

Review on Control of Emissions of Volatile Organic Compounds from Polluted Air

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Abstract: *The most common air pollutants emitted from chemical, petrochemical and allied industry are Volatile Organic Compounds (VOCs). Stringent regulations on control of VOCs have been put up due to growing environmental awareness as they are main sources of photochemical reactions taking place in the atmosphere which may lead to various environmental hazards. It has been made mandatory for each industry or facility emitting VOCs to install proper VOCs control measures. Different control techniques are available for the control of VOCs emission based on destructive and recovery methods. Each method has its own advantages and limitations. Deciding the best applicable technique based on the type of process is of utmost importance as these VOCs have their own economic value. The paper reviews various available technologies for VOCs control along with its merits, demerits and applicability for each option. The paper aims at providing critical analysis of the requirements and accordingly deciding on the appropriate strategy to control VOCs*

Keywords : VOCs, photochemical,

1. Introduction

Volatile Organic Compounds (VOCs) are organic compounds having high vapor pressure even at normal room temperatures. Most of the solvents, thinners, degreasers, cleaner, lubricants and liquid fuels are VOCs. Some common VOCs are benzene, toluene, xylene, tetrachloroethane, hexane, isopropyl alcohol etc. Their volatility is due to their low boiling points which causes a large fraction of the mass to evaporate or sublime from the solid or liquid form of the compound and enter the surrounding air. Chemical and petrochemical industries are the main source of VOCs emitted to the atmosphere. The emissions are originated from losses in storage tanks, venting of process vessels, piping and equipment leaks, wastewater systems and heat exchange systems.

Emission of these VOCs is a major environmental concern that should be prevented as they affect the climate, growth and decay of plants, health of humans and animals. Hydrocarbons in presence of sunlight undergo photochemical oxidation with NO_x to form secondary pollutants which are more harmful than primary air pollutants. Thus control of VOCs being emitted to the atmosphere must be made by selecting appropriate technology for VOCs control after a detailed analysis of the type, source and concentration of the emission is done. This paper aims at providing different technologies available for the control of emissions of VOCs with their merits and demerits.

2.VOCs emission control technologies and techniques.

VOCs control technologies or techniques can be basically classified into two different verticals:

1 Control at source and (2) End of pipe

treatment. The first vertical include control of VOCs emissions though cleaner production principles by carrying out modification in process equipment, raw material and/or process. The second vertical comprises of different applicable technologies for the control equipments required to reduce the emission to the prescribed norms. The cleaner production approach is the most viable both technically and economically but it has very limited applications. The control technologies at the end of pipe can be further classified to two sub groups (i) Destructive and (ii) Recovery. A tree diagram showing various VOCs control technologies is provided in Fig. 1.

3.Control of VOCs at source

Application of cleaner production practices reduce and control emissions at source itself. Process and/or equipment modification has to be done in order to reduce the VOCs emissions. It can be done by either changing or substituting the raw materials in order to reduce VOCs input in that process or by changing the process operating conditions so as to minimize the volatilization of VOCs and the modification of equipment to reduce the uncontrolled venting of the VOCs to the environment. The main objective of the equipment modification is to prevent the escape of VOCs. VOCs can be emitted vessel tops, vents or leaks in flanges and valves. Vessels shall be closed or shall be capped or equipped with vacuum vents to contain vapor emission. By proper maintenance through monitoring and repair programs these emissions due to leaks from valves, pimps and process piping connections can be regulated. Process enclosures can be designed to reduce emissions by capturing the exiting VOCs. But only capturing thorough enclosure doesnot reduce emissions, add on control techniques need to be places to process the collected VOCs back to the process else the will eventually escape to the environment.

4. End of pipe treatment

The VOCs which cannot be prevented from forming during the process needs to be removed before venting of the process air to the atmosphere. This process can be completed by either destroying the VOCs or by recovering them as reusable products. A tree diagram showing various VOCs control technologies is provided in Fig. 1

Figure 1 Classification of VOCs Control Techniques [2]

4.1 Destruction methods

VOCs can be destroyed by oxidation of carbon containing compounds to CO₂ and other by products which can be emitted to the environment. Oxidation of VOCs may take place thermally, catalytically or biologically. The processes for destruction of VOCs are termed as Thermal Oxidation, Catalytic Oxidation and Bio-Filtration

