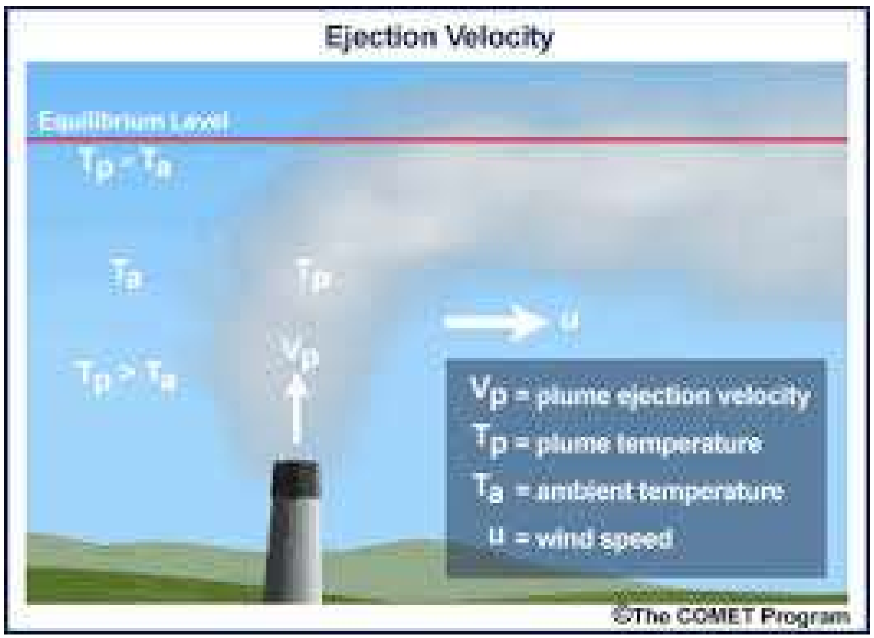
GAS STACKS AND PLUME RISE



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The taller, the better!

BAD ENGINEERING PRACTICE – POPE FRANCESCO ELECTION

(march13th 2013, new pope)

1. Chimney too short! The outlet of the domestic chimneys must be at least 1.0 meter higher than the ridge of roofs, and far from any other obstacle or structure within, generally, about 10 m.

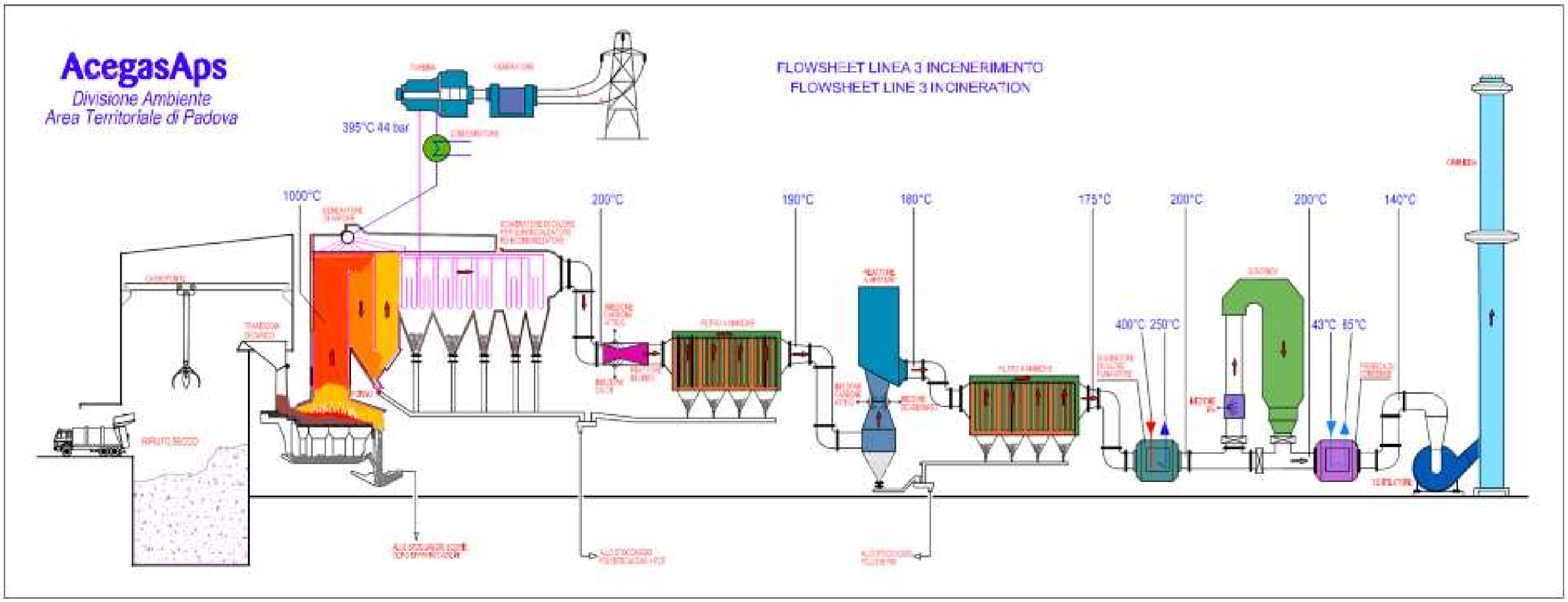
2. NO CAPS on the outlets of industrial chimneys! One of the main purposes of using a chimney cap is to keep water out. [→ **not important for industrial chimneys**!!]

Chinese Cap

.. vertical exhaust tips → better pollutants dispersion than horizontal..

Exhaust Systems for Heavy Trucks
- vertical exhaust pipes -

Stack in a complete Air Treatment System



ID-FAN (induced draft)

Under suction the entire line

Hierarchy approach

1st

REDUCE THE MASS FLOW RATES OF POLLUTANTSTO THE ATMOSPHERE – MAIN INTEREST OF EU AND MS (MEMBER STATES). EU STRATEGIC APPROACHES*:* NECD AND 2010/75/EU (--> Large Plants emissions) DIRECTIVES, ...

2nd

REDUCE THE EFFECTS OF EMITTED POLLUTANTS. THE MAIN INTEREST FOR PEOPLE LIVING NEARBY POLLUTING SOURCES IS THE REDUCTION OF POLLUTANTS GROUND CONCENTRATIONS *(sometimes called: IMMISSIONS, in It. "RICADUTE")* - LOCAL APPROACH

EU vs. LOCAL interest?

No!

We have to comply with both, simultaneously!

"AIR QUALITY" EFFECTS

1. Urban air pollutants have a wide range of effects, with **health** problems being the most enduring concern.
2. Air pollution also affects **materials** *(+ cultural heritage)* in the urban environment. The acid gases increase the rate of destruction of building materials and monuments. This is most noticeable with **calcareous stones**, which are the predominant building material of many important historic structures. Metals also suffer from atmospheric acidity.

In today's photochemical smog, natural rubbers crack and deteriorate rapidly. Soiling has long been regarded as a problem, originally the result of the smoke particles from wood, oil or coal fires, but now increasingly the result of fine black soot from diesel exhausts.

Air pollution also affects wildlife and **biological activities, crops, and vegetation**, "**AIR QUALITY**", **AQ, depends on the concentration of pollutants in the air**.

EU legislation sets the maximum levels of pollutants that can be acceptable.

Pollutants concentrations in the air depend on:

- the rate at which they are released from the various sources, and
- **how quickly the pollutants are dispersed** (or, conversely, how long they are trapped in an area) and/or converted in less harmful chemical compounds.

AQ is the result of this balance.

Weather conditions (e.g. UV irradiation, winds, temperature, and a temperature inversion), and/or terrain features (e.g., mountains) limit the transport of pollutants away from an area and their chemical/photo-chemical oxidation.

EMISSIONS TO ATMOSPHERE - MAIN STRATEGY FOR HEALTH AND ENVIRONMENT PROTECTION

THE LOCAL AIR POLLUTION, i.e. THE GROUND CONCENTRATIONS, is a central point in the EIA and AIA/IPPC AUTHORIZATION PROCEDURES: **PEC = BK + PG**

PREDICTED LOCAL AIR POLLUTION LEVEL OF A SPECIFIC POLLUTANT (PEC)=

BACKGROUND LEVEL (BK)* + *PREDICTED GROUND DEPOSITION LEVEL (PG)

(BK) BACKGROUND LEVEL = THE AVERAGE CONCENTRATION OF A SPECIFIC AIR POLLUTANT

a) ANTE A NEW INSTALLATION, or

b) WITH EXISTING INSTALLATION NOT IN OPERATION (*)

(PG) PREDICTED GROUND DEPOSITION LEVEL = THE CALCULATED POLLUTION LEVEL OF A SPECIFIC POLLUTANT DUE THE INSTALLATION UNDER EXAMINATION → MATH. MODELIZATION IS REQUIRED!

Generally, is (very) difficult to measure the contribution of existing plants to the level of pollutants in the air! Calculation can be more precise

EMISSIONS TO ATMOSPHERE - MAIN STRATEGY FOR HEALTH AND ENVIRONMENT PROTECTION

PEC, BK, PG must refer to the same period of time! HOMOGENEOUS DATA!!

YOU SHOULD PREFER LONG TERM DATA, THAT IS YEARLY AVERAGES OF BK, PG, AND HENCE, OF PEC!

FIRST CALCULATIONS, CAN BE CONCENTRATED ON A SINGLE YEAR, GENERALLY LAST YEAR.

IN CASE OF IMPORTANT PLANTS, OR AREAS, IT IS BETTER TO GET THE DATA OF THE LAST THREE YEARS.

- ANNUAL AVERAGES DATA (AND ALSO SHORT TERM DATA) MAY BE DIFFERENT BECAUSE OF:
- METEO CHANGES (TEMPERATURE, WIND – direction and velocity -, SUN IRRADIATION, RAIN,…)
- EMISSIONS CHANGES (OPERATING HOURS, DIFFERENT RAW MATERIALS/FUELS, EFFICIENCIES OF APCDs, OPERATION CONDITIONS, …)
- OTHER NEW PLANTS HAVE BEEN INSTALLED, OR HAVE BEEN CLOSED, TRAFFIC CHANGES, …).

- THE WORST DATA (I.E. THE GREATER PG) SHOULD BE TAKEN INTO CONSIDERATION!

EMISSIONS TO ATMOSPHERE - MAIN STRATEGY FOR HEALTH AND ENVIRONMENT PROTECTION

FOR THE EMITTED POLLUTANTS WE MUST EVALUATE:

RATIO: **PG/BK x 100**	**% INCREASE DUE TO THE EMITTED POLLUTANT AGAINST THE BACKGROUND LEVEL**. IT SHOULD BE LOW, TYPICALLY NOT > THAN FEW %!
RATIO: **PEC/AQ x 100**	**% OF PREDICTED AIR LEVEL (including the emitted pollutant) AGAINST THE AIR QUALITY LIMIT (e.g. annual limit,..*homogenous periods*!!). Problems when the ratio > 100%.**

LEGISLATION ON INDUSTRIAL STACKS

IED, 2010/75/EU

Aticle 3. Definition

'STACK' means a structure containing one or more flues providing a passage for waste gases in order to discharge them into the air; ((26) Article 3 Definitions)

Article 30. Limit values

1. Waste gases from combustion plants shall be discharged in a controlled way by means of **a stack**, **containing one or more flues**, **the height of which is calculated in such a way as to safeguard human health and the environment.**

Italian legislation: D.Lgs. 152/2006

Art. 237-duodecies. Emissione in atmosfera

1. Gli effluenti gassosi degli **impianti di incenerimento e coincenerimento** devono essere emessi in modo controllato attraverso **un camino** di altezza adeguata e con velocità e contenuto entalpico tale da favorire una buona dispersione degli effluenti al fine di salvaguardare la salute umana e l'ambiente, con particolare riferimento alla normativa relativa alla qualità dell'aria.

Lifetime of chemicals in air

Lifetimes, τ, of air pollutants can be very different, under the same conditions.

Organics depend much on atmospheric species radical **OH**

Lifetime, τ, of a species in a chemical reaction is defined as the time it takes for the species concentration to fall to 1/e of its initial value.

Overall lifetime of a species, τ, that is removed is the result of several independent processes:

$$1/\tau = 1/\tau_1 + 1/\tau_2 + 1/\tau_3 + \ldots + 1/\tau_\iota$$

ATMOSPHERE LIFETIMES OF SOME Cl-VOC WITH OH

Lifetime	τ_{OH}
Methyl chloroform	4.8 years (*)
Dichloromethane	158 days
Perchloroethylene	105 days
Trichloroethylene	4.3 days
VCM *(CH_2=CHCl)*	1.5 days *(VCM is a gas)*

(*) Industrial solvent; has been banned by the 1987 Montreal Protocol because of its ozone-depleting potential (ODP**). During the 1990s, global emissions have decreased substantially and, since 1999, near-zero emissions have been estimated for Europe and the United States.)**

The principal uses of methyl chloroform (MCF) have been the degreasing of precision engineered components (31%) and cold cleaning (18%). Its low toxicity compared to other non-flammable halogenated solvents favoured its use in many other applications such as dry cleaning, inks and coatings. **The ultimate fate of MCF is evaporation into the atmosphere where its principal loss mechanism is oxidation by hydroxyl radicals (OH). The lifetime of MCF towards OH oxidation in the troposphere is relatively long (5–6 yr) and a significant MCF fraction is transported to the stratosphere where it releases chlorine through photolysis.** For this reason, MCF was included in the Montreal Protocol (1987) and its amendments with a final phase-out in 1996 in developed countries, and 2015 in developing countries.

CCl_4 τ_{OH}: 26 – 50 YEARS: http://www.dailykos.com/story/2014/8/24/1324222/-NASA-discovers-large-amount-of-carbon-tetrachloride-CCl4-continues-to-be-released-after-global-ban.

ON THE CHOICE OF CHEMICALS
WHICH IS THE "GREENEST" CHLORINATED SOLVENT?

Solvent	*Lifetime, t_{OH}*	Boiling Point (1 atm)	Vapour pressure (at 25 °C) mmHg	Condensation efficiency	GAC adsorption capacity (g solvent/g carbon)
Methyl chloroform *(Under Montreal Protocol)*	4.8 years (*)	145 °C	--	---	--
Methylene chloride, DCM	158 days	41 °C	415	*	0,10
Trichloroethylene, TRI	4.3 days	87 °C	65	**	0,15
Perchloroethylene, PERC	105 days	121 °C	18	***	0,20

Improved PERC condensation efficiency and GAC adsorption (*) compensate for its higher lifetime τ compared with that of TRI. DCM recovery is much less efficient than PERC and TRI; final recovery efficiency: PERC > TRI > DCM.

