THERMAL AND CATALYTIC COMBUSTION

A. Buekens
Department of Chemical Engineering – CHIS 2, Vrije Universiteit Brussel, Belgium

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Contents
1. Survey of VOCs treatment methods
2. Thermal combustion
3. Catalytic post-combustion
4. Process control optimization and improved firing technique
5. Combustion, Safety and Environmental Pollution
6. Conclusions
Acknowledgements
Glossary
Bibliography
Biographical Sketch
To cite this chapter

Summary

This chapter presents a survey of Volatile Organic Compounds (VOCs) Treatment Methods. Condensation applies to relatively concentrated flows of VOCs, e.g. solvents in air. Concentration may be enhanced beforehand, by suitable treatment, e.g. a cyclic operating adsorber/desorber. The efficiency of condensation is severely restricted by the residual vapor pressure at treatment temperatures, as well as by the possible formation of fog or aerosols. It is enhanced by operating under cryogenic conditions, featuring a direct or indirect contact with boiling nitrogen, or by combining condensation proper with absorption into an auxiliary liquor.

Adsorption allows an almost unlimited deep reduction in VOCs concentration: the residual concentration after adsorption mainly depends on imperfections in gas/adsorbent contacting. Since it is limited by the adsorption capacity of the amount of adsorbent used, it may be used as an add-on to condensation units or as a police filter after any treatment method: in these cases it is treating only low residual concentrations, reduced by preliminary treatment.

Biological treatment mostly proceeds on trickling bed filters. Its limitations are (as usual in biochemistry): temperature dependence (freezing in wintertime!), slow conversion rates, presence of recalcitrant molecules, and sensitivity to toxicants.

Combustion of VOCs and other combustible compounds is an advantageous, safe treatment method, since the oxidation products are mainly water and carbon dioxide and conversion is quite fast. Thermal combustion of VOCs proceeds at temperatures of 800° C or more. However, at these temperatures harmful by-products, such as nitrogen
oxides and carbon monoxide are also formed and care must be taken to attain a high combustion efficiency under variable input conditions. Catalysts can lower the required combustion temperature to 200 - 400°C so that:

- fuel consumption is lower or even nil (auto-thermal operation).
- formation of secondary pollutants is negligible.
- less CO₂ is formed, since the auxiliary fuel consumption is lower.
- inexpensive construction materials such as plain carbon steel can be used.

The cleaning efficiency by catalytic combustion is high. Some 10 g per normal cubic meter of VOCs are easily reduced to the typical emission threshold of 20 mg per normal cubic meter or lower - a cleaning efficiency of 99.8 percent, or more, depending on the ratio of amount of catalyst provided per unit of flow rate to be treated. Technically, the latter is often expressed as GHSV, standing for Gaseous Hourly Space Velocity. A GHSV of 20 means that 1 cubic meter of catalyst can treat 20 cubic meter of gas per hour.

1. Survey of VOCs Treatment Methods

Volatile Organic Compounds (VOCs) originate in a variety of processes, involving e.g.

- Solvents, paints, varnishes, lacquers, inks, glues...
- Miscellaneous organic compounds, their production, storage, and application,
- Monomers, migrating from polymers,
- Biological and biochemical processes, such as fermentation, digestion, and putrefaction, and
- Thermal treatment, e.g. of coffee beans, smoking of fish and meat.

Somewhat similar compounds may appear as Products of Incomplete Combustion (PICs). Such effluents can be treated by (see Control of Gaseous Emissions):

- Condensation,
- Adsorption,
- Biological treatment, or
- Thermal treatment.

Condensation applies only to relatively high concentrations of VOCs, e.g. solvents in air. Its efficiency is severely restricted by residual vapor pressure, as well as by the possible formation of fog or aerosols. It is enhanced by operating under cryogenic conditions or by combining condensation with absorption.

Adsorption allows an almost unlimited reduction in VOCs concentration. Since it is capacity-limited, it may be used as an add-on to condensation or as a police filter.

Biological treatment mostly proceeds on trickling bed filters. Its limitations are as usual in biochemistry: temperature dependence (freezing!), slow conversion rates, recalcitrant molecules, and sensitivity to toxicants.
Combustion of VOCs and other combustible compounds is advantageous, since the main oxidation products are water and carbon dioxide and conversion is fast. Thermal combustion of VOCs proceeds at temperatures of 800°C or more. However, at these temperatures harmful by-products, such as nitrogen oxides and carbon monoxide are formed and care must be taken to attain high efficiency under variable input conditions. Catalysts can lower the required combustion temperature to 200 - 400°C so that:

- fuel consumption is lower or even nil (auto-thermal operation).
- formation of secondary pollutants is negligible.
- less CO$_2$ is formed, since the auxiliary fuel consumption is lower.
- inexpensive construction materials such as normal carbon steel can be used.

The cleaning efficiency by catalytic combustion is high. Some 10 g per Nm$^3$ of VOCs are easily reduced to the typical emission threshold of 20 mg per Nm$^3$ or lower - a cleaning efficiency of 99.8 percent, or more.

2. Thermal Combustion

2.1. Technology

Incineration of VOCs, PICs and hydrocarbon fumes is usually accomplished in an afterburner or post-combustor. Typically, such an afterburner consists of a steel shell lined internally with refractory material, such as firebrick. The refractory lining and a layer of thermal insulator protect the steel shell. Sometimes, heat is stored in a refractory mass, piled in the combustion chamber and serving as a thermal flywheel, if the supply of gas to be treated is irregular or variable. Such a refractory mass is also used in hot stoves, operating in a cyclic mode, first storing heat of combustion from hot gases, later transferring this heat to the incoming gas to be fired.

To achieve almost complete combustion, the afterburner must provide appropriate levels of burning time, temperature and turbulence (the 3 T’s). Direct-flame incineration is used when the waste gas is combustible (after sufficient preheating) and does not need additional fuel or air, a situation involving, however, very serious safety issues.

The thermal combustion unit is composed of:

- a burner, first firing auxiliary fuel to preheat the furnace and thus raising the temperature up to the ignition temperature,
- a mostly empty combustion chamber to provide appropriate mixing conditions and,
- a heat exchanger to preheat the gas stream to be treated and save fuel.

Off-gas is extracted by a fan, preheated in the heat exchanger and injected into the furnace, where it is rapidly brought to combustion temperature. There are several alternative arrangements to this scheme, e.g. regarding the method of:

- Injecting the flow of vitiated gas to be treated into the combustion chamber, i.e.
Radially into the flame,
- Tangentially to it,
- At an angle with the wall, or
- Through the burner, either as air, giving a whirling flow to the flame, and possibly even
- Premixed with gaseous fuel.

The last option is seldom used, because of evident safety problems, i.e. a possible flame flashback into the duct, if the outlet gas velocity descends below the flame propagation rate.