4.1.1 Thermal oxidation

In thermal oxidation systems VOCs are combusted between 700-1200 OC. The actual operating temperature is a function of the type of thermal oxidizer, VOCs concentration, type of VOCs and desired DRE (Destruction and Removal Efficiency). Compound having higher ignition temperatures or having low concentrations will require higher heat input and retention time in the oxidizer to ensure achieving desired DRE. Thermal oxidation systems have an efficiency to destroy 95% to 99% of VOCs. So basically they can achieve destruction of virtually all VOCs. Thermal oxidizers can be designed for the operating flow capacity of 1,000 to 500,000 cfm having inlet concentration ranging from 100 to 2,000 ppm. Due to potential explosion hazards in combusting VOCs, inlet concentrations in excess of 25% LEL (Lower Explosive Limit) are avoided by the oxidizer manufacturers. The nominal retention time for such oxidizers is between 0.5 to 1.0 s. High operating temperatures greater than 850 OC can lead to increase in nitrogen oxides concentrations. Halogenated compounds may be converted to their respective acidic counterparts. It adds up to the cost as it requires corrosion resistant materials as well as additional acid gas control systems.

Thermal oxidizers use two types of energy recovery systems, regenerative and recuperative. In both systems the heat content of the combustion exhaust gas is utilized to heat the incoming air stream prior to entering the combustion zone.

Regenerative systems use ceramic beds to capture heat from gases exiting the combustion zone. As the bed approaches the combustion zone temperature, heat transfer becomes inefficient and the combustion exhaust gas stream is switched to a lower temperature bed. The incoming gas stream is then passed through the heated bed where it recovers the captured heat prior to entering the combustion zone. By using multiple beds, regenerative systems have achieved up to 95% recovery of the thermal energy input to the system as fuel and the heat content of the combusted VOCs. Where the incoming gas stream contains sufficient thermal energy potential from VOC combustion, regenerative systems can operate without external fuel (excluding the need for a pilot light). The efficiency of the thermal recovery system depends on the process operating characteristics. A process where the flow rate and VOC content are relatively constant has a good potential for achieving virtual no-fuel operation. Cyclic processes generally are not as compatible with regenerative oxidation systems. The absorbed heat is lost to the environment during periods of low activity. Operation with insufficient VOC content to supply

thermal input requirements necessitates the use of external fuel sources.

Recuperative thermal oxidation systems recapture thermal energy with a simple metallic heat exchanger, typically a shell-and-tube design. The maximum thermal energy recovery of a recuperative system is around 70% of the fuel and VOC combustion energy input to the system. The advantage over the regenerative system comes from the relatively short period required for the heat exchanger to reach operating conditions. The larger mass of the regenerative heat recovery system requires time and relatively large initial fuel inputs to reach operating conditions, while the recuperative heat exchanger reaches operating conditions within several minutes of start up. Recuperative systems are best suited to cyclic operations where the versatility of an oxidation system is required along with the ability to respond to cyclic operating conditions. The high concentrations of organics in the regeneration stream, combined with the short duration of the desorption cycle, permits economical destruction of the VOCs in a thermal oxidiser. Thermal oxidation is a costly disposal method for treating low concentrations of organics contained in the process exhaust. A properly designed thermal oxidiser, which incorporates an effective heat exchanger and advanced refractory lining, is able to utilise the calorific value of the desorbed VOCs to generate the temperatures required for destruction with minimum auxiliary fuel consumption. A destruction efficiency of more than 99% can be achieved for most organics at temperatures ranging from 800 OC to 1,200 OC with residence times of 0.5 s to 2.0 s

4.1.2 Catalytic oxidation

Catalytic oxidation systems directly combust VOCs in a manner similar to thermal oxidisers. The main difference is that the catalytic system operates at a lower temperature typically about 350 to 500°C. This is made possible by the use of catalysts that reduce the combustion energy requirements. The incoming gas stream is heated, most often in a recuperative heat exchanger followed by additional input from a burner if needed, and passed through a honeycomb or monolithic support structure coated with catalyst. Catalyst systems can be designed to handle a capacity of 1,000 to 100,000 cfm and VOC concentration ranges from 100 to 2,000 ppm. The catalytic system is well suited to low concentration operations or those that operate in a cyclic manner. They are often used for vent controls where flow rates and VOCs content are variable. Destruction efficiencies in excess of 90% are common with a maximum DRE of 95% (Patkar & Laznow, 1992; Ruddy & Carroll, 1993). High concentration vent streams can also be treated with catalytic technology; however, as with thermal oxidation, it is not advisable for concentrations in excess of 25% of LEL. Lower operating temperatures, combined with a recuperative heat exchanger, reduce the start up fuel requirement. Large catalytic systems have been installed, but are not as popular as direct thermal oxidation systems, mainly due to the high costs of catalyst replacement. Catalyst materials can be sensitive to poisoning by non-VOC materials such as sulphur,