(*) Both techniques can be used for the recovery of Cl-Solvents from solvent laden air flows; GAC is, however, always required to reach the ELV!)

AIR POLLUTION CONTROL STRATEGY

A. What to do, to reduce Emissions of Pollutants ?

1st Prevention *(e.g. cleaner materials and fuels)*

2nd Emission Control (Air Pollution Control Devices - APCDs)

3rd …. Plume rise

B. What to do to improve Air Quality?

1st Improve emissions

2nd Reduce pollutants deposition, *particularly in the nearby areas*, by means of a suitable location and an appropriate "effective height" of chimneys ($H_{effective}$)

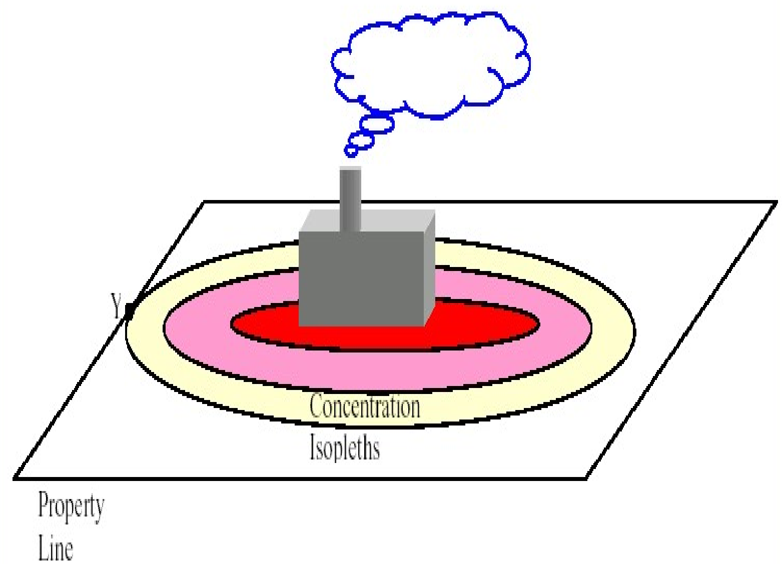
- physical height (H_S)

- "plume rise" (ΔH)

Localization of: industrial activities and stacks

Local pollution
None of us would like to live, or to stay, in these red or pink areas!

An isopleth is a line of equal value
(= isoconcentration curves)



Pollutant Plume Rise

An **increase** in the height of the plume results in a better dispersion (dilution) of the emitted gas and, consequently:

- a lower level of local air pollution,
- a longer **residence time** of pollutants in the atmosphere (*).

Longer resident time means more efficient chemical / photochemical degradation (1) of pollutants in the atmosphere before their deposition (dry/wet dep.) → better air self-cleaning process.

Remember that Not all pollutants can be degraded:
metals (Hg, Pb, Cr, …) of course remain unchanged!;
many inorganic pollutants may be efficiently degraded;
most organic pollutants may be degraded, but some recalcitrant pollutants, such as POPs, only a little, even after long residence times in the atmosphere!

Degradation is more important for short living pollutants!!
e.g. the lifetime of NOx in the lower atmosphere is approximately one day.
Longer NOx residence times in the air favour the complete oxidation to N_2O_5 and hence the conversion to HNO_3.
NOx have more negative environmental implications than HNO_3.

PLUME RISE AFFECTS DISPERSION AND TRANSPORT

- affects maximum ground level concentrations
- affects distance to maximum ground level conc.

Residence time

The residence time tells us on average how long a representative molecule of a substance (or a particle) will stay in the atmosphere before it is removed.

The atmosphere presents two ultimate exits: precipitation and the surface of the Earth itself. Species released into the air must sooner or later leave by one of these two routes.

Atmospheric species removal processes can be conveniently grouped into two categories: dry deposition and wet deposition.

Dry deposition *denotes the direct transfer* of species, both gaseous and particulate, to the Earth's surface and proceeds without the aid of precipitation.

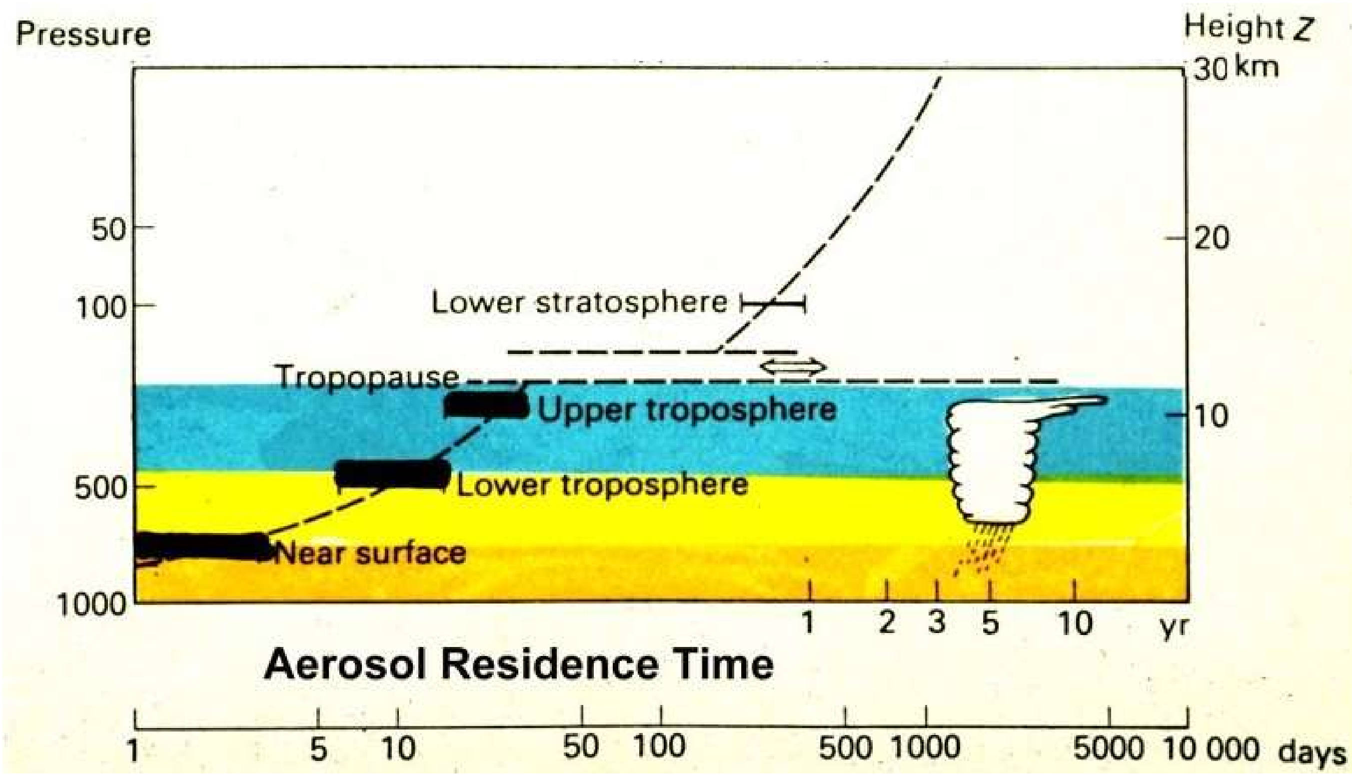
Wet deposition*, on the other hand, encompasses all processes by* which airborne species are transferred to the Earth's surface in aqueous form (i.e., rain, snow, or fog):

1. dissolution of atmospheric gases in airborne droplets, for example, cloud droplets, rain, or fog;
2. removal of atmospheric particles when they serve as nuclei for the condensation of atmospheric water to form a cloud or fog droplet and are subsequently incorporated in the droplet; and
3. removal of atmospheric particles when the particle collides with a droplet both within and below clouds.

By "**particulate matter**" we refer to any substance, except pure water, that exists as a liquid or solid in the atmosphere under normal conditions and is of microscopic or submicroscopic size but larger than molecular dimensions.

Before deposition, both particulate and gaseous molecules generally undergo physical, chemical and photo-chemical processes. *New pollutants can be produced, e.g.* O_3 *and fine dust (*PM_1 *and* $PM_{2.5}$*).* Secondary particulate matter forms from aerosols and gaseous species in the ambient air, downstream of the source. There are numerous formation processes in ambient air for secondary particulate matter, which include chemical reactions, nucleation, condensation, coagulation and the evaporation of fog and cloud droplets in which gases have dissolved and reacted. Secondary particles make up most of the fine particle pollution.

Residence Time Dependence on Height



The $PM_{2.5}$ residence time increases with height of the plume:

- within the atmospheric boundary layer (the lowest 1-2 km), the residence time is 3-5 days;
- in the upper troposphere, particles are transported for weeks and for hundred km before removal. *(<u>care</u>: possible interference with the stratosphere!)*

Plume Rise: an introduction

Introduction

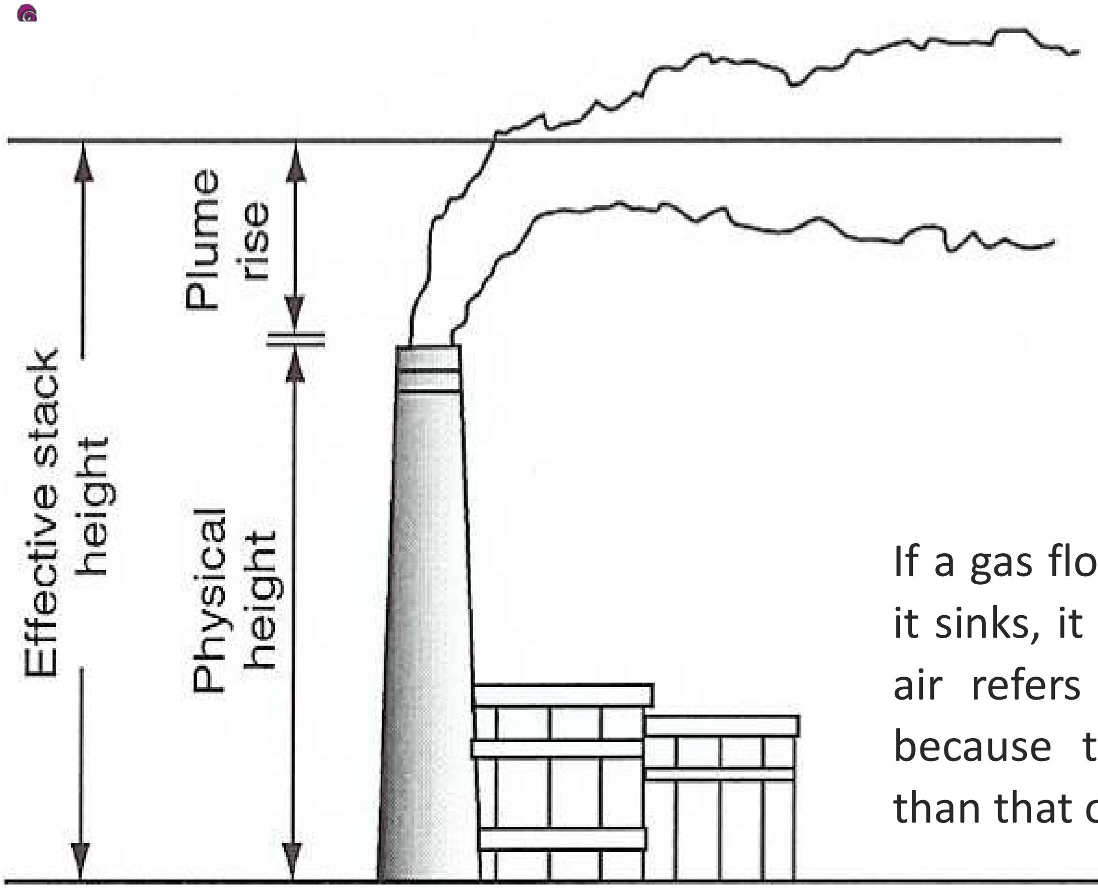
Pollutants enter the atmosphere in a number of different ways. For example, wind blows dust into the air. When plant material decays, methane is released. Automobiles, trucks and buses emit pollutants from engine exhausts and during refueling.
One method of pollution release has received more attention than any other: pollution released from stationary point sources, i.e. stacks. Stacks come in all sizes from a small vent on a building's roof to a tall stack. Their function is to release pollutants high enough above the earth's surface so that emitted pollutants can sufficiently disperse in the atmosphere before reaching ground level. All else being equal, taller stacks disperse pollutants better than shorter stacks because the plume has to travel through a greater depth of the atmosphere before it reaches ground level. As the plume travels it spreads and disperses, and pollutants degradation increases.

Plume Rise

Gases that are emitted from stacks are often pushed out by fans. As the turbulent exhaust gases exit the stack they mix with ambient air. This mixing of ambient air into the plume is called entrainment. As the plume entrains air into it, the plume diameter grows as it travels downwind.
These gases have momentum as they enter the atmosphere. Often these gases are heated and are warmer than the outdoor air. In these cases the emitted gases are less dense than the outside air and are therefore buoyant. A combination of the gases' momentum and buoyancy causes the gases to rise. This is referred to as plume rise and allows air pollutants emitted in this gas stream to be lofted higher in the atmosphere. Since the plume is higher in the atmosphere and at a further distance from the ground, the plume will disperse more before it reaches ground level.
The final height of the plume, referred to as the effective stack height (H), is the sum of the physical stack height (h_s) and the plume rise (Δh). Plume rise is actually calculated as the distance to the imaginary centerline of the plume rather than to the upper or lower edge of the plume. Plume rise depends on the stack's physical characteristics and on the effluent's (stack gas) characteristics. The difference in temperature between the stack gas (T_s) and ambient air (T_a) determines the plume density which affects plume rise. Also, the velocity of the stack gases which is a function of the stack diameter and the volumetric flow rate of the exhaust gases determines the plume's momentum..

Plume Rise

Plume rises from stack exit.



If a gas floats on air, it is less dense than air; if it sinks, it is more dense than air. Lighter than air refers to *gases* that are *buoyant* in air because they have average densities lower than that of air.