- The method of exchanging heat, featuring
  - a gas/gas heat exchanger,
  - a fixed (hot stoves), or
  - a mobile (Ljungström type) regenerative heat exchanger, to preheat the off-gas with heat derived from the treated gas.

Firing auxiliary fuel is required to maintain and control the temperature of combustion in the most usual case that it is not self-sustaining. Moreover, a process in which combustion is more or less self-sufficient, after recycling heat from the hot combustion gases to the incoming flows, still needs facilities for starting up the process and navigate it through possible plant upsets. Prerequisites to a smooth thermal post-combustion are:

- Attaining an adequate temperature for ignition, so that combustion becomes self sustaining,
- Sufficient reaction time, so that combustion is complete,
- Adequate oxygen levels,
- Good mixing between the off-gas and the hot combustion gas.

2.2. Ignition Temperature

Gases are flammable only within a specific domain of concentrations, situated between a lower explosion limit (LEL), below which the mixture is too lean in fuel to sustain combustion, and an upper explosion limit (UEL), above which the mixture is too lean in oxygen. The flammability limits for a mixture methane/oxygen/air are represented in the triangle diagram of Figure 1.

The ignition temperature for a series of stoichiometric fuel/air mixtures at atmospheric pressure increases with the stability of the compound:
Figure 1: Triangle Diagram indicating the flammability domain in a methane – oxygen – nitrogen mixture

<table>
<thead>
<tr>
<th>Compound</th>
<th>Ignition Temperature, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-octane</td>
<td>210</td>
</tr>
<tr>
<td>n-pentane</td>
<td>285</td>
</tr>
<tr>
<td>Ethane</td>
<td>425</td>
</tr>
<tr>
<td>Propane</td>
<td>470</td>
</tr>
<tr>
<td>Benzene</td>
<td>555</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>560</td>
</tr>
<tr>
<td>carbon monoxide</td>
<td>605</td>
</tr>
<tr>
<td>Methane</td>
<td>610</td>
</tr>
</tbody>
</table>

Table 1: The ignition temperature for a series of stoichiometric fuel/air mixtures at atmospheric pressure

Non-stoichiometric fuel/air mixtures require even higher temperatures to react.

2.3. Design Calculations

The design calculations of a thermal post-combustor are based on:
• Stoichiometric equations, relating the amount of fuel to that of oxygen; in dilute streams oxygen is only rarely in short supply,
• Heat balances, allowing to estimate the operating temperature; cf. computation of adiabatic temperatures; relevant thermo-chemical data are discussed in *Combustion Research and Computer Fluid Dynamics*,
• Residence times, derived from the simple relationship

\[
(\text{Residence time, s}) = \frac{\text{(Volume of the Combustion Chamber, m}^3)}{\text{(Volumetric Flow, m}^3 \text{s})}
\]

The Volumetric Flow is calculated at combustion chamber temperature and pressure. Since the temperature is not constant the volume must be split into quasi-isothermal segments, and the resulting fractional times integrated.

A sufficient residence time is required to guarantee adequate **destruction efficiency**. A lower residence time can somewhat be compensated by a higher temperature, as far as mixing between reactants is adequate. Some pollution codes specify:

• minimum residence times at a given combustion temperature (850° C),
• maximum residual CO-contents,
• maximum residual content of specific organic compounds,
• maximum residual VOC-values.

It is a common fallacy that temperature and time together determine (non-)ideal combustion conditions. Often mixing of streams of different temperature, density, oxygen content, and origins, etc. is the real key to adequate destruction efficiency. Computer Fluid Dynamics allows prediction of such mixing patterns (see *Combustion Research and Computer Fluid Dynamics*).

2.4. Case Study: Elevated Flares

A practical environmentally important example of a diffusion flame is that of elevated flares, erected to great height in oil fields, refineries, petrochemical plants, or landfills, to dispose safely of excess amounts of flammable gases. In case of equipment failure volatile hydrocarbons in oil and/or organics should be purged from operating equipment, so that it can be serviced. Since these volatile compounds form explosive mixtures with air they are delivered by closed piping systems to the flare, and burned in a controlled manner. Under normal conditions only a pilot flame light, maintained by a small base flow, is visible (see *Control of Pollution in the Petroleum Industry*)

**Elevated flares** feature a refractory-lined tubular furnace mounted on a platform.

**Ground flares** consist of an arrangement of small burners, activated progressively with increasing flare gas load, and contained in a refractory-lined enclosure, screening most of the light, diminishing radiant heat losses, and promoting turbulent mixing by creating artificial draft. In both cases a continuous observation of the flame (generally based on its UV-radiation and monitoring flaming combustion) and the presence of a pilot flame, situated right in the tip of the flare, are essential. Eigenfrequencies are a property of
flames, related to their flame stability: flames show a characteristic wave effect, the amplitude and frequency of which characterizes flame stability.

Such flares typically dispose of excess refinery gas, composed of various hydrocarbons. All these gases have a distinct sooting tendency, a consequence of hydrocarbon pyrolysis, which increases with rising molecular weight (methane << ethane < propane < etc.), rising chain branching, declining thermal stability according to the generic series:

\[
\text{aromatics} > \text{dienes} > \text{olefins} > \text{paraffins} \tag{1}
\]

or adopting IUPAC terminology (still little used in industry):

\[
\text{arenes} > \text{dienes} > \text{alkenes} > \text{alkanes} \tag{2}
\]

Methane, carbon monoxide and hydrogen burn without visible flame. Higher hydrocarbons burn with a yellow flame, due to the formation of soot, which enhances the thermal coupling between hot combustion zones and fuel, for soot is a prime absorber of heat radiating from the combustion zone. Carbon structures gradually grow initially from an aromatic nuclei, forming large sized polycyclic aromatic structures (PAHs) further condensing to soot particles that are problematic to burn out completely, if one of the values of the 3 T’s is inadequate.

A safe height is required, not only to ensure adequate dispersion in case of flame failure, but also because of extremely high heat fluxes arising in case of an emergency. During emergency conditions the flare system disposes of large quantities of volatile gases, while steam and air suppress sooting of the flame by their well-timed addition and premixing with the flare gas. Air is aspired into the tip by the suction effect of a ring of injection nozzles, operated with steam, fed from a manifold arranged around the flare tip. A circular steam line feeds a set of small steam nozzles located in holes pierced in the refractory-lined flame tip wall. Each nozzle entrains ambient air into the flame tip, creating turbulent mixing with the flare gas.