chlorides and silicon. Many catalyst manufacturers have overcome sensitivity to some of these substances, but every catalyst has susceptibilities that must be considered at the process

selection stage. For example, some catalysts are sensitive to deactivation by high-molecularweight hydrocarbons or polymerising materials. Also, the catalyst support may become deformed at high temperatures and high concentrations. Researching these issues should be part of the process selection activity if catalytic oxidation is under consideration (William & Lead, 1997).

Figure 4 Schematic of catalytic oxidation [2]

4.1.3. Biofiltration

The bio-filtration process, which was originally developed for the odour abatement of waste gases, has proven recently to be an effective and inexpensive method for the removal of VOCs produced during various industrial activities [2]. This technique is based on the ability of microorganisms (generally bacteria) to convert, under aerobic conditions, organic pollutants to water, carbon dioxide and bio-mass. The bio-filter consists generally of a simple structured packed bed, intensively surrounded with an immobilised micro-flora. The contaminated gas is directed through a bio-layer around the packing material. In practice, various types of packing material are used, e.g. compost, soil, peat, etc. [3] [4]. The filter bed material should have certain mechanical and physical properties (structure, void fraction, specific area, flow resistance and water retention capacity), and biological properties (provision of inorganic nutrients and specific biological activity). In the past decade increasing attention has been paid to bio-filtration as a waste gas purification process due to some important advantages this technique has compared to conventional purification methods. In addition to the mild operating conditions, a biological decontamination process does not generally transfer the pollution problem to another environmental compartment (gas to solid and/or gas to liquid), which is often the case with many other purification methods. Moreover, biological treatment is especially effective when the odours or toxic waste gas emission are in the lower concentration range, i.e. at few ppm levels.

Figure 5 Schematics of biofiltration [2]

5. Recovery methods

Techniques like condensation, absorption, adsorption and membrane separation are used for VOCs removal by recovering the exiting pollutants.

5.1. Condensation

Condensation is done to recover VOCs which are being emitted to the atmosphere. It is achieved chilling or pressurization or both of the waste gas stream. It is done when the gaseous stream is over saturated with the VOCs. Condensation is most effective for VOCs with boiling points above 40 °C at a relatively high concentration of 5000 ppm. Low-boiling VOCs can require extensive cooling or pressurisation, which sharply increases operating costs. Exceeding the 25% LEL threshold is more common with condensation systems. In fact, some systems begin operation above UEL (Upper Explosive

Limit). This is dangerous, because the concentration will likely fall through the explosive range during the condensation process. Therefore, inert gas blanketing of the vessels or unmanned process enclosures is advised to avoid the explosion hazard associated with high VOC concentration. However, this causes additional operating costs. Polymerisation materials should also be avoided in the condensation system due to the potential for fouling the heat-exchanger surface. Best suited to mono solvent systems, condensation produces a liquid product that must be treated to remove condensed water and possibly to separate various chemical species. Recovered VOCs can be reused within the process, used as wash solvents during equipment cleanup, burned as an alternative boiler fuel, shipped off-site for disposal or resold for reuse by others.

5.2. Absorption

Absorption is used to remove VOCs from gas streams by contacting the contaminated air with a

liquid solvent. Any soluble VOCs will transfer to the liquid phase. In effect, the air stream is scrubbed. This takes place in an absorber tower designed to provide the liquid vapour contact area necessary to facilitate mass transfer. Using tower packing and trays as well as liquid atomisation can provide this contact. Packed bed and mist scrubbing absorption systems are detailed here. An absorption system can be designed to handle a capacity of 2,000 to 100,000 cfm and VOCs concentration ranges from 500 to 5,000 ppm. An absorber can achieve VOC removal efficiencies of 95 to 98% [2]. The design of an absorption system for VOC control is similar to the design of an absorber for process application, using vapour liquid equilibrium (VLE) data, liquid and vapour flux rates, liquid and vapour handling information, and material balances. Packed bed scrubbing uses packing material to improve vapour-liquid contact. Packing can either be randomly dumped or stacked in the tower. Packing varies widely in size, cost, contact surface area, pressure and material of construction, and each packing design has its own advantages under different conditions. Packed bed scrubbers can be used well with a low solubility system due to the high liquid and vapour residence time (.10 s) associated with the entraining nature of packing. Packed bed scrubbers should, however, be used when liquid flow rates are low which causes inadequate wetting of the packing material. Also, the particulates on entering the air stream or absorbent create absorbate/reaction products which can foul or plug the packing. Mist scrubbers use spray nozzles to atomise the liquid stream into tiny droplets. These droplets provide the surface area for liquid-vapour contact. Mist scrubbers require a very low-pressure drop and must not be fouled by particulate in the incoming gas stream [2] [3]. The residence times of liquid and vapour are low (1-10 s). Therefore, mist scrubbing should only be applied to highly soluble systems. Absorption is not particularly suitable for cyclic operation due to start-up time constraints. It is, however, good for a high humidity air stream (50% RH).