Plume Rise

$$\mathbf{H = h + \Delta h}$$

H : effective stack height

h : physical stack height (we could have physical constrain)

Δh : plume rise due to both thermal buoyancy and momentum

Correlations of various complexity exist between plume rise and stack gas temperature, stack gas velocity, atmospheric conditions, etc. (e.g. Holland's)

AFTER:

1. *Pollution Prevention*
2. *Air pollutants abatement (**with recovery**, whenever it is possible) by efficient APCDs),*
3. ***..we must do our best to disperse the emitted pollutants by tall stacks** (or better, **by tall plumes**).*

Stacks have a central role in the dispersion of pollutants into the atmosphere.

Under normal operating conditions, the installations are managed in such a way that the emissions do not exceed the emission levels prescribed by the competent authority, but …

EV emissions values are expected to be higher :

- during start-up and shut-down operations;
- in case of malfunctioning or breakdown of abatement equipments.

"The height of stack is calculated in such a way as to safeguard human health and the environment" ***(Art. 30 of Directive IED). A very poor definition!***

Specific indications are set in the Permits for mulfunctioning and start-up/shut-down periods.

<u>Exercise</u>. Several air polluted streams from different processes are conveyed in the same stack; the exit air stream velocity is 18.6 m/s. If the total air flow is reduced by 60%, due to the shutdown of some activities, what will be the effective rate of emission? Ans.: v = 7.4 m/s

<u>Resolution</u>:

$G_1 = A \times v_1$

Due to activities shutdown: $G_2 = A \times v_2$

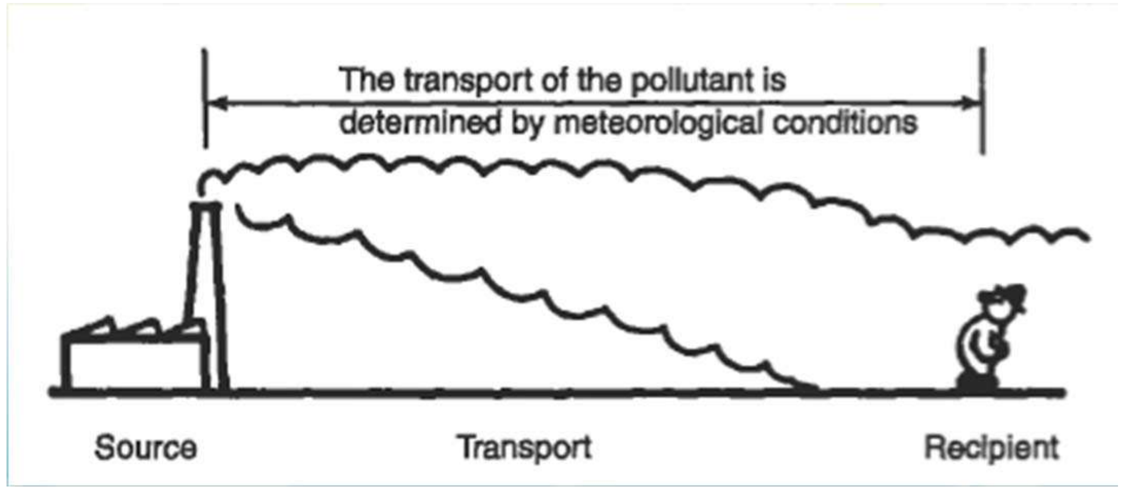
$A_1 = A_2 = A$ *(the stack exit section does not change!)*

$G_2 = 0.4 \times G_1$

$v_2 = G_2/A = 0.4 \times G_1/A = 0.4 \times [A \times v_1 /A] = 0.4 \times v_1 = 7.4$ m/s

WHAT WOULD YOU SUGGEST TO KEEP CONSTANT THE EXIT VELOCITY?... A decrease of the stack inner cross section!

Fumigation



To avoid "fumigation" or deposition of high pollutants concentrations → <u>rise the plume</u>, by:

1. high $v_{exit\ gas}$
2. high $T_{exit\ gas}$
3. high stacks

Recommended operating ranges (GEP)

- **$v_{exit\ gas}$ < 30 m/s ($\Delta P \propto v^2$; noise and vibrations at high ΔP): 10 ÷ 20 m/s**
- **$T_{flue\ gases}$ 100 - 150 °C (heat is wasted with hot flue gas!), better < 120 °C in summer**
- **Stack height: depends on place and applications: ≤ 250 m (in Italy)**

(GAS TURBINES: around 50 m; WASTE INCINERATORS: around 100 m; …)

FINAL CHOICE on $H_{effective}$ (= H + ΔH) for large, or impacting, plants are based on the results of the emissions dispersion modelling (e.g. based on CALPUFF + CALMET). CALPUFF (EPA) is a Lagrangian puff model widely used, which makes use of MM5 meteorological model outputs.
Dispersion modeling is a mathematical simulation of emissions as they are transported throughout the atmosphere.
These models replicate atmospheric conditions, (which includes wind speed and direction, air temperature and mixing height), and provide an estimate of the concentration of pollutants as they travel away from an emission source. They have a central role in the EIA procedures!!
They can also generate estimates of secondary formation of pollution by incorporating atmospheric chemistry into the model.
They are commonly used to determine whether a new source, or a change of existing sources, will adversely impact an area, or to predict whether the control of an individual source will have a beneficial effect. Dispersion models are used when a prediction of ambient concentrations is necessary, such as in a new source review or evaluating emissions reduction plans.

Parameters affect plume rise

Plume rise depends on both plume and ambient parameters

- Plume and stack parameters
  - Exit velocity
  - Stack diameter
  - Gas temperature
  - Stack height
- Ambiente air parameters
  - Stability
  - Wind speed
  - temperature

No law (EU and National) prescriptions concerning minimum or maximum:

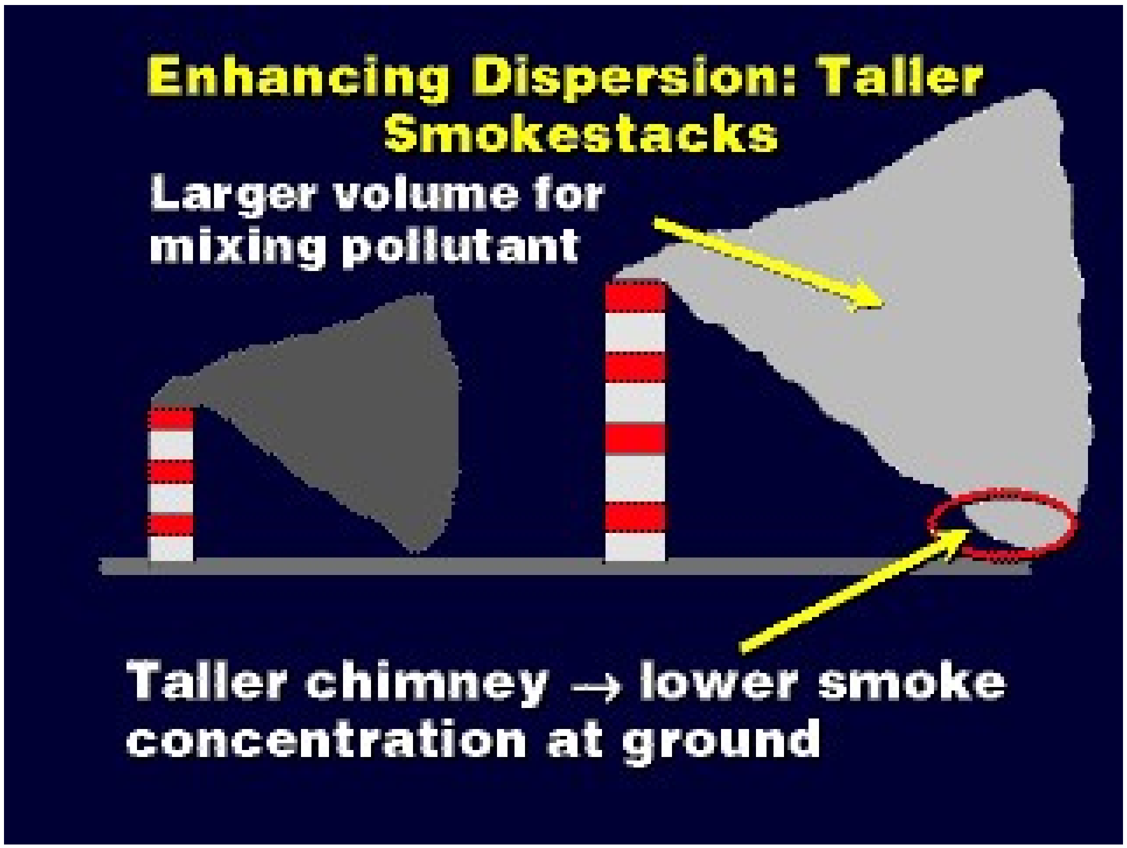
- stack height
- exit gas velocity
- exit gas temperature.

They are, however, often prescribed in the permits by Competent Authorities:

- EIA and/or IPPC permits;
- Ordinary emission to atmosphere permits (ex. Art. 269 D. Lgs. 152/2006).

Stacks height

Pollution emitted from a taller stack has to travel a longer distance to get to the ground, so it will become more diluted.



<u>Remember</u>: the longer the distance, the longer the atmospheric residence time for the pollutants, i.e. higher degradation!

Water cooling towers

Tallest chimney in ITALY - 250 m high

Centrale a carbone Torrevaldaliga Nord di Civitavecchia – Stack height 250 m (costruita negli anni **'60**).
I gas combusti sono espulsi in atmosfera attraverso una **ciminiera multiflusso** di altezza pari a 250 metri composta da **tre canne metalliche** (una per ogni sezione) aventi ciascuna diametro interno all'uscita di 5,7 m. **Brucia 4,5 milioni di tonnellate/anno di carbone e 150.000.000 Sm^3 di gas naturale (per le fasi di avviamento).**

MSWI in Padova – old stack, demolished in summer 2011

Old 1-flue stack, 60 m tall, connected to two ducts (*line 1 and line 2*).

Poor stack configuration: when one line was stopped → half exit gas velocity, and < T flue gas, ...).

Exit temperature about 100 °C *(visible plume → steam condensation; a wet scrubber on line 1, increased the H_2O content of the flue gas → higher dew point).*

MSWI in Padova – NEW stack

Old: 1-flue stack *demolished in summer 2011*

New: 3-flues stack
h = 80 m

Three WI lines. Each flue connected to 1 duct → one *line*.
Exit temperature about 100 °C (*no wet scrubbers* → less *visible plume*).
This is the best configuration of the stack that you can design:
1. no change in exit gas velocity, when one line is stopped;
2. higher plume rise, being a multiple-flue chimney.

A stack containing multiple flues, or multiple stacks close together, will have enhanced buoyancy and a higher plume rise (by 10 to 45%), and will therefore generate lower ground-level concentrations than would be the case if the flues or stacks were modelled as separate sources.

Brescia - MSW Incineration Plant – 3 lines (the biggest in Italy: 800,000 tonn/y)

Brescia - MSW Incineration Plant – 3 lines (the biggest in Italy: 800,000 tonn/y)

Spittelau waste incineration plant

Spittelau waste incineration plant
Vienna, decorated by Arch. Hundertwasser. The WI is connected to a district heating network.

The exhaust gas is released into the atmosphere at 115 °C through a **126 m** high stack.

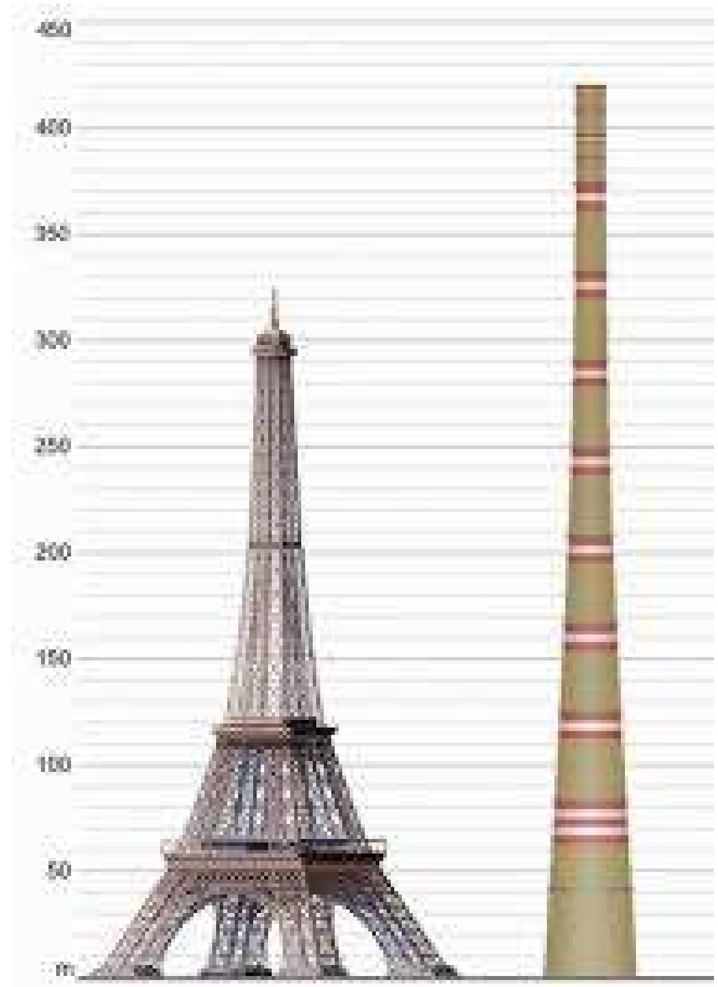
Trbovlje Chimney

The Trbovlje Chimney is the tallest chimney in EUROPE.

The 360 m high chimney of the coal power plant on the shore of the river Sava, Slovenia, was built in 1976 to spread the pollution over a much larger area of Central Slovenia, instead of concentrating it in a small, single spot.