The use of flares creates several problems and hazards:

- Ignition loss creates dangerous operating conditions, particularly with ground flares. Pilot burners and flame detectors are hence basic equipment,
- Flashback of the flame into the burner tip must be prevented, by means of a continuous gas purge, a flame arrestor, a water seal, or a combination of these measures,
- Water seals maintain a positive pressure in all up-stream equipment and prevent air leaking in. Potential problems are freezing, corrosion by sour gas, and occurrence of periodic oscillations of the water level, causing rhythmical changes in flame intensity. Installing baffles or perforated plates acts as a damper on oscillations,
- Air leaking into ducts is a hazard, when part or all of the gas relief system is somewhat below atmospheric pressure, e.g. when vapors condense in the system.
or interconnected flares display siphon effects, during disposal of gases with different densities,
- Flame impingement may damage the flare tip and its associated auxiliary equipment (pilot burner, steam lines, flame monitors),
- Entrained liquid droplets give rise to ‘flaming’ rain. Hence, such droplets should be separated, before the flare gas enters the stack.

An alternative is a ground flare, where the heat of combustion can be shielded from the surroundings by firewalls.

Numerous views and drawings of flares and auxiliaries can be found at the site: http://www.johnzink.com/products/flares/html/flar.htm.

2.5. Case Study: Products of Incomplete Combustion (PICs) in Incinerators

PICs, in incinerator furnaces are formed by the following sequence of events:
- Organic materials are dried, heated, and ignited by heat radiating from flames and walls, or derived from adjacent materials that were prompt to ignite,
- Flaming combustion is fed by volatiles, generated from less than 250° C for cellulose-based materials, and at 350 to 450 °C for most plastics. Thermal decomposition creates considerable excess of volatiles above what can be burned by oxygen available in and above the bed, resulting in erratic formation of strands of oxygen-depleted hot gases. Such strands grow in volume, in case more material is subject simultaneously to this fast thermal decomposition.
- To ensure a correct consecutive burnout of oxygen-lean strands there must be:
  - Intensive mixing with oxygen rich gas, e.g. by injection of high-velocity air that deeply penetrates into the oxygen-lean strands, creating turbulent macro and micro-mixing,
  - Sufficient time of contact, counted from the moment of providing the deficient oxygen and at a sufficiently high temperature to ensure essential completion of oxidation processes,
  - Avoidance of soot formation, since soot takes much more time to burn out completely than gases do. Sooting flames are more likely to occur in reducing strands, albeit that certain material, such as rubber or polystyrene has strong sooting tendencies.

It follows that the generation of PIC depends on the following factors of influence, assembled in Table 2, which implicitly criticizes the rules contained in the E.U.-Directives on incineration, as inadequate and inefficient.

<table>
<thead>
<tr>
<th>Nr</th>
<th>Process</th>
<th>Factors of influence</th>
<th>Possible remedial action</th>
<th>Influence of the 850 °C, 2 s Rule</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Drying</td>
<td>Radiating heat</td>
<td>Mix dry and wet waste Preheat air</td>
<td>May be mildly</td>
</tr>
</tbody>
</table>
Table 2: Processes influencing the formation of Products of Incomplete Combustion in incinerators

<table>
<thead>
<tr>
<th>Step</th>
<th>Process Description</th>
<th>Key Factors</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Heating &amp; Ignition</td>
<td>Radiating heat from other adjacent materials</td>
<td>Non-critical process, almost no influence</td>
</tr>
<tr>
<td>3</td>
<td>Thermal decomposition</td>
<td>Material type and temperature, heat supply rate</td>
<td>Premixing refuse, poking and mixing action of the grate, no influence</td>
</tr>
<tr>
<td>4</td>
<td>Flaming combustion</td>
<td>Rate of Thermal decomposition, supply of air</td>
<td>Adapt air distribution along the grate, enrich with oxygen, may be mildly negative, by a hot furnace operation</td>
</tr>
<tr>
<td>5</td>
<td>Mixing the gases</td>
<td>Furnace geometry &amp; location of air injection nozzles</td>
<td>Improve the design to increase turbulence, injection of secondary air at high velocity, no influence</td>
</tr>
<tr>
<td>6</td>
<td>Post-combustion</td>
<td>Contact time, temperature</td>
<td>Apply the 850 °C, 2 s rule, important</td>
</tr>
<tr>
<td>7</td>
<td>Avoidance of soot formation</td>
<td>Correlated with (3), (4), and (5)</td>
<td>As for (3), (4), and (5), no influence</td>
</tr>
</tbody>
</table>

2.6. Formation of Dioxins, or PCDD/F, in Incineration

Dioxins, or polychlorinated dibenzo-p-dioxins and dibenzofurans PCDD/F, occur invariably in incinerator effluents because of:

- their presence, prior to combustion, in the original materials to be incinerated,
- their formation at high temperature, during post-combustion in a temperature window ranging from flame temperature to ca. 500° C (trace chemistries of fire theory, based on reactive species synthesizing various cyclic and dioxin structures),
- their formation at low temperature, below 500° C, during heat recovery and/or gas cleaning (the ‘de novo’ and precursor pathways).

At the time the 850° C, 2 s rule was devised the mechanisms of dioxin formation were still poorly understood. It was assumed that in one way or another dioxins form because of incomplete combustion, and correlations were sought with the emissions of carbon monoxide, or other dioxin indicators, surrogates and precursors.
Truly, dioxins are almost always already present in materials to be incinerated (they are present in house dust, dissolve into common plastics from ambient air, etc.) but such dioxins are deeply destroyed by the fire and reduced to levels close to present limit values. In other words the dioxins leaving the plant are different from those entering.

Active dioxin formation mainly takes place once gases are cooled in a boiler and cleaned in an electrostatic precipitator (ESP) or a bag-house plant. The ESP generates more dioxins, the higher its operating temperature is. The most temperature active range for dioxin formation is generally 300 to 350° C.

Dioxins probably can be formed by several mechanisms, operating in parallel and with relative importance still subject to scientific dispute. The following steps all play a role in the ‘de novo’ pathway, based on a low-temperature, metal-catalyzed gasification of charred material:

- Dust particles, entrained from the refuse layer gradually burn out their carbon content, while moving with the flue gases, typically leaving 0.5 to 5 % of carbon in ash.
- During flaming combustion some sooting occurs, creating additional carbon particulate.
- Heavy metals, such as copper, lead, or zinc, above 500° C form volatile chlorides that evaporate during combustion.
- Common salts volatilize in flames, at a rate observable under laboratory conditions at 650° C.
- Thermal combustion of carbon continues in fly-ash up to 500° C, then becomes too slow to be of practical importance. At this temperature level the volatilized salts and heavy metal chlorides condense upon the outer surface of particulate, typically constituting 2 to 5 % of Zn, 0.5 to 2 % of Pb, 0.05 to 0.2 % of Cu.
- Heavy metals, such as copper, catalyze carbon combustion, so that the oxidation process resumes, generating carbon dioxide and monoxide mainly, as well as arene structures (benzene, naphthalene, anthracene, phenantrene, pyrene, benzo[12]furan, dibenzo[12]furan, dibenzo-p-dioxin, etc. at a µg/g level).
- Condensed chlorides react with carbon structures with copper as a catalyst, providing chlorinated arenes.