5.3. Membrane separation

Membrane based separation has been reported over a long period. Gas permeation and reverse osmosis are the techniques used in the application of solvent recovery (recovery of VOCs) from air. This technique is in the field of experimental

research and has yet to be commercialised, though a few pilot plants have been developed and are continuously monitored for performance. A brief analysis of this is presented below: Baker, Yoshioka, Mohr & Khan [2] conducted air and vapour permeation experiments for various polymeric films, most of the experimental work reported so far is concentrated on composite silicon rubber membranes. Pinnau, Wijmans, Blume, Kuroda & Peinemann[3], Kimmerle, Bell, Gudernatch & Chmiel [4] and Paul, Philipen, Gerner & Strathmann[5] tested silicon rubber membrane coated on a porous polysulfone substrate. Behling [6] and Behling, Ohlrogge, Peinemann & Kyburz [7] have chosen poly (ether imide) as the supporting material because it is much more stable to organic vapours than polysulfone. Buys, Martens, Troos, Van Heuven & Tinnemans [8] used polyhydantoine and polyimide as the porous support to the silicon rubber-coating layer in their study. A membrane system for the treatment of low-volume, high vapour concentration gas streams was tested, but information was disclosed concerning the membrane materials by Wijmans & Helm [9]. The resistance of silicon rubber to some organic vapours, for example gasoline, is however poor. An attempt was made, therefore, by Deng, Sourirajan & Matsuura [10] to prepare membranes from a single polymeric material of high organic resistance. In their previous studies, asymmetric aromatic polyimide membranes were investigated for the purpose. It was shown that controlling the conditions of the membrane preparation properly could produce membranes of both high selectivity and reasonably high permeability.

Deng et al. [10] have conducted a thorough experimental study on the recovery of organic solvent from air with the help of an aromatic poly membrane. The study promises encouraging results. The important outcomes of the study are as follows:

- Hydrocarbon mixtures can be effectively separated from air by an asymmetric aromatic poly (ether imide) membrane without a silicone rubber coating. O Water permeability is higher than hydrocarbon permeability.
- The presence of water vapour in the feed does not affect the hydrocarbon permeability. In other words, water and hydrocarbon molecules permeate through the membrane independently.
- Gasoline vapour can be separated effectively by an asymmetric aromatic poly (ether imide) membrane.
- Aromatic poly membranes are very good commercial value for removing volatile organic compounds when the amount of air to be treated is relatively small.

Although the membrane-based recovery system promises good results at the experimental stage, its adaptability is dependent on many factors, a few of which are discussed below.

5.4 Adsorption

The adsorption process is classified into two types, namely, physical adsorption and chemisorption based on the interaction between adsorbate and adsorbent. Physical adsorption has been found to be more significant in the case of separation processes. Physical adsorption is again classified into Thermal Swing Adsorption (TSA) and Pressure Swing Adsorption

(PSA), based on the operation of the process. Both the processes have their advantages and disadvantages. Physical adsorption occurs when organic molecules are held on the surface and in the pores of the adsorbent by the weak Van der Waals force of attraction and is generally characterised by low heat of adsorption, and by the fact that the adsorption equilibrium is reversible and rapidly established [11] A very low VOC concentration in exhaust air is expensive to treat. For many low-concentration situations it is possible to use adsorption to increase the concentration to a level at which it is more feasible to clean up the air using a reasonable sized recovery plant. Recovery of some organics like 1,1,1-trichloro ethane (TCA) and styrene vapour are not well-suited for steam-regenerated temperature swing adsorption (TSA) or thermal incineration. Because of its thermal sensitivity and tendency to form degradation products, including HCl, TCA could not be recovered with traditional steam-regenerated TSA processes. Thermal incineration of TCA and other chlorinated solvents required tail gas treatment and subsequent wastewater disposal. The potential of styrene to polymerise at elevated temperatures likewise made TSA processes undesirable for styrene vapour recovery [12]. In these situations PSA is the best alternative. The proper adsorbent choice depends upon the application, but activated carbon and styrene/divinylbenzene macroporous resins are the preferred adsorbents for VOCs recovery.