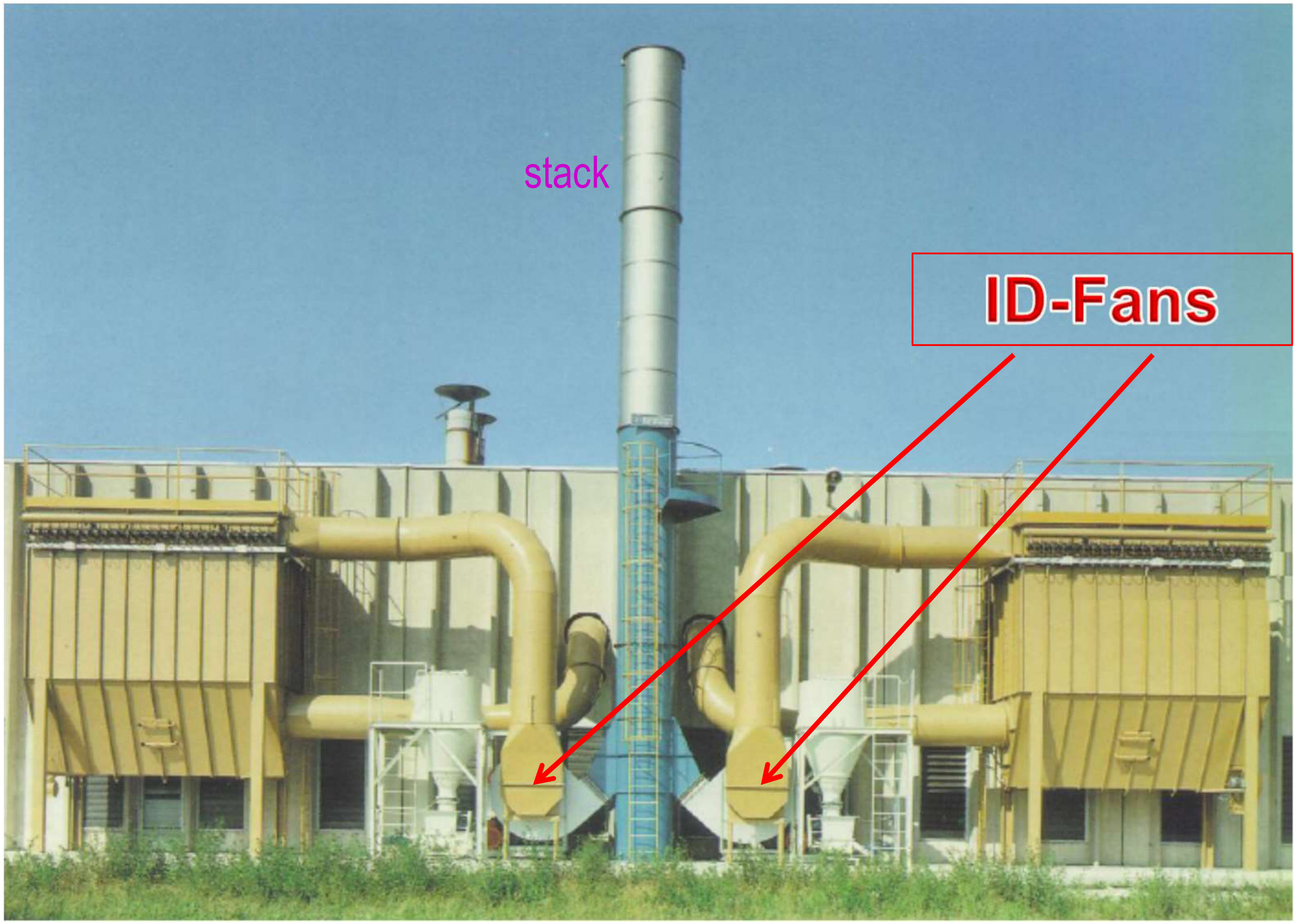
Power Plant in KAZAKHSTAN

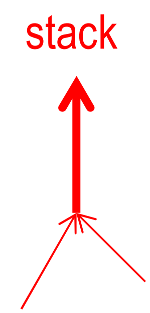
Comparison with Eiffel Tour



Flue gas stack at a coal Power Plant in KAZAKHSTAN is **420 meters tall**. Tallest chminey in the world.

Stack configurations:Two ID fans and one stack…...not the best!





You'd better prefer a 2-flues configuration in the same stack, instead of the single flue in the picture!
The exit velocity wouldn't change if one line were stopped, for some reasons (no production, maintenance, ..)

Stack configurations:Three ID fans and two stacks (1 for each line)…… the best!

A spare fan!

Stack configurations: MULTI-FLUE vs. SINGLE-FLUE STACKS

Whenever it is possible, we prefer multi-flue stacks to single-flue stacks! (e.g. multi-flue stacks: waste incineration plants in padova, brescia, acerra)

A LOT OF REASONS IN FAVOUR OF MULTI-FLUE STACKS:

- Lower cost
- Aestethic reasons
- Heat conservation (better thermal insulation)
- Unique monitoring platform (installation of elevators is possible, e.g. WI in Padova)
- ……..
- GREATER PLUME RISE of emitted waste gases! (lower heat dispersion, lower impulse decrease)

SINGLE-FLUE STACKS

MULTI-FLUE STACKS

AN EXAMPLE OF REVAMPING THE EXISTING STACKS

A PROJECT OF THAMES WATER AUTHORITY LONDON – MOGDEN STP (Sewage Treatment Plant)

Conveying the flue gas from engines burning the biogas produced by anaerobic digestion of sludge (production of electrical energy)

EXISTING PLANT

The existing **four flue stacks** on top of the Power House are being replaced by a free-standing multi-flue stack.

The proposed increased flue stack height, **from 15 to 26 metres**.

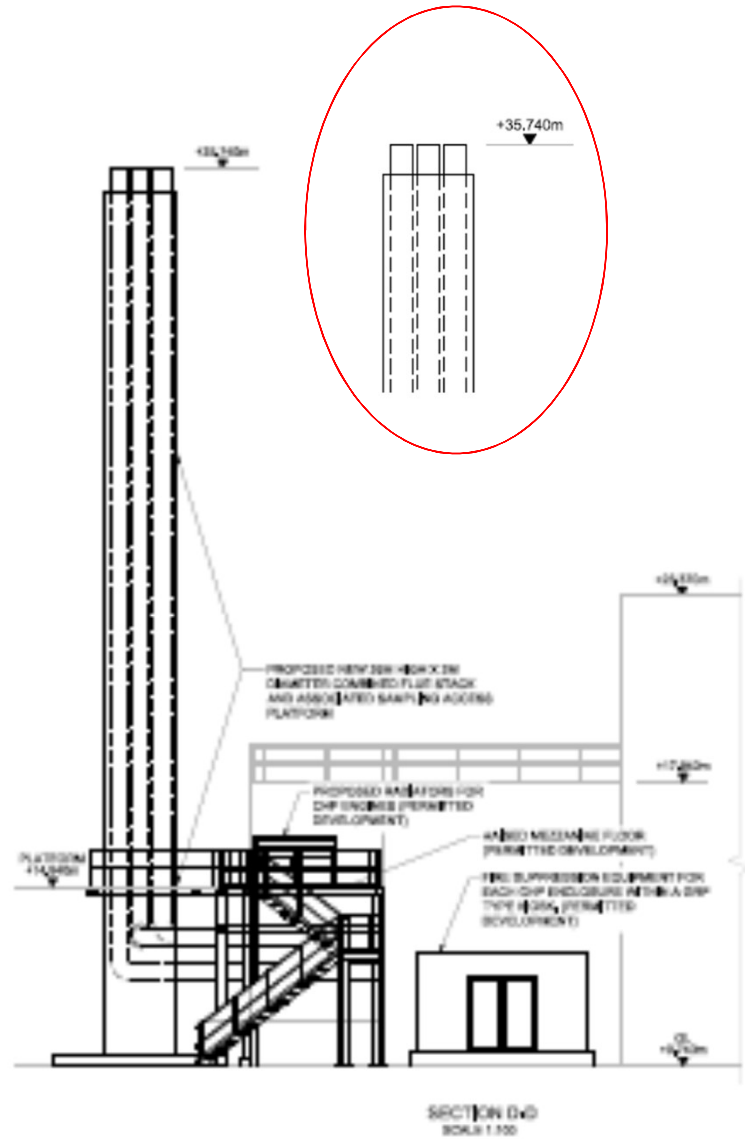
The CHP Plant currently comprises **four** dual-fuel compression ignition engines, each rated at 6.53 MW thermal input (MWTh) burning the biogas of LONDON – MOGDEN STP (Sewage treatm. plant).

AN EXAMPLE OF REVAMPING THE EXISTING STACKS

NEW PLANT

The proposed sewage gas spark ignition engines are each rated at 4.68 MW_{Th}. The 3-new engines are more efficient and each generates the same electrical output of 2.0 MWe as the normal operation of the existing engines. ($\eta \sim 40\%$)

The proposed 3-flues stack will discharge the emissions of the new CHP engines that will replace the existing ones in the Power House



Aesthetic considerations, local regulations, safety reasons(*) (static, corrosion, erosion..), cost, ... can prevent the construction of tall stacks!!|

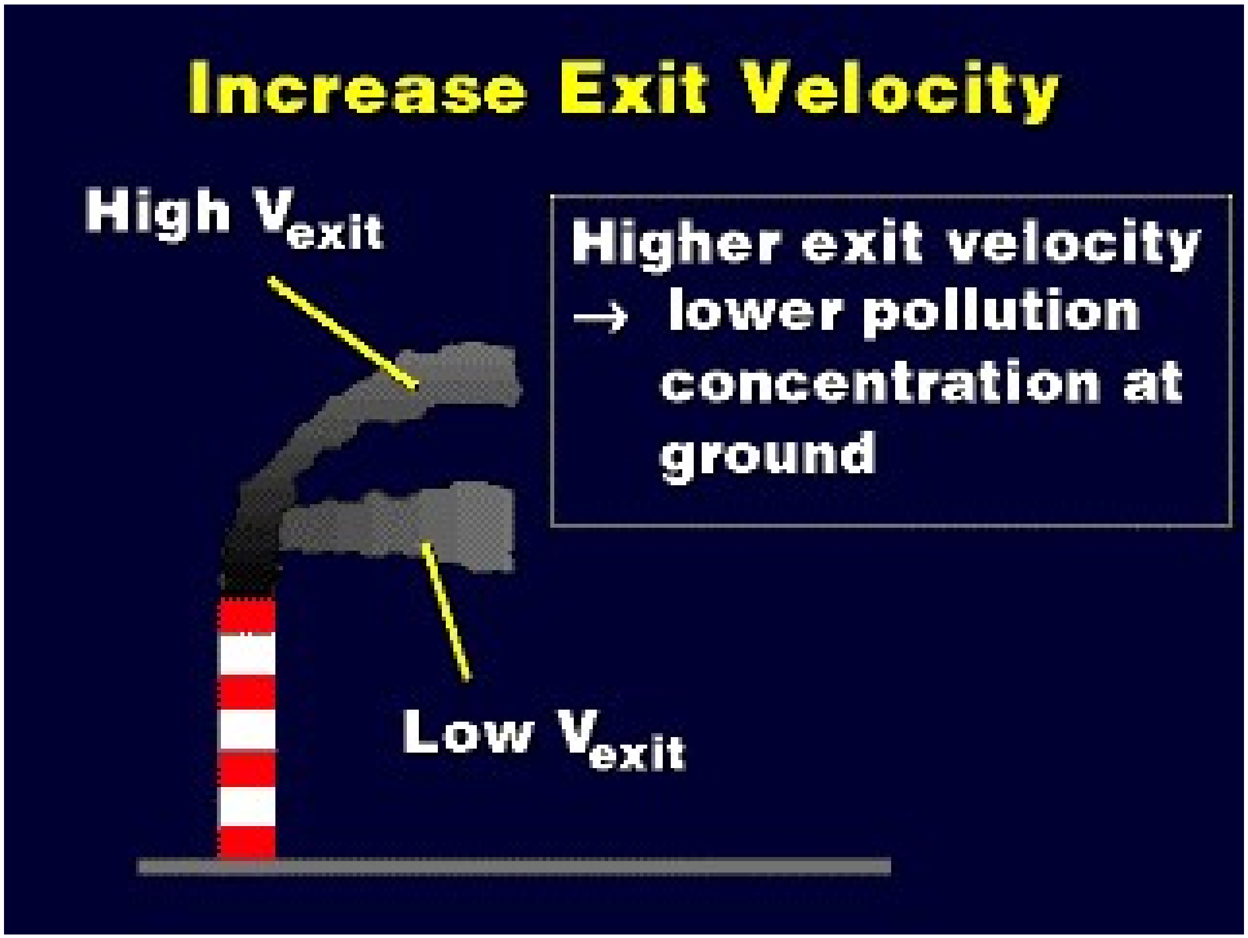
In such events, plume rise - *without raising the chimney* – becomes the only solution.

(*) Collapse of chimneys were not exceptional events in the past because of serious damage due to:

1. more frequent start-up and shut-down *(thermal shocks),*
2. much higher contents in the flue gases of corrosive species (HCl - incinerators, and SO_2 - power plants), abrasive dusts, more humidity, .., and
3. poor thermal insulation of stacks.

Exit Velocity

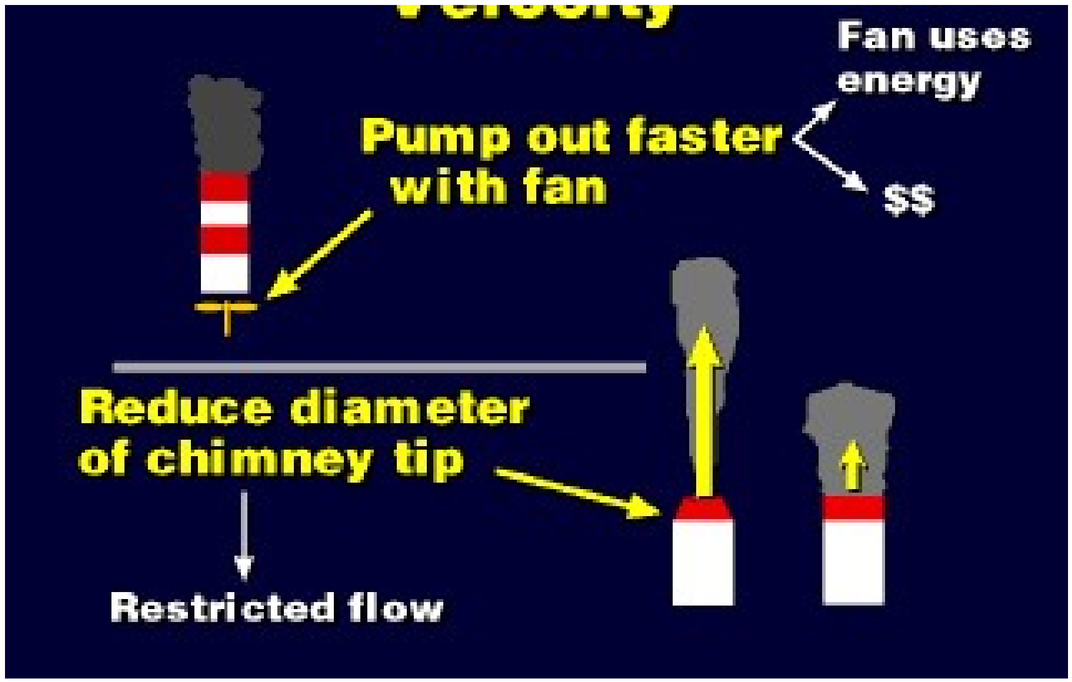
The faster the smoke comes out, the more momentum it has, and the higher it will fly before it levels out and disperses toward the ground.