Precursors, such as chlorinated phenols, benzenes, biphenyls, also condense to structures, such as chlorinated dibenzo-p-dioxins (PCDD). The process proceeds under similar conditions as the ‘de novo’ synthesis, and may even be a consequence of 'de novo', since it generates precursors in parallel with dioxins. Kinetics and mechanisms have been studied at laboratory-scale and compared with full plant data. Dioxin formation was simulated using Computer Fluid Dynamics.


3.1 Scope and Applications.

Catalytic processes are pre-eminent in chemical industry, including petrochemistry and oil refining, e.g. reforming, alkylation, isomerization, hydrogenation, oxidation,
chlorination, and all processes, involving organic chemicals. A comparatively novel, but increasingly important domain is catalytic post-combustion, Selective Catalytic DeNOx (see Control of Nitrogen Oxides) and DeDiox.

Catalytic after-combustors are employed at a variety of industrial facilities to treat flammable solvent vapors, control odors, destroy toxic compounds, or reduce the release of photo-chemically reactive substances to the air. Catalytic post-combustion lowers both oxidation temperatures and fuel requirements of the combustion process. Most used are platinum group catalysts, but some mixed-oxide types gradually are gaining importance. Catalysts are employed as pellets, i.e. spherical, cylindrical or annular particles or as monolith honeycomb blocks. Fibers are only seldom used.

Catalytic postcombustion is used for off-gases free from dust and catalytic poisons, e.g. arsenic, phosphorus, sulfur or halogen compounds. Nitrogen compounds are partly converted to NO/NO\(_2\), sulfur dioxide to sulfur trioxide, hydrogen chloride to chlorine gas.

Precious metals, such as platinum, are potent combustion catalysts, allowing complete oxidation of combustible gases at low temperatures, with typical inlet temperatures in a range of 200 to 350°C, depending on reactivity and absorptivity of the compounds to be destroyed. Once the reaction is started, the temperature of the gas augments, approaching adiabatic combustion temperatures, is derived from the enthalpy of the reactants. The final temperature is limited by the onset of sintering, generally above 500°C, and other undesirable thermal reactions, such as volatilization of active components.

### 3.2. Physical and Chemical Phenomena

Catalytic processes are composed of a series of consecutive transport, mixing, mass transfer, adsorption, desorption and chemical reaction steps:

- Reactants transport, from the gas stream to the catalyst boundary layer,
- External diffusion transport of reactants through the boundary layer, surrounding the catalyst, towards the catalytic surface,
- Internal diffusion transport of reactants inside the inner pores of the catalyst,
- Adsorption of reactants on a catalytic site,
- Chemical conversion, in this case (often stepwise) oxidation of adsorbed organics to combustion products, adsorbed on a catalytic site,
- Desorption of reactants from this catalytic site,
- Internal diffusion transport of reaction products inside the inner pores of the catalyst,
- External diffusion transport of products through the boundary layer towards the gas stream,
- Diffusion transport of reaction products from the boundary layer to the bulk of the gas stream.

The numerous transport operations are enhanced by an adequate internal pore distribution and turbulent flow conditions, leading to thin boundary layers. High
catalytic activity implies a large catalyst surface. Heat is transferred by conduction (inside the catalyst), convection (gas phase; catalyst/gas) and radiation (catalyst to gas).

3.3. Catalytic Chemical Reactions

Catalytic reactions are complex and what happens at a molecular level on catalytic sites deeply inside the catalyst is not incompletely understood.

Catalytic reactor design is based on first order kinetics, i.e. a reaction rate of the form:

\[ r = k C_{org} \]  

\( r \) = reaction rate, mol C m\(^{-3}\) s\(^{-1}\)
\( k \) = first order rate coefficient, s\(^{-1}\)
\( C_{org} \) = concentration of the organic compounds to be combusted, mol C m\(^{-3}\).

As long as it is sufficiently ample, oxygen does not notably affect the rate. The rate parameter varies with temperature, according to Arrhenius’ Law:

\[ k = A \exp\left(\frac{-E}{RT}\right) \]  

With
\( k \) = first order rate coefficient, s\(^{-1}\)
\( A \) = frequency factor, s\(^{-1}\)
\( E \) = activation energy, kcal per mol\(^{-1}\) (1 kcal mol\(^{-1}\) = 4.18 kJ mol\(^{-1}\))
\( R \) = 1.986 kcal mol\(^{-1}\) K\(^{-1}\)
\( T \) = temperature, K.

Only experimental study allows determination of the values for \( A \), \( E \) and the reaction orders. However, most reactions are assumed to follow the simple first order rate law because of the complexity of experimental study. Often, only an empirical Gaseous Hourly Space Velocity (GHSV) value, allowing a given Destruction and Removal Efficiency (DRE), is put forward.

3.4. Diffusion Control

At low operating temperatures the over-all rate is chemically controlled: in the above sequence chemical conversion much slowest and determines over-all velocity. Diffusion supplies organics into the deepest pores. An enormous catalytic bed would be required to attain a high conversion.

As the operating temperature is raised chemical reaction rates rise rapidly. The activation energy is often of the order 20 to 50 kcal mol\(^{-1}\), which implies multiplication of chemical reaction rates by a factor.

The rate of diffusion increases slowly with temperature, so that chemical reaction gradually overtakes internal diffusion in rate. It can be shown that the activation energy is halved, when a first order chemical reaction becomes (internal) diffusion controlled.
Since the rate $r$ is proportional with $C$, $r$ gradually decreases as the value of $C_{\text{org}}$ is lowered by depletion, due to oxidation. The rising gas temperature, a consequence of the liberation of heat of combustion, more than compensates this.

At even higher temperatures external diffusion becomes rate determining: conversion is so fast, that any organics attaining a catalytic surface are immediately oxidized. The internal pores are almost inactive, since no organics penetrate the inside any more. At that moment a further rise in temperature has barely any accelerating effect on conversion, the rate of which merely depends on the rate of mass transfer to the catalyst. Such mass transfer rates are normally described by an empirically established relationship between the relevant dimensionless groups, i.e. the Numbers of Sherwood ($Sh$), of Reynolds ($Re$), and of Schmidt ($Sc$):

$$Sh = f(Re, Sc)$$ (5)

Postcombustion catalysts are developed and selected in order to obtain acceptable results, i.e. operating reliably, safely and economically during a long lifetime at a substantially complete oxidation of organic contaminants. Economic conditions imply:

- relatively low operating temperature,
- low auxiliary fuel requirements,
- high space velocity,
- low pressure drop,
- long lifetime, and
- easy recovery of precious metals, whenever these are used.

