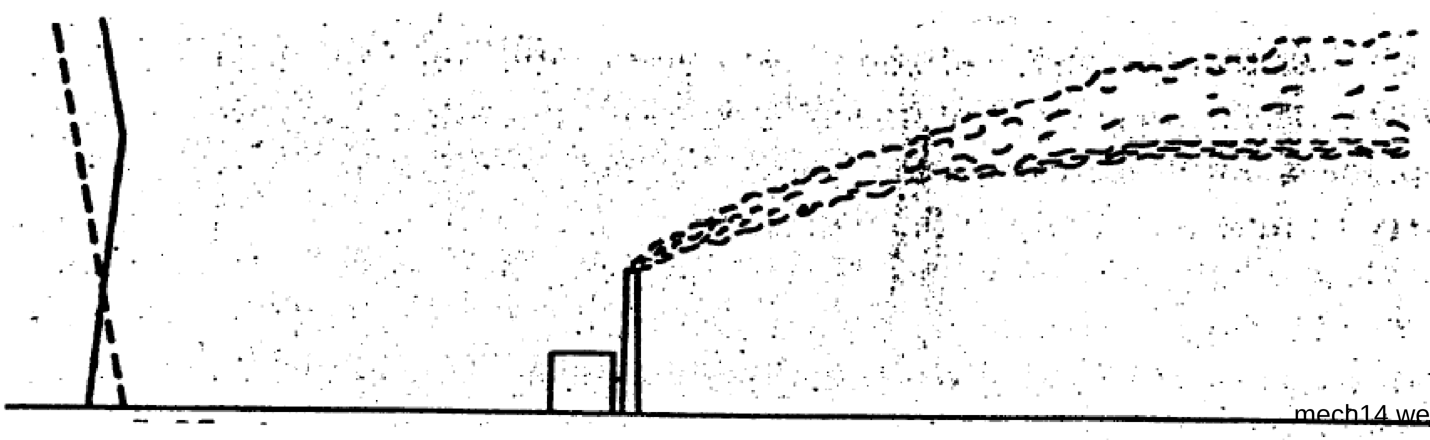
Gradually with time, the plume rises, forming a **coning plume**



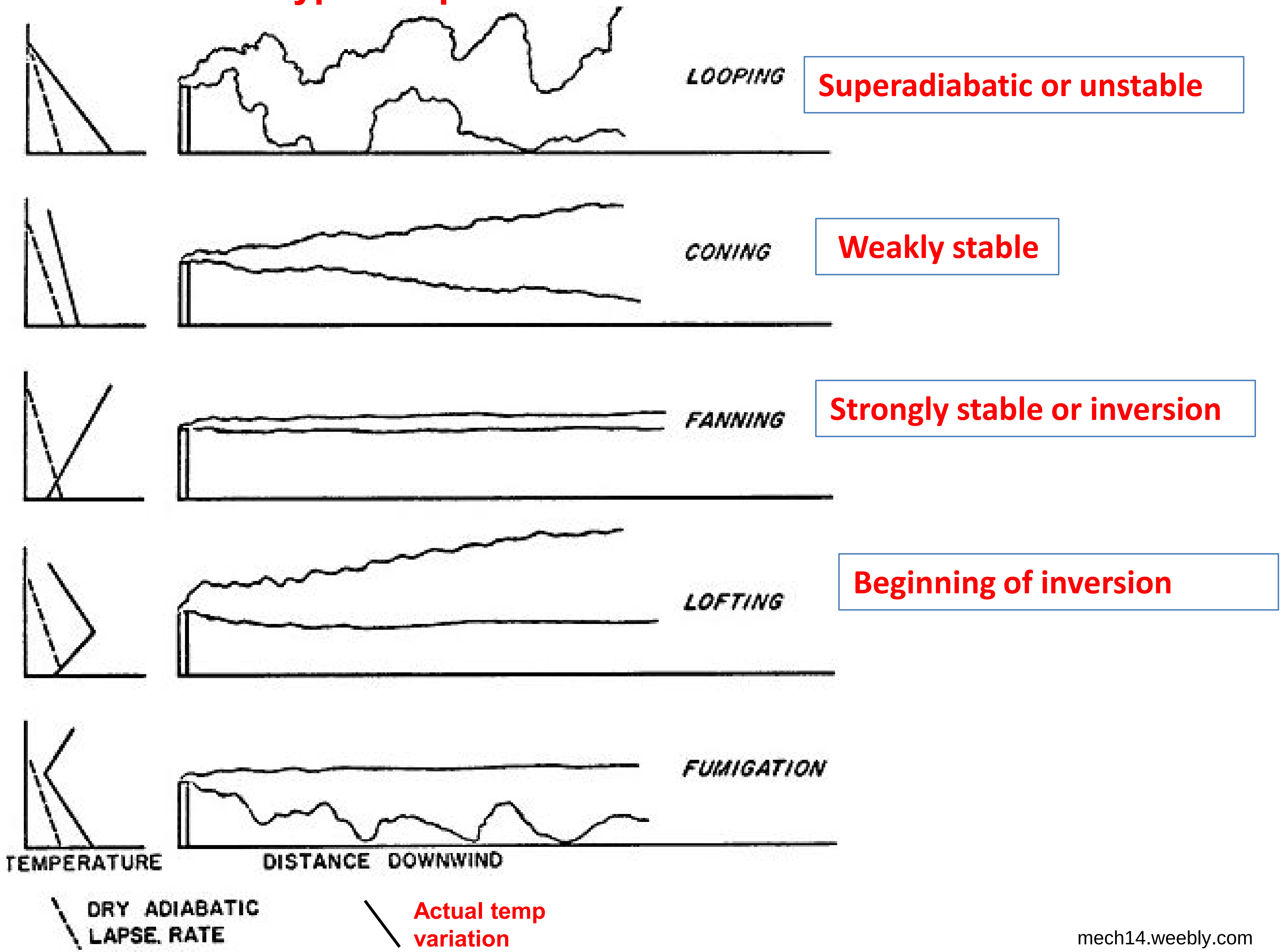
If the heating near the surface is intense, the eddies formed break the plume, leading to a **looping plume**



However, as sun starts setting, inversion begins to form, giving rise to a **lofting plume** to begin with



Types of plumes



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End of Module 3B