5.1.1. Activated carbon based adsorption Carbon adsorption is a very common method of VOC emission control. VOCs are removed from the inlet air by physical adsorption onto the surface of the carbon. The system is sized according to the maximum flow and concentrations expected, and anything less usually improves efficiency. Carbon adsorption systems are flexible and inexpensive to operate. Installation costs are often lower than those of other systems [12]. The adsorption capacity of activated carbon for a given VOC is often represented by an adsorption isotherm of the amount of VOC adsorbed (adsorbate) to the equilibrium pressure (concentration) at constant temperature. VOC molecules are physically attracted and held to the surface of the carbon. Activated carbon is such a good adsorbent because of its large surface area, which is a result of its vast infrastructure of pores and micropores and micro-pores within micro-pores. In a commercial activated-carbon solvent-recovery plant, solvent laden air passes through a tank containing a bed of activated carbon. The solvent is adsorbed on the carbon surface and clean air is exhausted to atmosphere. When all of the available surfaces of the carbon pores are occupied it will not capture any additional solvent. Now, to recover the solvent for reuse, it must be released from the carbon surface. This is most commonly done by heating the carbon with steam. The hotter the carbon, the less solvent it can hold, so as the steam heats the carbon, solvent is released and flushed away by the steam. The mixture of steam and solvent is condensed by cooling and then separated in the simplest case by gravity decanting. If the solvent is soluble in water, distillation is required instead of decanting. The carbon can then be reused as well. The batch process of adsorption and desorption as described above can be made continuous by the use of multiple carbon beds so that one is off-line for desorption while the other is on adsorption. Regeneration can be done on-site with hot air or hot nitrogen, depending upon process conditions and local utilities. Moisture is one of the crucial parameters to dictate the efficiency and effectiveness of the adsorption process. In many cases the

activated carbon that has adsorbed moisture will lose this moisture by displacement in its preference for organic vapours. Halogenated compounds are strongly affected by increased relative humidity, whereas aromatic compounds are only weakly affected. However, because water vapour competes with the VOCs in the emission stream for adsorption sites on the carbon surface, emission stream humidity levels exceeding 60% RH are not desirable. For these reasons, activated carbon becomes the right adsorbent for high capacity, nonselective adsorption of gases at ambient temperature, suitable for most VOCs with molecular weights between 40 and 150 and boiling points from 40°C to 260 °C.

Many parameters need to be studied in detail before deciding about the adsorption process, a few important ones are:

- description of the process emitting the VOCs
- exhaust volume
- temperature, pressure and relative humidity of the exhaust air
- composition of the VOCs and their concentrations
- recovery efficiency required
- quality of recovered solvent required, any contaminants present, such as dust, high boiling components, resins, and so on,
- possibility of future expansion of plant,
- whether cooling water is available, and if so, its temperature
- whether steam is available, its pressure, and whether it is saturated,
- steam costs (which will determine the economy of the steam recovery operation).

5.1.2. Zeolite based adsorption

As elaborated in an earlier section, it has been recognised that activated carbon is the most suitable adsorbent for this application [12]. However, [13] pointed out that the applications of activated carbon present some disadvantages as they are flammable, difficult to regenerate for high boiling solvents, promote polymerisation or oxidation of some solvents to toxic or insoluble compounds, and require humidity control. Therefore, it is necessary for a new type of adsorbent to replace the activated carbon. As a result, hydrophobic zeolite is now considered an alternative adsorbent since it has good properties such as thermal stability and hydrophobicity [13]. Hydrophobic zeolite can be manufactured with precise pore size, allowing selective adsorption of some compounds while excluding others. Zeolites are inorganic materials that have a crystalline structure and fixed pore sizes. The homogeneous pore size prevents molecules larger than a certain size from entering the lattice, so zeolites are sometimes called molecular sieves, which allow them to adsorb selectively. The non-flammable, thermal-stable, and hydrophobic characteristics of zeolites can also play an important role in adsorption. The thermal stability and hydrophobicity of zeolites increase with the Si/Al ratio in the zeolite framework. Synthetic hydrophobic zeolite, a pure crystalline silica molecular sieve, is non-flammable and capable of withstanding temperatures as high as 850°C [14]. Furthermore, hydrophobic zeolite has a low affinity for water, which is a useful physical property. [15] reported that up to 90% relative humidity could be handled with little adverse