Table 3 lists some of the desirable properties of catalysts at large,

<table>
<thead>
<tr>
<th>Property</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catalytic Activity</td>
<td>Capacity to enhance the rate of chemical reaction, by suitable catalytic</td>
</tr>
<tr>
<td></td>
<td>properties, allowing a fast reaction at a low temperature, often combined</td>
</tr>
<tr>
<td></td>
<td>with suitable surface conditions and transport properties</td>
</tr>
<tr>
<td>Selectivity</td>
<td>Faculty to promote desirable reactions, compared to less desirable ones;</td>
</tr>
<tr>
<td></td>
<td>here a total oxidation is desirable of all organics, but excluding the</td>
</tr>
<tr>
<td></td>
<td>oxidation of nitrogen compounds to NO/NO$_2$ or of sulfur compounds to</td>
</tr>
<tr>
<td></td>
<td>SO$_3$</td>
</tr>
<tr>
<td>Thermal shock Resistance</td>
<td>Starting-up, shutting down and changes in regime (concentration or flow</td>
</tr>
<tr>
<td></td>
<td>rate of gas) may provoke thermal shocks that are damaging to catalyst</td>
</tr>
<tr>
<td></td>
<td>structure and mechanical integrity</td>
</tr>
<tr>
<td>Pressure change Resistance</td>
<td>This property looses importance in case combustion takes place at</td>
</tr>
<tr>
<td></td>
<td>atmospheric pressure, as is most commonly the case</td>
</tr>
<tr>
<td>Attrition Resistance</td>
<td>Important mainly for oxidation in catalytic fluidized beds, which is</td>
</tr>
<tr>
<td></td>
<td>unusual in these applications</td>
</tr>
<tr>
<td>Low pressure drop</td>
<td>A low pressure drop is ensured by selecting an appropriate particle size</td>
</tr>
<tr>
<td></td>
<td>and by avoiding deposition of particulate and catalyst attrition</td>
</tr>
</tbody>
</table>
Chemical Stability

Stability against chemical attack is to be considered on a case-by-case basis. Some chemicals (Flour) attack many catalyst carriers; others may poison the catalyst by permanent strong bonding (arsenic, antimony), by promoting sintering (any low melting phase, e.g. Boron and Phosphorus-compounds). Water reacts with MgO carriers, forming Mg(OH)$_2$, with mechanically destructive effects.

<table>
<thead>
<tr>
<th>Table 3: Some Desirable Catalyst Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space velocity refers to the ratio between the Volumetric Flow Rate of Gas to be Treated (m$^3$ h$^{-1}$) and the Volume of Catalyst (m$^3$) in use:</td>
</tr>
<tr>
<td>GHSV = Gaseous Hourly Space Velocity (h)</td>
</tr>
<tr>
<td>= Volumetric Flow Rate of Gas to be Treated (m$^3$ h$^{-1}$) per Volume of Catalyst (m$^3$)</td>
</tr>
<tr>
<td>For reactions in the liquid phase a LHSV is defined similarly.</td>
</tr>
</tbody>
</table>

The GHSV (or SV) merely indicates how many m$^3$ h$^{-1}$ can be treated per m of catalyst and is a most important, though simple in use, industrial experience factor. At a higher SV the contact time between gas to be treated and catalyst is reduced and the conversion tends to be lower. It follows that:

- Higher hydrocarbons are easier to oxidize than lower, but have a higher tendency to coke the catalyst.
- Oxygenated compounds are easier to convert, chlorinated compounds more difficult.

Thus SV is a compromise between conversion efficiency and productivity.

Two different shapes of catalysts are most used:

- spherical, annular or cylindrical catalyst carriers, containing a small amount of active ingredients, applied by impregnation or co-precipitation of the catalytic ingredients;
- honeycomb ceramic catalyst carriers. The catalyst is generally a platinum group precious metal (platinum proper, palladium, rhodium, etc). Because of its high activity and cost only 0.1 to 0.5 % of the metal is fixed on the carrier, e.g. by impregnation with a solution, followed by reduction to finely divided metal.

### 3.5 Design of Catalytic Units

The design of catalytic postcombustion units is relatively simple on one hand, quite complex on the other. Main design parameters are:

- Volume flow of the off-gas to be treated, m$^3$ h$^{-1}$,
- Minimum, maximum and average concentration of organics to be fired, mg C per normal cubic meter (Nm$^3$),
- Individual gas concentrations.

The important factors are:

- Amount of catalyst required, kg,
- Volume of the required catalyst, m$^3$,
- Selected value of the Space Velocity, in h$^{-1}$ or s$^{-1}$,
- Selected value of the final operating temperature, °C.

Before the catalyst layer a guard bed is often placed, in order to homogenize the gas flow and possibly filter out catalyst poisons.

Table 4 shows how unit design parameters are related to design characteristics:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Determines the following characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volumetric gas flow</td>
<td>Reactor Volume</td>
</tr>
<tr>
<td>Pollutant concentration</td>
<td>Amount of Catalyst</td>
</tr>
<tr>
<td>Required exhaust emission values</td>
<td>Amount of Catalyst, Space Velocity</td>
</tr>
<tr>
<td>Nature of the Pollutants</td>
<td>Amount of Catalyst, Space Velocity</td>
</tr>
<tr>
<td>Exhaust temperature</td>
<td>Operating Temperature</td>
</tr>
</tbody>
</table>

Table 4: Design parameters and their influence

3.6 Case Study: Commercial Catalytic Units

CATOX and REGENOX are commercial catalytic combustion units offered by the Topsoe Company. Depending on the type of VOC the catalyst requires a gas temperature of 200 - 400°C to initiate combustion. In case the temperature of the gas to be treated is lower than required, heat generated by oxidation of the pollutants is used for preheating, optimizing the energy efficiency of the catalytic unit.

REGENOX is suitable in case of relatively low pollutant concentrations, since equipped with the most efficient energy recovery, featuring regenerative heat exchange (cf. hot stoves). CATOX is selected for higher pollutant concentrations, when a highly efficient energy recovery is not required (Figure 2).

Both CATOX and REGENOX units are easily designed for a purification grade of 99% or higher, or for a maximum emission level of 20 mg per Nm$^3$ of organic matter in the cleaned gas.
Off-gas is preheated in a tubular heat exchanger, heated by the catalytically treated gas. The temperature is further enhanced by a burner firing natural gas, so that the required entrance temperature is attained (with ageing catalyst, the latter may be increased progressively, until catalyst replacement is needed).

In the Catox Regenox unit (Figure 3) a metered amount of natural gas is fired, preheating the catalyst layer and an active heat carrier.