Momentum
$p = m\,v$

Methods for Increasing Exit Velocity

Narrowing the stack's opening, forces the smoke out as a faster streaming, narrower jet.



G *= exhaust gas flow rate, m³/s*
A *= exhaust stack area, m²*
v *= exhaust gas exit velocity, m/s*

G = **A** x **v = const.** *(The gas flow is considered incompressible since the pressure changes are small).*

Issues Associated with reduced exit velocity exhaust stacks

PRO:

- Smaller fan or motor requirements
- Lower energy consumption
- Reduced noise and vibration

CONS:

- Stack-Tip-Downwash
  - Decresed plume rise
  - Increase downwind concentrations
  - Need for greater stack height
- Potential rain infiltration

Exercise: Increasing Exit Gas Velocity

Given that the stack gas velocity is 17 ms^{-1}, the internal stack diameter is 2.5 m, calculate the required stack diameter to increase the gas velocity to 22 ms^{-1}.

Resolution

A narrower tip diameter is required.

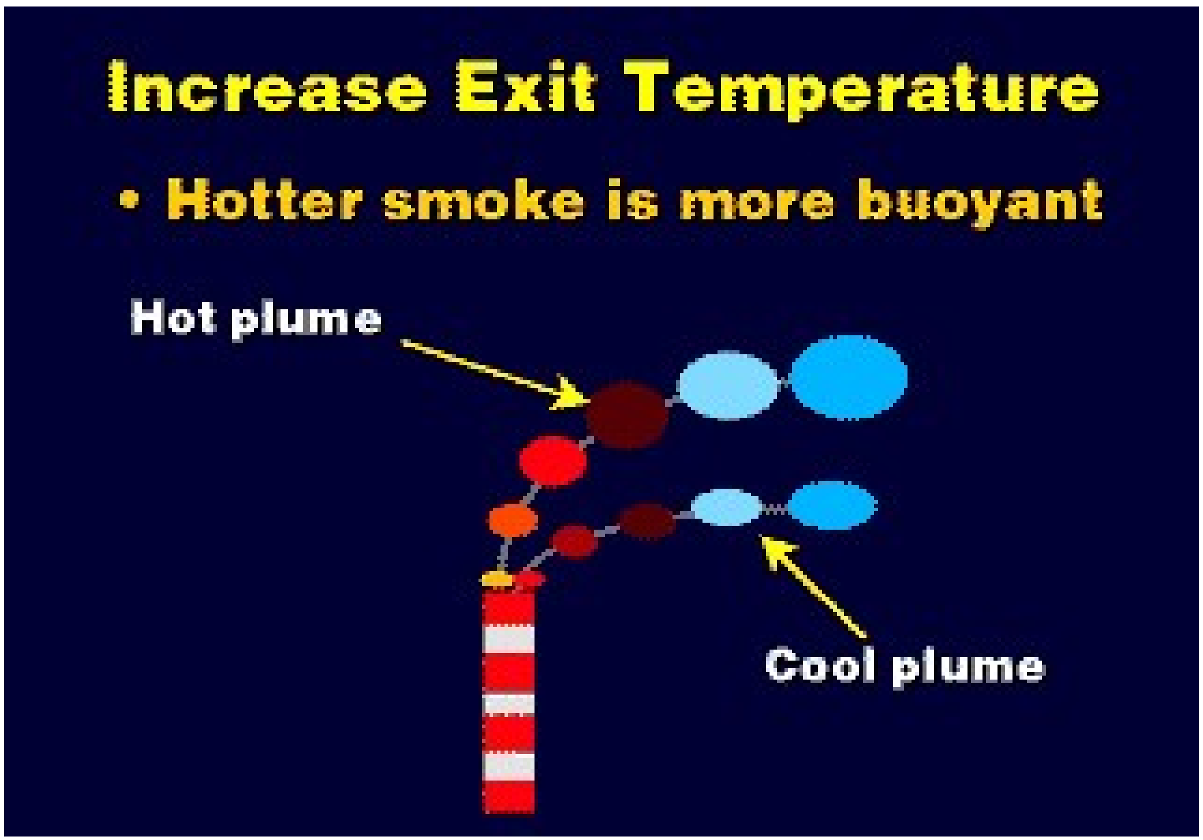
$\boldsymbol{G = A_1 v_1 = A_2 v_2}$

$A_2 = A_1 \times v_1 / v_2 = [3.14 \times (2.5)^2 / 4] \times 17/22 = 3.80\ m^2$

$\boldsymbol{D_2 = 2.2\ m}$

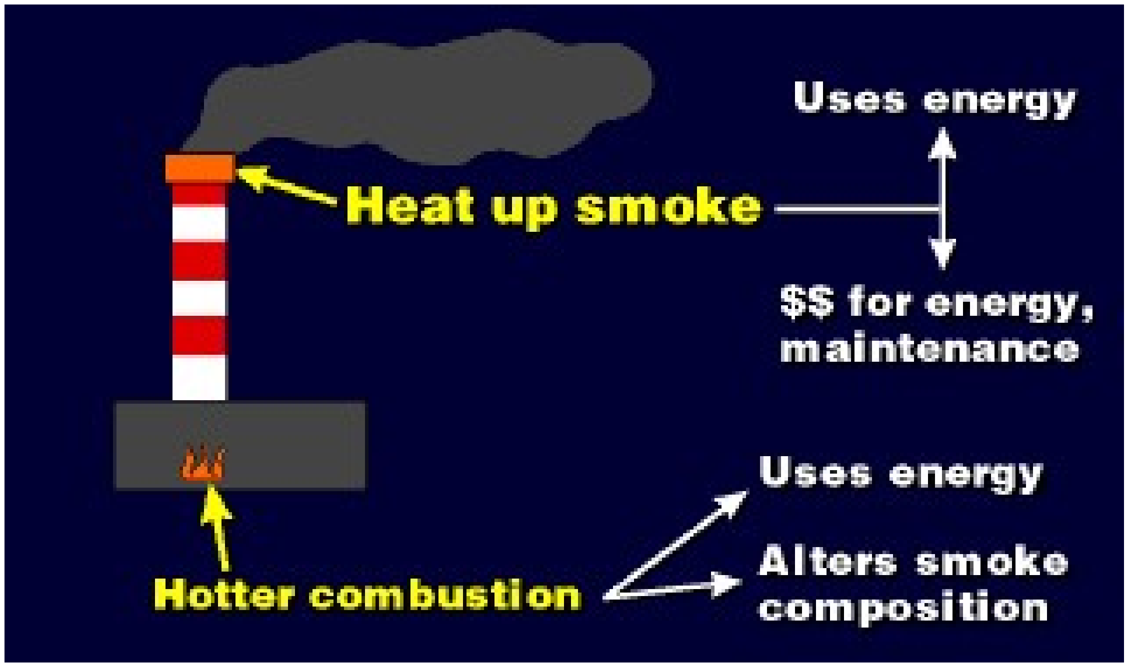
Exit Temperature

The higher the temperature, the greater the positive buoyancy in smoke streaming out of the smokestack.
The smoke has to rise higher before it has adiabatically cooled to a neutral buoyancy temperature



T effects on:
- Flue gas density
- Volume of gas flow

How to increase exit temperature



Heat exchanger before the chimney

or

Post-heating (afterburner)

Maximum Downwind Ground-Level Concentration (C_{max})

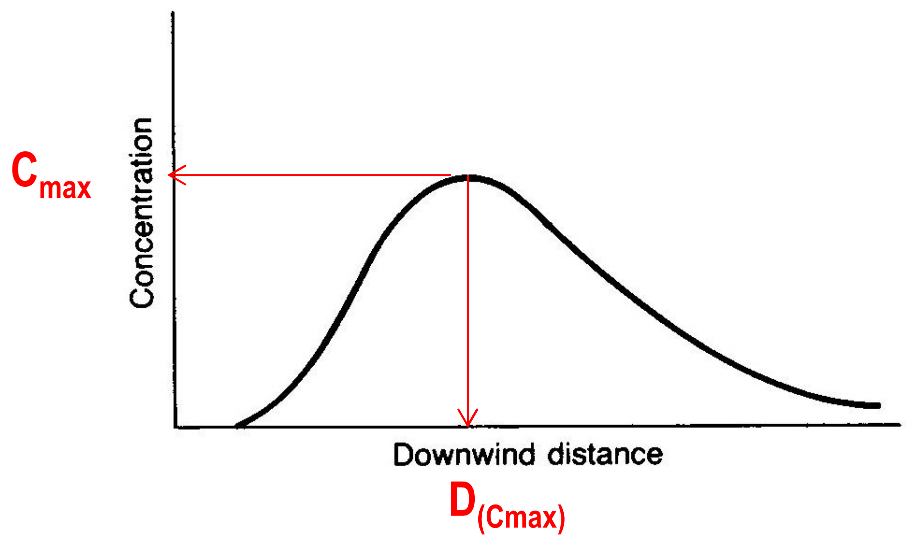
- Suppose that a chimney emits *q* kgs^{-1} of pollutant, the height of the chimney is *h* m, and the wind speed at chimney height is *u* ms^{-1}.
- It has been shown that at ground level the **maximum pollutant concentration C_{max}** is:

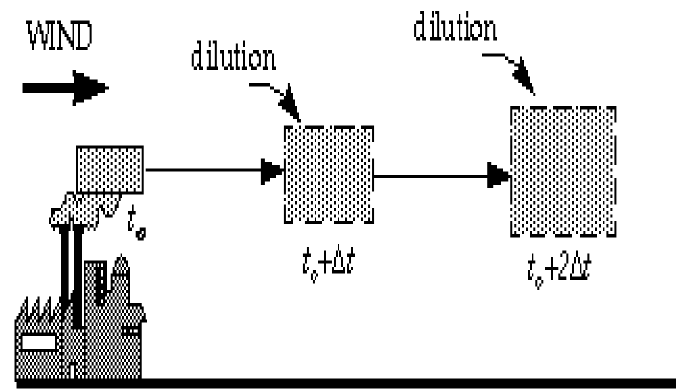
$$C_{max} \propto q / (h^2 u)$$

- Note that the maximum concentration decays with the inverse square of the chimney height — **so tall chimneys are always a good idea**.
- Note also, however, that to predict the dispersion, we need to know the wind speed at chimney height. This can be measured directly, or inferred from measurements closer to the ground using the logarithmic velocity profile.
- Indeed, instead of the stack physical height, the effective stack height can be used to obtain a more realistic picture.

Maximum Downwind Ground-Level Concentration (C_{max})

- Pollutants travels to some distance before reaching the ground.



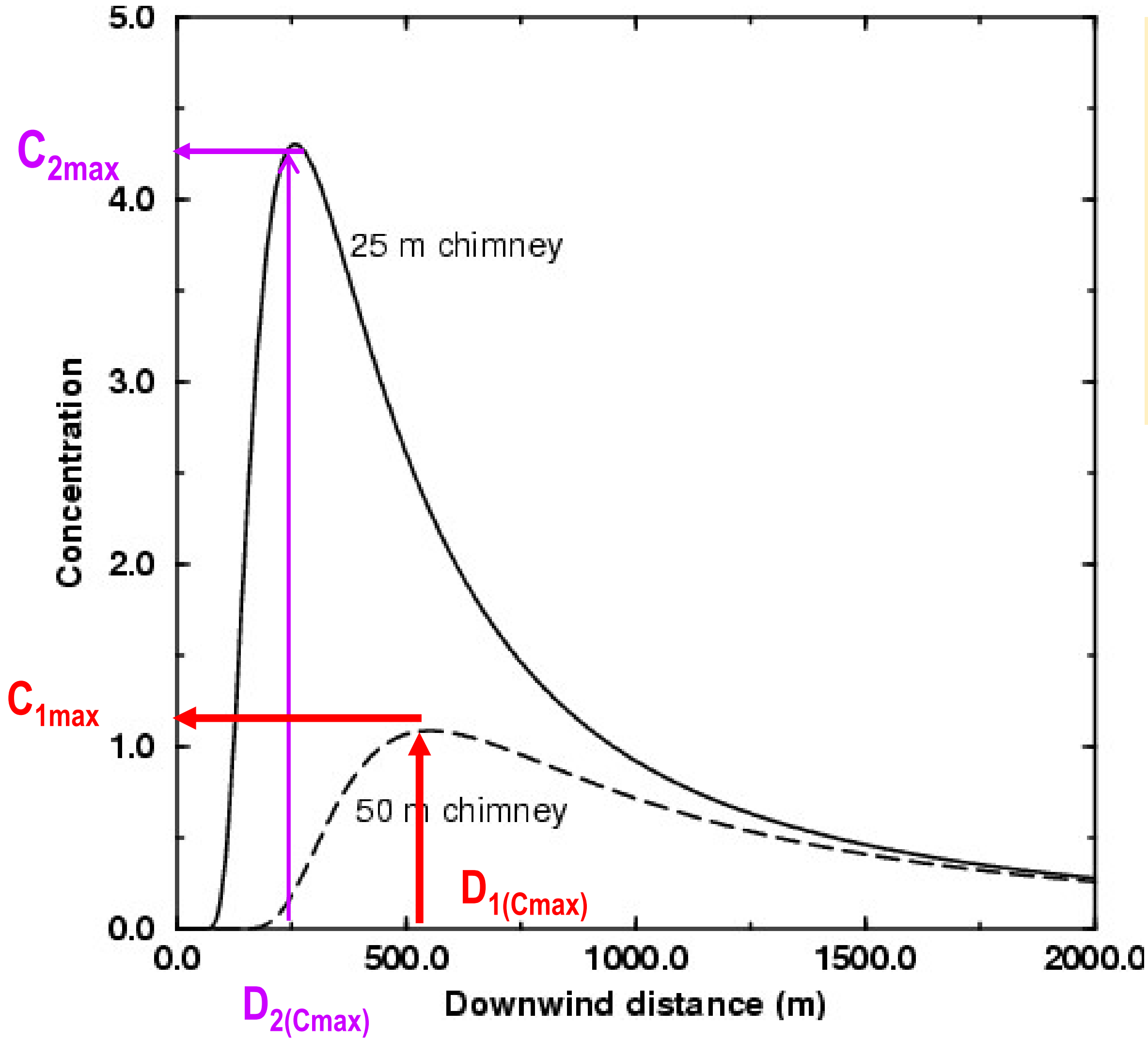


- C_{max} decreases as effective plume height, H, increases.
- Distance to C_{max} increases as H increases.