effect on the capacity of hydrophobic zeolite. Also, [16] reported that the

presence of water was found to reduce the amount of adsorption of the solvent–hydrophobic zeolite system, but water vapour showed no effect on the adsorption kinetics (thus overcoming the major limitation encountered in carbon adsorption). Hydrophobic zeolites are also non-flammable, so it can be used for some compounds that might catch fire with activated carbon (e.g. cyclo-hexane). The cost of hydrophobic zeolite is still very high, so its use is economically limited to applications for which activated carbon is not well suited.

Figure 6 Schematic of VOCs removal by adsorption (Solvent recovery) plant [2]

6. Discussion and conclusion

A brief information on parameters of operation and design for each technique is provided in Table 1

This article reviews various available techniques for VOCs control. The following

conclusions have been drawn by a thorough study of the available options for VOCs control.

1. Oxidation is the most commonly used technique, though it destroys the valuable VOCs. Further, the oxidation process with heat recovery is a good economical option. However, this process requires specific operating conditions and design of incinerator depending upon the composition of the VOCs. It may also generate toxic combustion products, which need further processing. These limit its applicability. Catalytic combustion is a good alternative that overcomes some of its limitations. However, the Reverse Flow

Reactor is the best alternative to oxidation in today's context of energy management.

2. Adsorption is the next most favoured technique. It has good removal (recovery) efficiency, though it requires higher capital investment and operating costs. Desorption of adsorbent and separation of VOCs from desorbed solution increase the complexity and cost of the process. Activated carbon, though a cheap adsorbent, has many limitations, e.g. the possibility of firehazard, less selectivity, etc., whereas zeolite is more costly but has many advantages such as no fire hazards, uniform pore size distribution, etc. If VOCs recovery is important, the authors recommend adsorption as a good technique to be implemented. There are many solvent recovery units available commercially based on the adsorption principle.

3. Bio-filtration is a cheap and effective alternative for VOCs elimination. However, due to selective destruction, sluggishness, the applicability of this process is limited in commercial applications. This technique is in current research and the authors feel that in future it would be the most preferred alternative.

4. The absorption process involves high initial investment as well as difficulties in design, due to the lack of availability of vapour liquid equilibrium data. Moreover, stripping of VOCs from the absorbing solvent requires further separation, and thus costs. Along with many limitations (a few cited above), this technique has some advantages, e.g. the ability to handle a wide range of concentrations, simple process and equipment, and good efficiency.

5. Condensation is a safe alternative for VOCs recovery. It does not involve any second component and thus not much separation

technology. It is simple. It suffers from many limitations such as it requires high concentration, extreme-operating conditions (temperature and pressure), high boiling VOCs, high operating costs, etc. These limitations have restricted its commercial applicability

Finally, it is concluded that oxidation (catalytic) is a good option when VOCs recovery is not important (both in terms of efficiency and cost), whereas, if VOCs recovery is important, adsorption is the best alternative. Biofiltration is a bright option, still in research, and we hope that in the near future it will become the most potent technology for VOC control.

Techniques	VOC Content			
(ppm)	Moisture			
Content (%)	Capacity			
Range (CFM)	Temperature			
(OC)	Removal			
Efficiency (%)				
Thermal				
Oxidation	20-25% of			
LEL	10-40	100-500000	700	95-99
Catalytic				
Oxidation	100-1000 but			
<25% LEL	10-40	1000-10000	300	90-98
Bio-Filtration	<5000	>90	<14000	50-105 60-95
Condensation	5000-10000	20-80	100-20000	
	Ambient	70-85		
Absorption	500-15000	Normal	2000-10000	
	Normal	90-98		
Carbon				
Adsorption	700-10000	<50	100-6000	
	<130	80-90		

Zeolite			
Adsorption	1000-10000	94-96	100-6000
	Ambient	90-96	
Membrane			
Separation	Very low-		
25% LEL	90-99	200-1500	Ambient 90-99

Table 1 Details of VOCs control Technique SCHEMES

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