Figure 2: Scheme of the Catox catalytic combustion unit

Figure 3: Scheme of the Catox Regenox catalytic combustion unit
The off-gas is preheated by passive hot heat carrier and catalyst, is further heating with
gas and passes over the preheated catalyst and the second layer of heat carrier. When the
passive heat carrier and catalyst get too cold, the tables are turned, valves switch active
for passive parts, and vice versa (principle of hot stoves).

Another possibility is pre-concentration in a rotor/Catox unit: VOCs are adsorbed at low
temperature, and again desorbed after heating the adsorbent to 180° C using a small
fraction of the original airflow. The concentration in the hot air is 10 – 15 times higher
than in the original gas.

Topsoe combustion are based on porous alumina or silica carriers, available as spheres
or rings, or as honeycomb monolith structures. These monoliths are used in case of dust
or low pressure drop requirements.

The most common Topsoe combustion catalysts and their applications are:

- Metal oxides on alumina (Most common solvents; silicon tolerant)
- Noble metals on alumina (Most applications, CO; sulfur tolerant)
- Metal oxides and noble metals on alumina (Chlorinated hydrocarbons, Special
  applications)
- Metal oxides and noble metals on silica (Sulfur compounds, ammonia)

3.7 Case Study: Catalytic Treatment Unit for Dioxins Removal

Some important questions are raised when considering catalytic systems or when
comparing alternative catalysts or configurations:

- Above which temperature is this catalyst active?

The starting temperature depends on the composition and condition of the catalyst and
the nature of the compounds to be oxidized. In principle, there is little or no activity
below a given temperature threshold. Once this value is reached, conversion and
temperature both rapidly rise with bed depth, because of the self-accelerating effects of
the exothermic combustion process. This rise slows down, once a complete combustion
is in sight, and attaining almost complete conversion requires a sufficient time of
contact. The maximum temperature attained corresponds to the adiabatic temperature
rise at complete conversion.

- What is the design GHSV value of the system?

In industrial applications, time of contact is always expressed in the simplest possible
manner, i.e. merely by stating a typical GHSV value. The Gaseous Hourly Space
Velocity (s⁻¹) is the volumetric flow (m³ s⁻¹) treated per m³ of catalyst. This value is
derived empirically, from results obtained on a bench-scale experimental rig. (If the
feed is liquid, a LHSV value is defined similarly).

- How much dust can the system tolerate, and what happens after accidental
  exposure to coarse or fine dust?
Catalytic systems should beware of dust, whether coarse, or fine. Dust collects in the catalytic layer, plugging it gradually and sometimes showing undesirable interactions with the catalyst. Periodically time must be taken to discharge the catalyst sieve and restore it. This cumbersome and delicate undertaking can largely be avoided by opting for a honeycomb type of catalyst, with less plugging tendency and easily cleaned using jets of pressurized air. As a trade off, there is the higher cost for baking the honeycomb structure, and a much larger catalyst requirement: a bed of catalyst pellets achieves a GHSV of 20 000 s\(^{-1}\), against 3 000 s\(^{-1}\) for the honeycomb version.

- What specific catalyst poisons may deactivate (typical compounds of a DeNO\(_x\)/DeDiox-catalyst) TiO\(_2\), V\(_2\)O\(_5\), or WO\(_3\)?

It is important to ensure that the catalyst will survive in the presence of unforeseen compounds, derived from say, printing inks, or from metallurgical processes.

- What happens after exposure to sudden CO and VOC-peaks?

After an upset in the upstream process, there may be much more VOC and CO than foreseen in the design values. If the amount of combustible is double of that expected, so will be the adiabatic temperature rise. Hence, a peak load will gradually overheat the catalyst.

Moreover, most catalysts convert organics in a range of 250 – 450\(^{\circ}\) C, but start oxidizing carbon monoxide only from this temperature upwards. The onset of CO-combustion liberates extra heat, in certain cases leading to a temperature run-away and sintering of the catalytic bed, requiring premature replacement of this expensive auxiliary commodity.

Finally, some organics tend to polymerize to tars, depositing and further carbonizing onto the catalyst. Ignition of such deposits also may lead to destructive sintering.

- How does exposure to HCl, to SO\(_2\), to NH\(_3\), to NO/NO\(_2\) affect performance?

Post-combustion catalysts excel in oxidizing organics, but also convert HCl to Cl\(_2\), SO\(_2\) to SO\(_3\), HCN, NH\(_3\) and NO to NO\(_2\) to some extent.

- What is the expected lifetime and after which time period will the catalyst need to be replaced, and at which cost?

This question is impossible to answer with certainty, given the various incidents possibly affecting catalyst activity (clogging, poisoning, fouling, sintering) and integrity (thermal shock). Since lifetime is somewhat unpredictable and replacement cost considerable, it is wise covering this point by a guaranteed lifetime and replacement cost: as a specialty product, the sales price of a catalyst is many times its intrinsic value, so that the delivery conditions and cost can better be agreed upon contractually.

Precious metal catalysts (platinum Pt, palladium Pd, rhodium Rh, and other members of the platinum group) have considerable intrinsic value and are reclaimed after use. A
catalytic muffler from a car exhaust may be presently worth ca. 35 €. Also molybdenum, nickel, and cobalt-based catalysts are reclaimed, after a suitable deactivation procedure to reduce their pyrophoric character, in case they originate in hydro-treating or other oil refining processes.

- How rapidly will the catalyst reach activity?

Some catalysts are supplied in a safe, non-active condition and need to be activated after their loading in position.

- How to start up and shut down the catalytic unit?

Specific instructions should be supplied with each delivery.

- What are the guarantees offered with respect to conversion efficiency?

Guarantees are offered on a basis of past experience during the development of the catalyst. When required, a pilot plant can be brought on-site, for testing catalytic activity and stability. After a certain operating period the catalyst surface and characteristics are again examined and evaluated carefully.

3.8 Economic Aspects

Post-combustion units are supposed to fulfill numerous economic, ecological and technical requirements, i.e.

- Acceptable investment cost, determined by:
  - Required volume of the thermal or catalytic post-combustor,
  - Surface requirements of the gas/gas heat exchanger,
  - Fans, blowers or compressors, required for surmounting the pressur drop,
  - Length of connecting ducts,
  - Amount of catalyst required.

- Operating cost, consisting of:
  - Auxiliary fuel cost,
  - Power requirements, related to the pressure drop to be surmounted,
  - Catalyst replacement cost (only for catalytic units).

Typical technical requirements are:

- Design, engineering, manufacturing, catalyst supply,
- Proven catalyst and catalytic process,
- Cleaning efficiency, e.g. > 99.5 percent
- No NOₓ and SO₃ formation.
4. Process Control Optimization and Improved Firing Technique

4.1 Emission Control

Industrial boilers and furnaces are major sources of CO, SO₂, NOₓ, soot and particulate matter (PM). These emissions depend on the composition of the combustibles used, and on the technical properties of the combustion unit, i.e. design and operation of burners (or stokers) and combustion chamber. Emissions can be reduced using different strategies and techniques.