Short distance dispersion → higher ground concentration
(more negative effects → environment/health: people living nearby, but also workers inside the installation → safety concern!).

Long distance dispersion → better dilution, no acute local health problems and less chronic problems; longer residence times for the emitted pollutants before reaching the ground.

Maximum Downwind Ground-Level Concentration (C_{max}): plume height influence

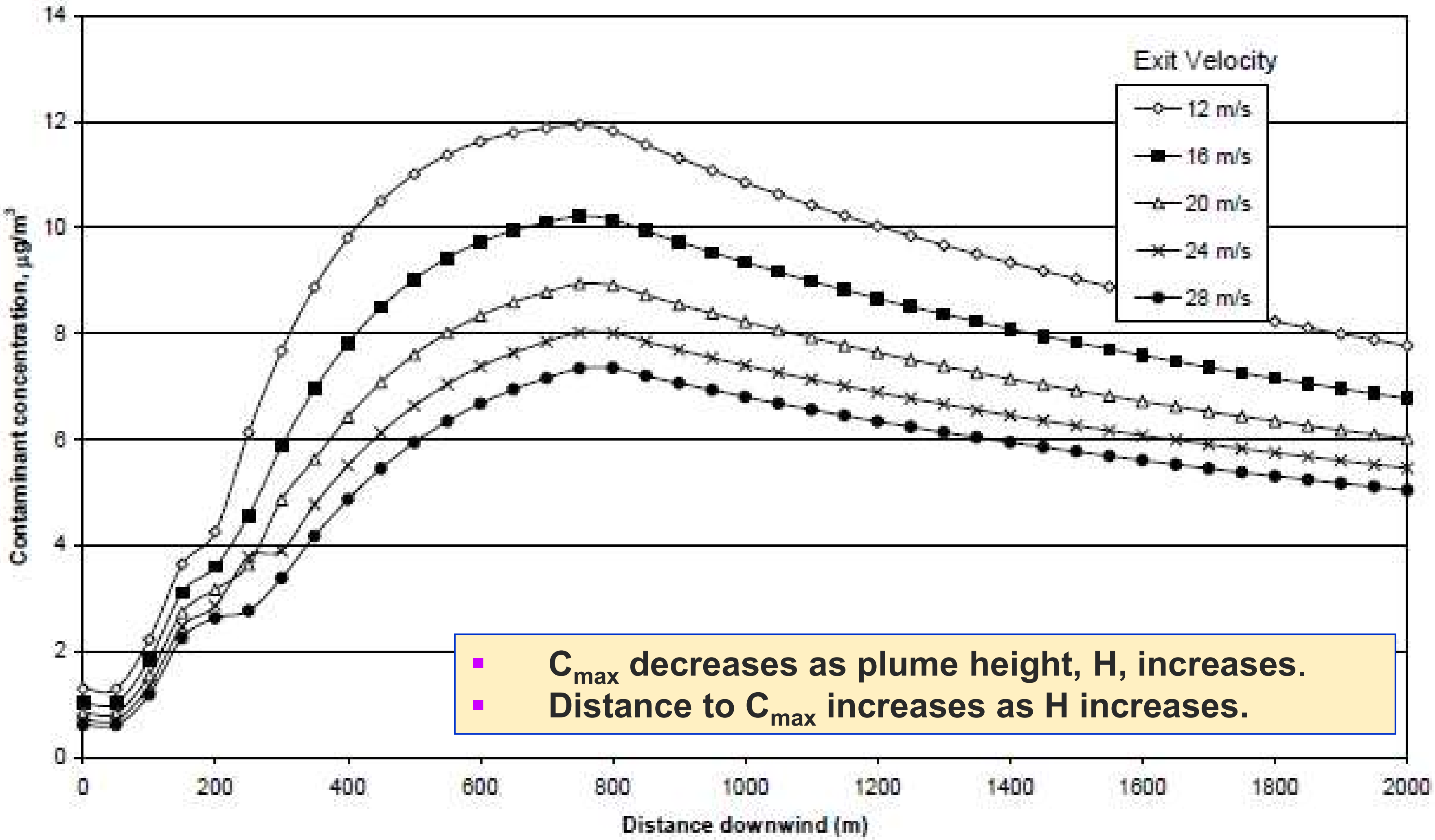


- C_{max} decreases as plume height, H, increases.
- Distance to C_{max} increases as H increases.

Ground-level concentrations from two chimneys of different heights (other parameters being unchanged)

Maximum Downwind Ground-Level Concentration (C_{max}): exit velocity influence

Example of the effect of exit velocity on dispersion (stack height = 30m)



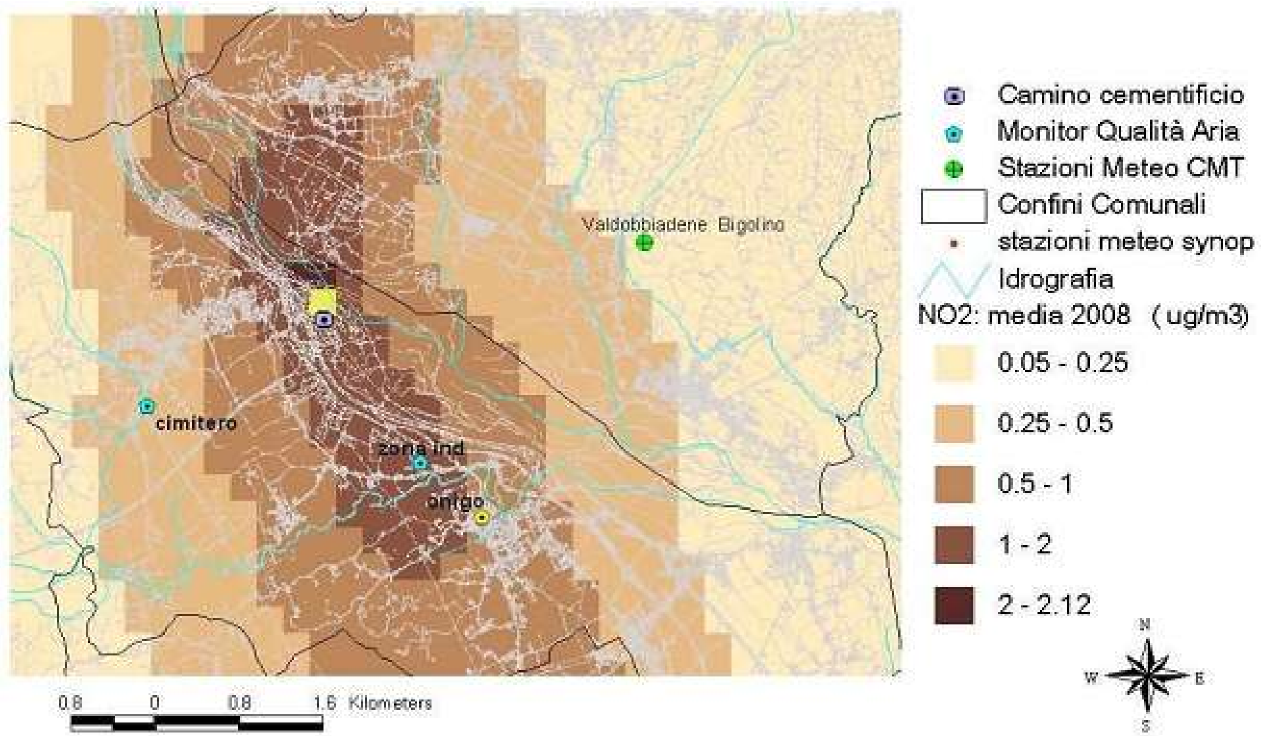
- C_{max} decreases as plume height, H, increases.
- Distance to C_{max} increases as H increases.

Predicting ground pollution effects

Several well proven air dispersion models that take account of all the described factors are available (e.g. Calpuff + Calmet). They require specialist expertise in air sciences, environmental engineering and computing.
Air pollution concentrations (***deposition concentrations***) can be predicted by use of validated models of air pollutants dispersion and meteorological data elaboration.

The results are usually plotted as concentration isopleths on a map around the source. An isopleth is a line joining points of equal predicted concentration.
It is possible to produce concentration isopleths for time periods corresponding to the averaging periods in different air quality goals.
For example, for nitrogen dioxide, figures could be drawn separately to show isopleths for any or all of the predicted 1-h and annual average concentrations. *(see example in next slide)*

Predicting ground pollution effects



Modellistica di dispersione degli inquinanti atmosferici dal Cementificio Rossi di Pederobba (Treviso)

[Doc. Arpav: http://www.arpa.veneto.it/arpav/chi-e-arpav/file-e-allegati/dap-treviso/cementi-rossi/modellsitica_qa_sintesi.pdf/view]

Predicted ground pollution: **NO_2 ($\mu g/m^3$)** for 2008.

Air Quality Standards – EU

Annual average limit value for NO_2: 40 $\mu g/m^3$

That is: **5% of annual limit = 2.0 $\mu g/m^3$**

Conclusion: predicted maximum deposition is slightly higher than 5% of the limit.

Background air quality

In undertaking an assessment (*e.g. EIA - Environmental Impact Assessment*), consideration must also be given to the existing air quality of the area surrounding the stack(s), the so-called existing background concentrations due to the diverse range of activities operating, which will not be included in the dispersion modelling.

Both predicted deposition concentrations from new or modified installations and background concentrations are important in EIA procedures.

Pollutant ground concentration = background + predicted deposition
in all cases the concentration estimates are assumed to be the sum of the pollutant concentrations contributed by the source and an appropriate background concentration.

Often information on existing air quality will not be available and it must be estimated from nearby, or similar, areas.

In areas with high background concentrations the addition of a new emission source may result in unacceptable predicted air quality impacts, requiring the consideration of mitigating measures.

STACK TIP DOWNWASH

For $v_s < u_s$

(v_s stack gas velocity, u_s wind velocity at stack height)

Building downwash

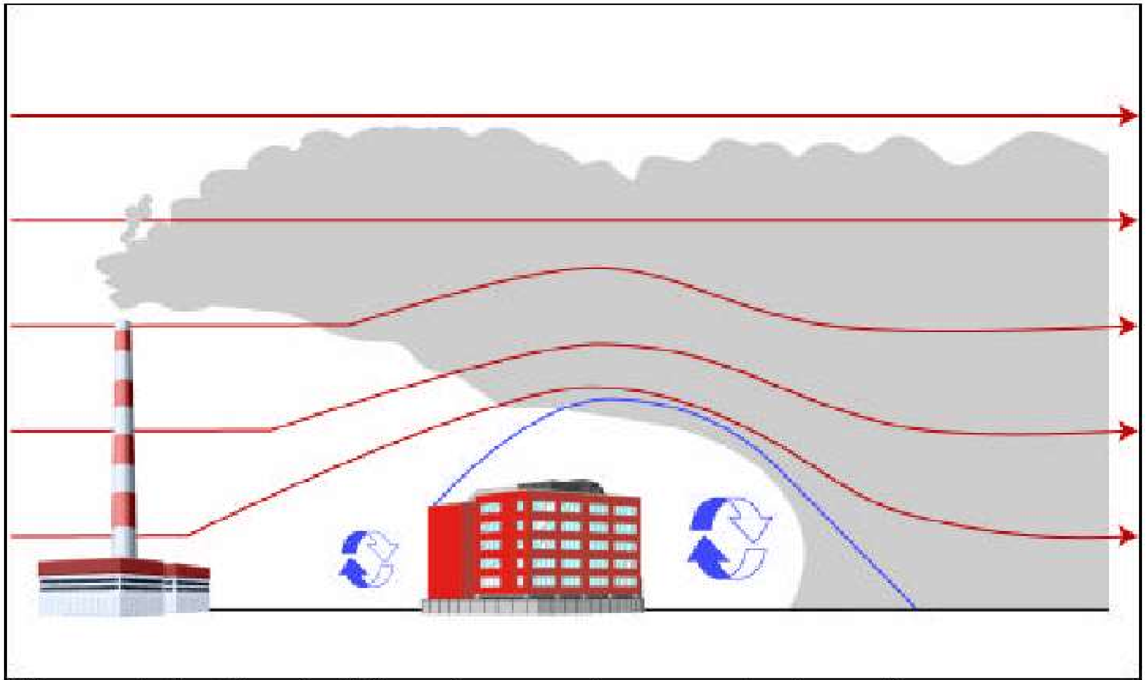
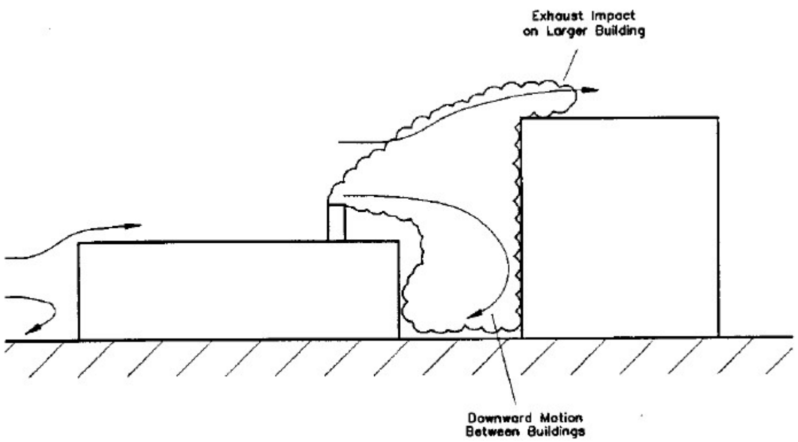
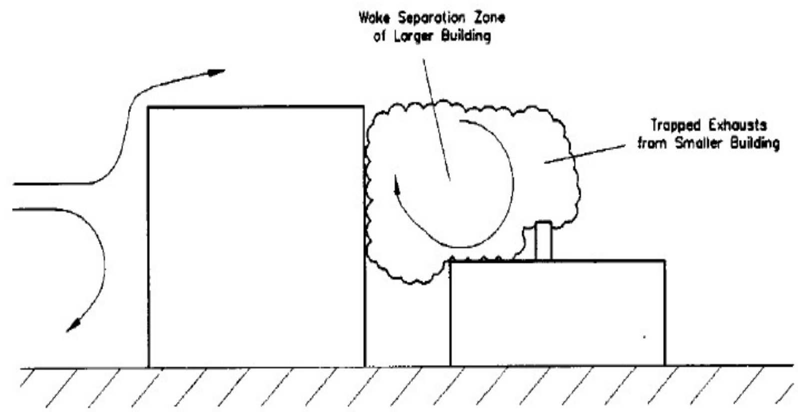
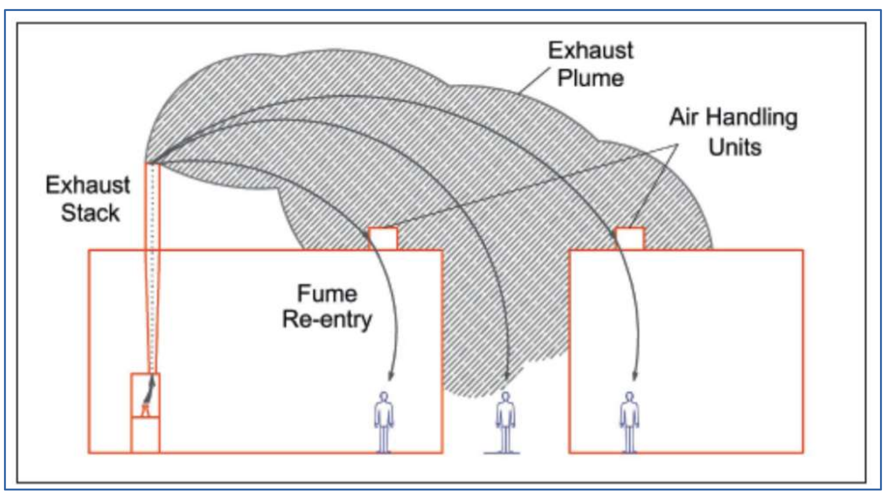


Figure 4.4 - The building downwash concept where the presence of buildings forms localized turbulent zones that can readily force pollutants down to ground level.