Primary measures involve:

- selecting cleaner fuels, low in sulfur, nitrogen, and ash and
- using low-NOₓ burners,

reducing the formation of pollutants at the source. Also secondary measures, i.e. treating flue gases, are often required to reduce certain pollutant emissions (dust, SO₂, NOₓ). Thirdly, process control and firing techniques must be optimized, as discussed hereunder.

Optimizing process control, combustion air supply and fuel usage, the emissions of CO, NOₓ, particulate matter and even greenhouse compound CO₂ can be minimized. Continuously monitoring operating temperatures and excess oxygen, lowering the main flame temperature, and cooling the furnace can achieve this.

Typically, boiler losses are of the order of 15 to 20 %, mainly sensible heat of the flue gas. Effective control of the burner air/fuel ratio, within the boundaries of safe and reliable operation, leads to more efficient fuel usage, hence to considerable cost reductions, as well as a significant reduction in emissions. The ratio of air to fuel, supplied to the burner, may need to be adapted, depending on the firing level in the boiler. Secondary air is controlled by a damper, fuel supply by a valve. Usually valve and damper are linked mechanically. A characteristic cam is inserted into this linkage to enable the damper setting to be matched to the valve setting. The cam is at a preset ratio-controlling position, set up coarsely on the basis of previous experience and finely tuned to attain optimum efficiency. Optimal settings are established by first carrying out a series of combustion tests over the full firing range, and then study the resulting flue gas analyses. Due to drift, affecting the optimal operating point of the burner, a frequent control is necessary to maintain an optimal setting of the system. This drift can originate from a variety of reasons:

- The fuel characteristics (viscosity, preheat temperature, calorific value) may change.
- The burner suffers from wear and becomes damaged or dirty.
- The cam and its linkage could wear or stick.

The consequences of this drift depend on circumstances. Old boilers and burners drift more rapidly than new equipment. This problem is solved by continuous or periodic resetting of various set-points, ensuring optimum combustion conditions and efficiency.
at all times. Oxygen monitoring using air-zirconia’s analyzers (see *Effluent Gas Monitoring*), provides feedback control. A CPU receives the signal from the flue position sensor and corrects flue gas oxygen levels by a signal to the trim actuator to adjust the damper position, thus altering the fuel/air ratio and achieving the desired combustion performance. Both pre-set and measured oxygen levels are stored in the CPU memory for each possible valve position, this CPU-unit constantly updating the trim output value required to compensate for stochastic factors affecting combustion. Instead of oxygen also CO\textsubscript{2} measurement can be used, since for each fuel there is a simple relationship between O\textsubscript{2} and CO\textsubscript{2}-values. Normally, fuel savings of two percent can be realized using this kind of control system and maintenance becomes quicker and more efficient.

An appropriate selection of burners reduces the formation of NO\textsubscript{x} at the source. Recirculating part of exhaust gases to the burners, the oxygen content of combustion air will be lowered, resulting in lower combustion temperatures and formation of NO\textsubscript{x}. The cost of these primary measures is offset not only by emission reductions, but also by significant economic benefits, such as a reduced energy demand, maintenance and repair costs.

The emission of some pollutants is determined by the choice of fuels (see *Control of Pollution in Power Generation*). The SO\textsubscript{2}-emissions are directly related to the sulfur content of the fuel. Unless there is considerable basic ash, as may be the case for coal, almost all sulfur in the fuel is transformed into SO\textsubscript{2}. Greenhouse CO\textsubscript{2} and particulates are also influenced by type and elementary analysis of the fuel. The nitrogen content of the fuel influences the NO\textsubscript{x}-emissions, especially if the nitrogen is contained in aromatic structures. Fuel with low sulfur and nitrogen content, however, may command significantly higher prices.

### 4.2 Flue Gas Treatment

Flue gas treatment allows reduction of the emissions of almost all kind of pollutants to very low levels (see *Control of Particulate Matter in Gaseous Emissions* and *Control of Gaseous Emissions*).

Electrofilters are used to reduce dust emissions from coal-fired plants. The dust collection efficiency can be improved by enhancing the content of SO\textsubscript{3} in the flue gases. By addition of sulfur (or SO\textsubscript{3} at a certain stage in the boiler following the combustion process) a better collection of particulate can be achieved.

NO\textsubscript{x}-reduction can be achieved by selective non-catalytic reduction (SNCR), by selective catalytic reduction (SCR) or even by a combination of both. In both techniques NO\textsubscript{x} is reduced by a chemical reaction with a reducing agent (mostly ammonia or ammonia water) that is injected into the exhaust gas stream at a suitable temperature. The lowest NO\textsubscript{x}-emissions can be achieved by the SCR technique, provided that the catalyst is not destroyed by high dust concentrations.

The costs of these techniques are characterized by higher investment costs for SCR and by higher operating costs for SNCR. The capacity of the installation has a rather limited...
influence on the investment costs, but is crucial for the operating costs. For SNCR these
are dominated by the ammonia consumption, which is proportional to NH₃ dosage, the
exhaust gas volume and thus the boiler capacity. The NH₃-dosage used is relatively
lower for the catalytic reduction (SCR) technique that achieves optimum performance in
NOₓ-reduction at a lower stoichiometric ratio. For establishing costs for both SNCR and
SCR, key parameters are the initial NOₓ level in the raw gas and the target concentration
to be achieved. For calculation of SCR costs, an exchange of catalyst at regular times is
also to be taken into account. Other factors requiring consideration is NH₃ slip and N₂O
formation, especially where urea is used as a reducing agent.

5. Combustion, Safety and Environmental Pollution

Accidental losses of oil and gas products sometimes occur in much publicized oil tanker
accidents at sea, in fires, at war, or even in Unconfined Vapor Cloud Explosions
(UVCEs) or – for low boiling liquids and liquefied gases - Boiling Liquid Expanding
Vapor Explosions (BLEVE), that occasionally may hit an oil refinery, a tank terminal or
other storage, or a petrochemical plant.

Anti-explosion measures are termed:

1. Primary, when eliminating the creation of explosive mixtures, e.g. blanketing
flammable liquids with nitrogen or carbon dioxide, avoiding vapor and dust
accumulation,
2. Secondary, when avoiding potential ignition sources, as related to open flames,
electric equipment, and static electricity. The plant is subdivided in zones,
depending on the probability of formation of explosive mixtures.
3. Tertiary, when harnessing explosion by explosion-proof construction, providing
pressure-relief panels, shut-off valves, or injecting extinguishing powders upon
early detection of any pressure rise.

A combustion plant also shows some serious dangers, e.g., in case of flame failure, the
supply of fuel must be immediately interrupted. If the combustion chamber fills with
flammable mixes of gas or vapors and air, which – upon ignition – suddenly explode.
Hence, watching the presence of a flame by monitoring its electric conductivity or U.V.-
spectrum is essential. Looking for I.R.-radiation is less safe, since it is also radiated by
hot refractory.

Unexplained explosions at the end of the Second World War led to in-depth
investigation of poorly understood sources of ignition, namely static electricity. The
latter originates in friction, related to the relative movement of different and poorly
electrically conducive materials, such as oil fractions and synthetic materials, such as
plastics or rubber. It may generate differences in potential of hundreds and even
thousands of volts, even though the total amount of charges is rather limited.

Static electricity is linked to transfer of electrons between two materials in mutual
contact, rubbing one over another. Although the amount of charges transferred remains
rather modest the resulting differences in potential and accompanying electric fields are
often huge and, with destructive consequences, sparking may occur in explosive surroundings.

Obvious countermeasures are e.g.:

- Lowering friction levels, by reducing speeds of e.g. moving belts, of liquids being pumped, or of flowing gases,
- Avoiding friction between dissimilar materials, by using the same materials throughout (water droplets emulsified in oil and aerosols or particulate suspended in gases are also examples of dissimilar materials),
- Avoiding the constitution of electric capacitors by positive and negative charges, separated by a dielectric. Sudden discharge will lead to dangerous sparks.
- Enhancing electric conductivity of materials, by using additives (antistatic additives to gasoline or plastics, adding carbon black in rubber and plastics), or taking structural measures, such as steel wires weaving in rubber hoses and floor carpets,
- Electrically connecting all vessels and tubing to earth,
- Humidifying the atmosphere, which increases the moisture content and hence the electric conductivity of numerous materials, capable of moisture absorption. This measure is inefficient with hydrophobic materials, e.g. plastics,
- Ionizing ambient air by means of high voltage, alternating current ionizers (require further study under potentially explosive conditions), or with ionizing rays or radioactive substances (always require special permits!),

Nowadays prevention of the accumulation of static electricity is a must for all relevant activities. For instance, before filling a tank with gasoline it must be ensured that the entire line, starting at the vessel of origin and ending in the receiving tank is electrically connected to the earth (grounded) so that no electrostatic spark can arise.

6. Conclusions

This article deals with the combustion of off-gases and with the general and safety aspects of combustion units.

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Glossary

**Adsorption:** partition process, fixing molecules from fluids onto the surface of a solid or liquid.

**Boiling Liquid Expanding Vapor Explosion:** explosion following the release of expanding vapor and boiling liquid caused by the failure of a pressure vessel holding liquefied gas, e.g. LPG.
(BLEVE): low-temperature oxidation using an appropriate oxidation catalyst to control emissions of odors and organics.

Catalytic Combustion: branch of applied science concerned with mathematical modeling of the movement of gases and liquids.

Computer Fluid Dynamics: physical change of phase from vapor to liquid, featuring cooling of the solvent vapors by means of low-boiling gases.

Cryogenic condensation: removal rate, derived by comparing inlet and outlet flows of a given hazardous compound.

Dioxins: popular term for polychlorinated dibenzo-p-dioxins PCDD and dibenzofurans PCDF

Eigenfrequencies: characteristic eigenvalues, physically allowed solutions of wave functions.

Elevated flare: erected to great height in both oil refineries and petrochemical plant to dispose safely of any excess amounts of flammable gases.

Hot stoves: refractory mass operating in a cyclic mode, first storing heat of combustion from hot gases, then transferring this heat to the incoming gas and/or combustion air.

Ljungström heat exchanger: custom-engineered, regenerative heat exchanger with proven performance and reliability, effective leakage control, and adaptability to most processes.

Products of Incomplete Combustion (PICs): generic group of compounds formed during combustion because of either an inadequate supply of oxygen, or insufficient temperature, time or turbulence (three T’s).

Rate Controlling Step: slowest step in a sequence of events, required to reach a certain goal, e.g. chemical reaction.

Static Electricity: electricity generated by friction of dissimilar materials, possibly leading to high tension sparks and destructive explosions, quality problems and shocks.

Three T’s: the three major combustion parameters Temperature, Time period, and Turbulence that determine the quality of combustion.

Trickling Bed Filters: Biofilter treatment unit, in which and other organics odorous substances are absorbed and eventually metabolized by zoogleal mass, covering the bed spontaneously.

Vapor Cloud Explosion (VCE): explosion caused by ignition of a flammable vapor cloud.

Volatile Organic Compound (VOC): Any organic compound which evaporates readily to the atmosphere. VOCs contribute significantly to photochemical smog production and certain health problems.

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**Biographical Sketch**

**Alfons Buekens** was born in Aalst, Belgium; he obtained his M.Sc. (1964) and his Ph.D (1967) at Ghent University (RUG) and received the K.V.I.V.-Award (1965), the Robert De Keyser Award (Belgian Shell Co., 1968), the Körber Foundation Award (1988) and the Coca Cola Foundation Award (1989). Dr. Buekens was full professor at the Vrije Universiteit Brussel (VUB), since 2002 emeritus. He lectured in Ankara, Cochabamba, Delft, Essen, Sofia, Surabaya, and was in 2002 and 2003 Invited Professor at the Tohoku University of Sendai.

Since 1976 he acted as an Environmental Consultant for the European Union, for UNIDO and WHO and as an Advisor to Forschungszentrum Karlsruhe, T.N.O. and VITO. For 25 years, he advised the major industrial Belgian Bank and conducted more than 600 audits of enterprise.

Main activities are in thermal and catalytic processes, waste management, and flue gas cleaning, with emphasis on heavy metals, dioxins, and other semi-volatiles. He coordinated diverse national and international research projects (Acronyms Cycleplast, Upcycle, and Minidip). Dr. Buekens is author of one book, edited several books and a Technical Encyclopedia and authored more than 90 scientific publications in refereed journals and more than 150 presentations at international congresses. He is a member of Editorial Boards for different journals and book series.

He played a role in the foundation of the Flemish Waste Management Authority O.V.A.M., of a hazardous waste enterprise INDAVER, and the Environmental Protection Agency B.I.M./I.B.G.E. He was principal ministerial advisor in Brussels for matters regarding Environment, Housing, and Classified Enterprise (1989). Since 1970 he has been a Member of the Board of the Belgian Consumer Association and of Conseur, grouping more than a million members in Belgium, Italy, Portugal, and Spain.

He is licensed expert for conducting Environmental Impact Assessments (Air, Water, Soil) and Safety Studies regarding large accidents (Seveso Directive).

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