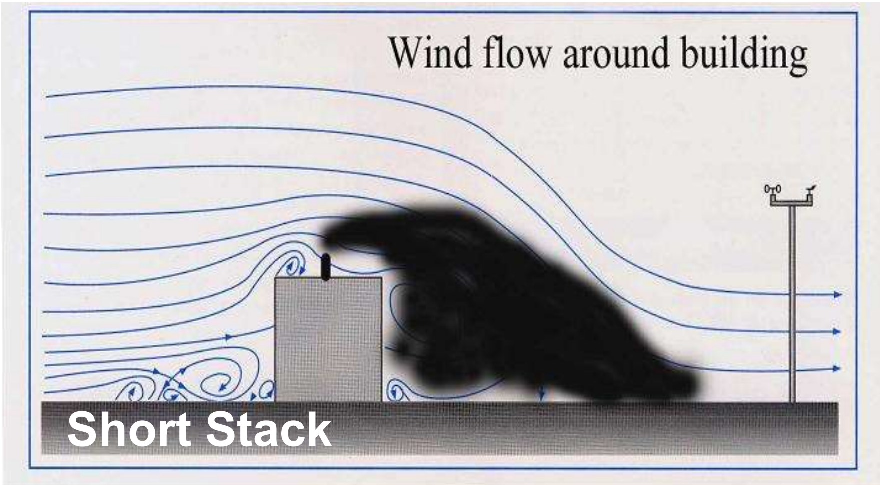
Effective plumes not high enough!

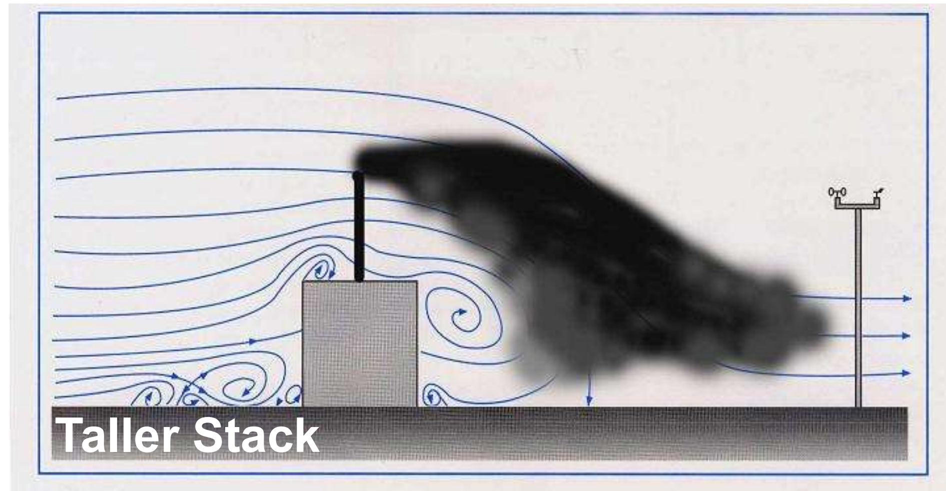


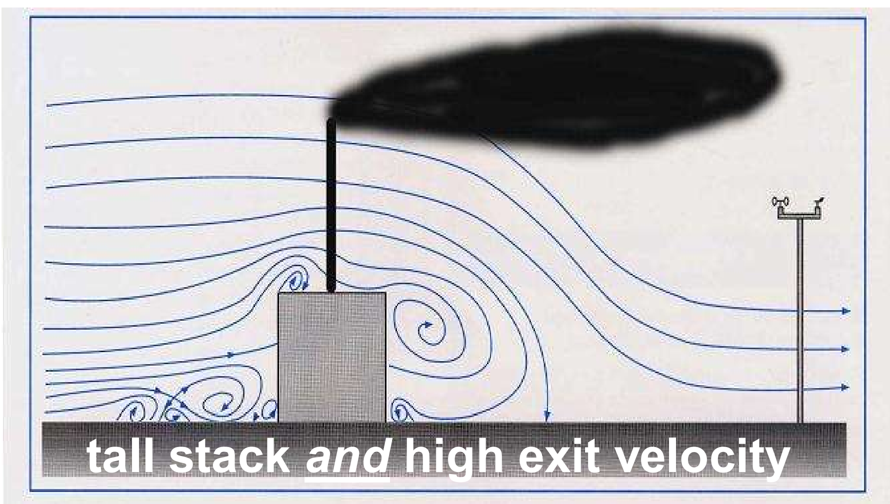




Building Downwash







Enhanced Plume Rise due to Closely Spaced Stacks

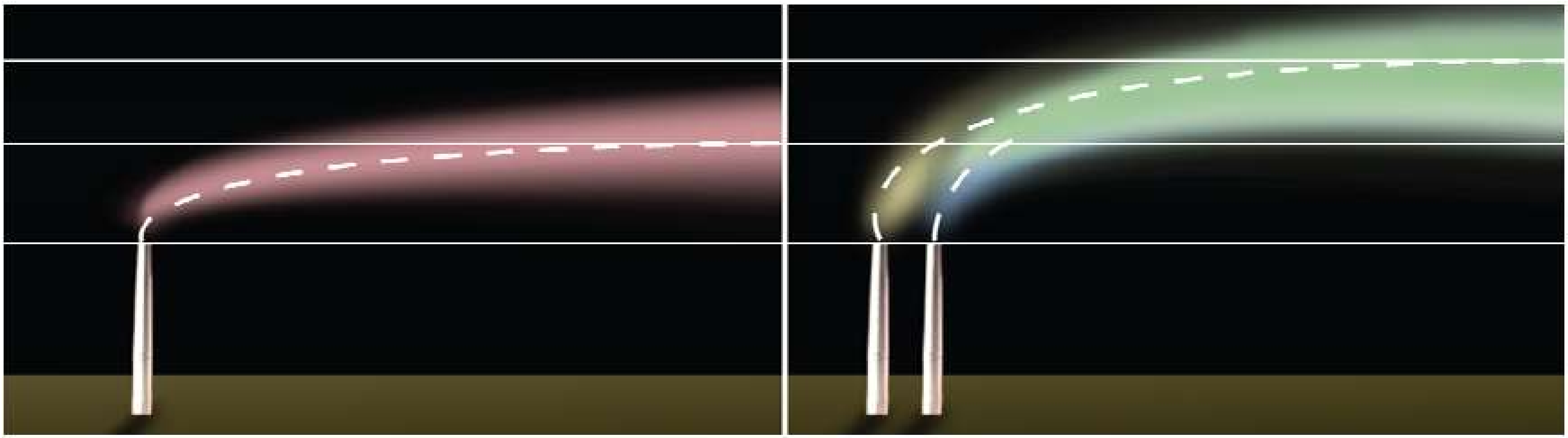
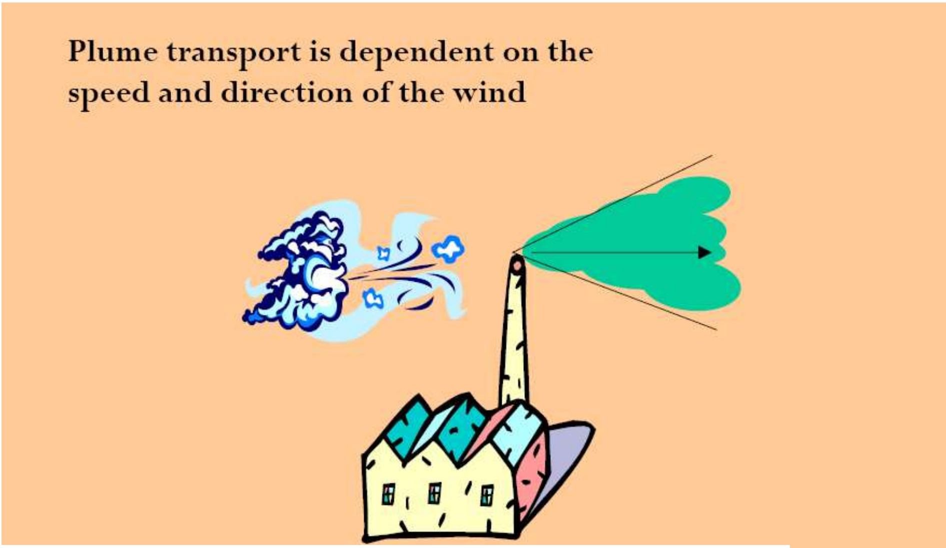


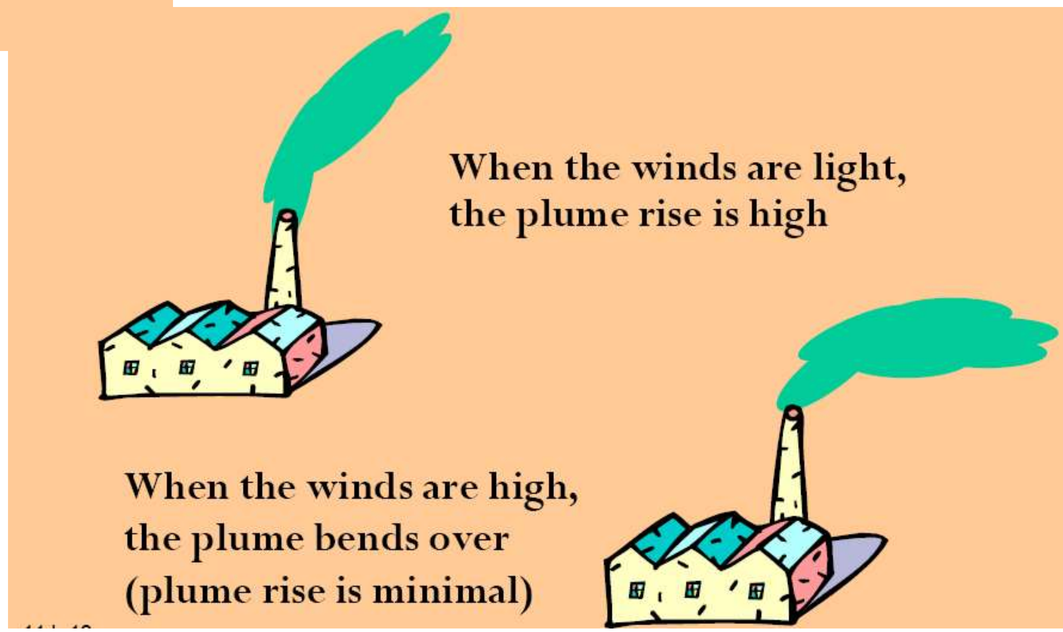
Figure: Rendering of typical plume visualization.

Plume rise due to stack ganging versus a single stack with the same flow parameters.

Plume rise enhancement for stack spacings of less than 2 to 3 stack diameters.

Metereological wind





Calculation of Effective Stack Height

$H = h_s + \Delta h$, where Δh is the plume rise.

* **Carson-Moses Equation:**

$$\Delta h = -0.029 \frac{V_s \cdot d}{u_s} + 2.62 \cdot \frac{\left(Q_h^{\frac{1}{2}}\right)}{u_s}$$

* **Holland Formula:**

$$\Delta h = \frac{V_s \cdot d}{u_s} \cdot \left[1.5 + 0.0096 \frac{Q_h}{V_s d}\right]$$

* **Concawe Formula:**

$$\Delta h = 4.71 \cdot \frac{Q_h^{0.444}}{u_s^{0.694}}$$

Where: $Q_h = m * Cp * (Ts - Ta)$

Q_h is the heat emission rate, *kJ/s*

m is the stack gas mass flow rate, *kg/s*

Calculation of Effective Stack Height: most popular equation HOLLAND'S EQUATION

$$\Delta h = \frac{V_s D}{u}\left(1.5 + 0.00268 \cdot P \cdot D \cdot \frac{(T_s - T_a)}{T_s}\right)$$

$\Delta h =$ plume rise, m
$V_s =$ stack exit velocity, m/s
$D =$ stack diameter, m
$u =$ wind speed, m/s
$P =$ pressure, mb (millibars)
$T_s =$ stack gas temperature, K
$T_a =$ ambient temperature, K

We observe an increase of Δh if:

1. *Vs increases*
2. *D increases*
3. *ΔT increases*

... as expected!

In industrial applications P is always very close to 1 atm, i.e. 1013 mbar.

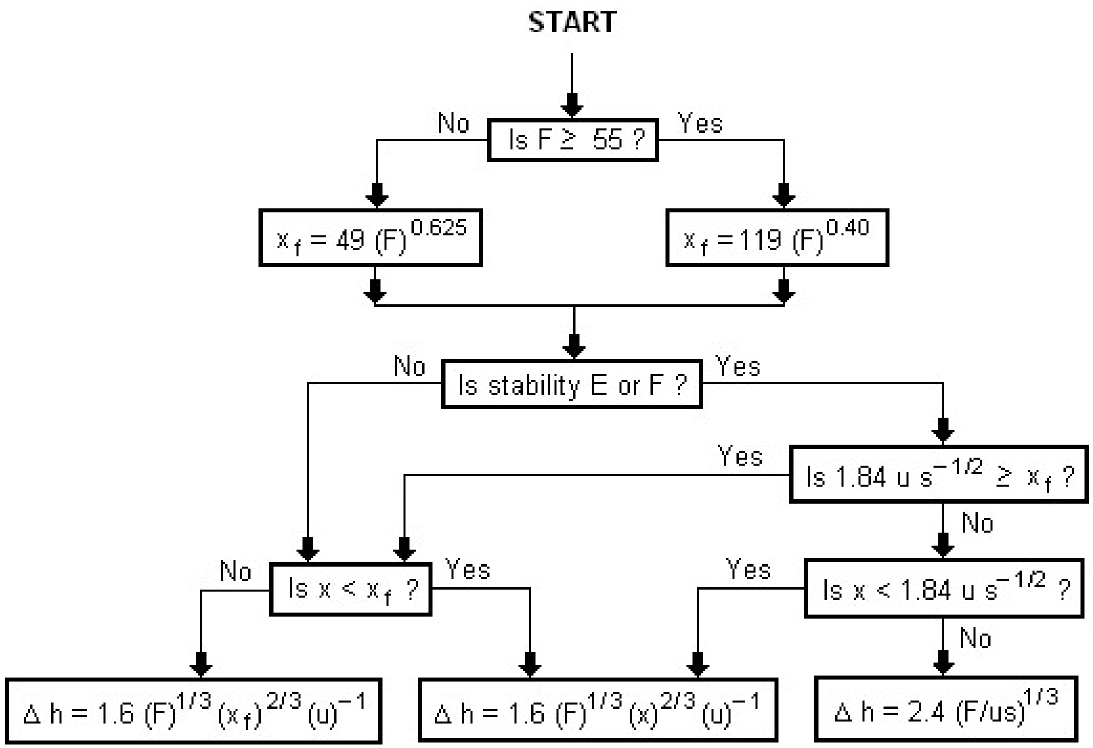
The plume rise due to the buoyancy of the emitted gaseous flow, Δh_B, is closely dependent on the gas flow rate, G. In fact, the second term would be: const x V x D^2 x $\Delta T/T_s$, or: $\mathbf{\Delta h_B = const \times G \times \Delta T/T_s}$

The Holland formula is valid for neutral condition and the plume rise obtained by it it should be corrected for other than neutral stability. Suggested multiplicative correction factors are 1.1 or 1.2 for class B or A stability and 0.9 or 0.8 for class E or F stability, respectively.

Buoyant plumes — Plumes which are lighter than air, because they are at a higher temperature and lower density than the ambient air which surrounds them (e.g.flue gases), or because they are at about the same temperature as the ambient air but have a lower molecular weight and hence lower density than the ambient air.

Calculation of Effective Stack Height: BRIGGS' EQUATIONS

LOGIC DIAGRAM FOR BRIGGS' EQUATIONS TO CALCULATE THE RISE OF A BUOYANT PLUME



Briggs recognized that even after a plume was bent over by the wind it continued to rise, owing to its thermal buoyancy.
Thus, his equations predict Δ**h** as a function of a buoyancy flux term $\mathbf{F_B}$ (or **F**) which is usually dominated by thermal buoyancy, wind speed and distance downwind. After a "long enough" travel time (or distance downwind, $\mathbf{x_f}$) the plume reaches its final rise.

Where:

- F buoyancy flux term
- u mean wind speed at stack height
- s is stability parameter
- xf is downwind distance to the point of final plume rise

Calculation of Effective Stack Height: BRIGGS' EQUATIONS

The buoyancy flux term, F_B (or F) is given as:

$$F = g * \left(1 - \frac{MW_s}{28.9}\right) * \left(\frac{T_a}{T_s}\right) * \left(\frac{v_s * {d_s}^2}{4}\right) + 8.9 * \left(\frac{P_0}{P_a}\right) * Q_H$$

Where:

- F= buoyancy flux (m^4/s^3)
- g= gravitational constant, 9.8 m/s^2
- MW_s= molecular weight of stack gas (approximately equal to 28.9)
- P_0= standar sea level pressure, mb
- T_a= atmospheric temperature, K
- T_s = stack gas temperature, K
- d_s = stack inner diameter, m
- V_s = stack gas velocity, m/s
- Q_H = heat emission rate, MW

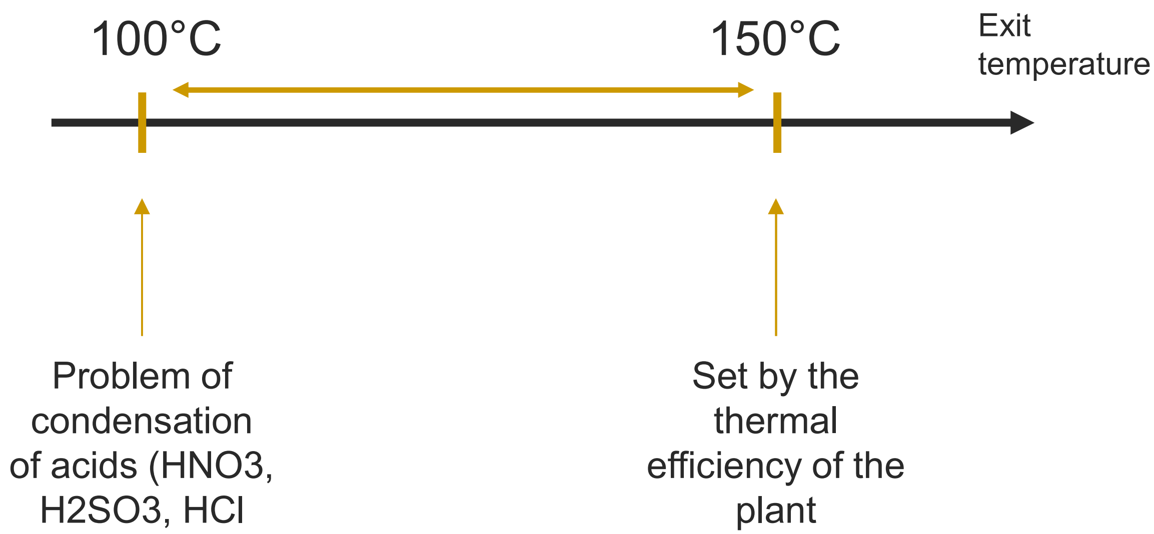
The parameter s (or S), stability parameters in s^{-2}, is given as:

$$s = \frac{g}{T_a} * \left(\frac{\Delta\theta}{\Delta z}\right)$$

Where:

- T_a= atmospheric temperature, K
- g= gravitational constant, 9.8 m/s^2
- $\frac{\Delta\theta}{\Delta z}$ = potential temperature gradient, K/m

Which stack gas temperature?



Exercise: calculation plume rise

Estimate the plume rise for a 2 m diameter stack whose the exit gas has a velocity of 34 m/s when the wind velocity is 4 m/s, the pressure is 1 atm, and the stack and surrounding temperatures are 85°C and 33 °C, respectively.

Solution: Δh = 38.9 m

Be careful: few applications have exit gas velocities > 20 – 25 m/s.

Exercise: calculation plume rise (2)

(T_s=393 K; T_a = 293 K (*ΔT = 100 ℃*); P = 1013 mbar; u = 0.3 m/s

Gas flow rate, G = 72,000 m^3/h *(=20 m^3/s)* = **constan**t

Case 1: v = 10 m/s, calculated D = 1.6 m; Δh = ?

$G = v \cdot (\pi D^2/4)$

Case 2: v = 20 m/s; calculated D = 1.13 m; Δh = ?

Case 2 T: The same as case 2), but Ts = 353 K (*ΔT = 60 ℃*): Δh = ?

.. What if u = 3.0 m/s?

Be careful when you will discuss case 2 T: Decreasing the gas temperature, at constant m', also decreases the gas flow **($G_2 / T_2 = G_1 / T_1$)**
G at 60°C will be 18.0 m^3/s, lower than 20 m^3/s . Then, with the same diameter (1.13 m), the effective gas speed will be lower.

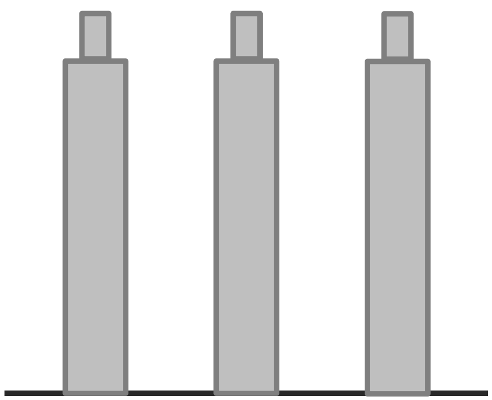
Exercise: calculation plume rise (3)

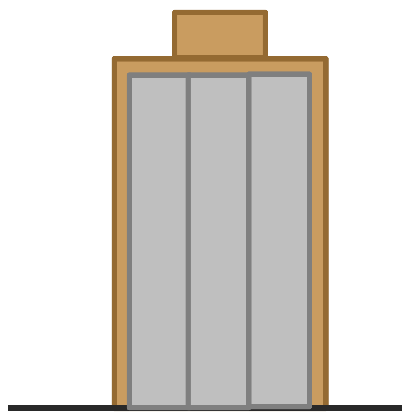
By putting more combustion flues inside the same stack which advantage can we get in term of plume rise?

Consider the following two scenarios:

Case a) We consider 3 independent stacks**;** each of them has 2 m diameter whose the exit gas has a velocity of 34 m/s when the wind velocity is 4 m/s, the pressure is 1 atm, and the stack and surrounding temperatures are 85°C and 33 °C, respectively (see previous exercise)

Case b) We consider only a stack of 6 m diameter with a flow equals to the sum of the flows of the 3 stacks of scenario a); the wind velocity is 4 m/s, the pressure is 1 atm, and the stack and surrounding temperatures are 85°C and 33 °C, respectively (see previous exercise)





This is the case of incinerator of Padua

If the distance between chimenys is lower than 2-3 diameters they work as a whole
The thermal insulation of case b) is better than case a), therefore the temperature Ts is higher

REGIONE LAZIO. PIANO DI RISANAMENTO DELLA QUALITA' DELL'ARIA - Norme di Attuazione

4) **Le bocche dei camini degli impianti devono essere posti almeno ad un'altezza minima dal suolo come indicato nella tabella seguente** ed avere una **velocità** e **temperatura** di uscita dei fumi tale che l'innalzamento all'equilibrio del pennacchio, calcolato con le relazioni di Briggs, con una velocità minima del vento allo sbocco pari a 3 m/s e in classe di stabilità atmosferica adiabatica (classe di Pasquill D), sia pari almeno all'altezza del camino per gli impianti sino a 50 MWt e pari al doppio dell'altezza del camino per gli impianti con potenza superiore a 50MWt.

Potenza	Altezza camino
$\leq$ 3 MWt	7 m
> 3 ÷ $\leq$ 10 MWt	10 m
> 10 ÷ $\leq$ 30 MWt	17 m
> 30 ÷ $\leq$ 50 MWt	24 m
> 50 ÷ $\leq$ 100 MWt	30 m
> 100÷ $\leq$ 300MWt	50 m

REGIONE LOMBARDIA. D.g.r. 6 agosto 2012 - n. IX/3934 “Criteri per l’installazione e l’esercizio degli impianti di produzione di energia collocati sul territorio regionale”

8 CAMINI E LORO ALTEZZE

8.1 Camini

Ogni focolare, motore o turbina, deve essere collegato ad una canna fumaria indipendente, coibentata e terminante oltre il colmo tetto.

Velocità

La velocità dei fumi, emessi dal singolo camino o dalla singola canna, relativa al massimo carico termico ammissibile, deve essere: per impianti a focolare > 10 m/s; per motori e a turbine > 15 m/s; per impianti a biomasse solide > 11 m/s.

Situazioni difformi (come ad esempio nel caso di generatori a recupero nei cicli combinati o caldaie di potenza inferiori a 3 MWt) dovranno essere motivate, eventualmente con l’ausilio di un modello di ricadute al suolo e valutate dall’Autorità Competente in fase di autorizzazione.

Altezza

Fermo restando i criteri definiti dalla normativa in materia di edilizia, l’altezza dei camini deve essere determinata in modo da garantire la massima dispersione degli inquinanti. In tal senso, l’altezza del camino dovrà essere determinata tramite uno studio con l’applicazione di modelli diffusionali delle ricadute, ritenuti idonei dall’Autorità di Competente al rilascio dell’autorizzazione, sulla base della tipologia e del consumo di combustibile; l’altezza da adottare deve essere quella che garantisce almeno una corretta diffusione dell’inquinante stesso anche nelle condizioni meteo più critiche (classe di stabilità).

L’innalzamento del pennacchio deve essere calcolato con la **formula di Briggs**. I consumi si riferiscono all’intero impianto, somma dei consumi dei singoli generatori.

In alternativa, in impianti con consumo dei combustibile < 3000 kg/h, l’altezza potrà essere ricavata direttamente dalla seguente tabella (CONTINUA SLIDE SUCCESSIVA):

REGIONE LOMBARDIA. D.g.r. 6 agosto 2012 - n. IX/3934 “Criteri per l’installazione e l’esercizio degli impianti di produzione di energia collocati sul territorio regionale”

consumo in kg/h	Altezza in metri
300	12
450	15
600	17
750	19
900	21
1050	22
1200	24
1350	25
1500	27
1650	28
1800	29
1950	30
2100	31
2250	32
2400	34
2550	35
2700	36
3000	38

La tabella vale nel caso di impiego di olio combustibile con tenore di zolfo < 1% in peso. Nel caso di impiego di combustibili diversi, le altezze possono essere ridotte:

- di un quarto nel caso di bio-liquido, gasolio o olio combustibile con tenore di zolfo < 0,3% in peso, oppure nel caso di biomasse solide
- di un terzo nel caso di metano, gpl o biogas esprimendo i consumi in Nm^3/h.

Esercizio. 3000 kg / h of natural gas is equivalent to a thermal power plant of 16 MW.

→ H min = 38 x 2/3 = 25 m