A Comparative Study of Volatile Organic Compounds Abatement Technologies

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Abstract— **This work focuses on the selection and application of abatement technologies in the reduction / elimination of the release of volatile organic compounds into the atmosphere. A benefit limitation analysis was carried on the various techniques. Factors considered in the selection process include vent stream, emission rate, cost, control equipment, and regulatory framework. The technologies were evaluated based principle of operation, design criteria, removal efficiency, process characteristics, legislation, environmental impact as well as emission composition, characteristics and source. It can be concluded that technology selection depends on the economics, operational flexibility and applicability. The paper also highlights the industrial application of various technologies.**

Keywords— **Abatement, economics, emission, regulatory, technologies, vent stream.**

I. INTRODUCTION

GOVERMENTS are under pressure to create and enforce regulations to reduce the impact of air pollutants. Volatile organic compounds (VOCs) are an example of air pollutants that require removal from contaminated industrial gaseous effluents. VOCs emissions result from natural and anthropogenic (man-made) sources. Natural sources of VOC include vegetation, forest fires, and animals. Although natural sources of VOC emissions are larger overall, it is anthropogenic sources in populated and industrialized areas that are the main contributors to air quality problems. Major sources of man-made VOCs are industrial processes (51%), transportation (40%), fuel consumption (5%) and miscellaneous (4%) [1]. VOC are primary precursors to the formation of ground level ozone and particulate matter in the atmosphere which are the main ingredients of smog. Ground level ozone is primarily formed through the photochemical reaction of volatile organic compounds (VOCs) and nitrogen oxides (NOx) [2] Smog is known to cause serious health effects for human beings as well as harmful effects on vegetation. It can inhibit photosynthetic activity through complex interactions affecting plant structure [3]. Some individual volatile organic compounds are believed to be a threat to human health. For example, benzene has been reported as cancer-causing and hexane as a cause of nervous system disorders. Whereas natural pollution cannot be controlled, man-made air pollution has become widespread and controllable. Many chemical and industrial plants aim to reduce the amount of VOCs released into the atmosphere. Recovery (absorption, adsorption, condensation, membrane separation) and destructive (oxidation, bio-filtration) techniques may be used for the abatement of volatile organic compounds [4]. Destruction technologies involve oxidation of VOC substances to their most oxidized form namely carbon dioxide and water and for hydrocarbons containing chlorine or sulphur, the exhaust will also include HCl and SO_2 [5]. Recovery technologies simply remove the contaminant from the exhaust stream for further treatment. Although a number of VOC emission control techniques are available, the application of a wrong technique substantially increases downtime, air pollution and as well as facility and maintenance costs. However, correct selection of the abatement technique improves pollution control and return on investments as well as reducing operating costs.

This study aims to identify effective VOC techniques for specific industries by conducting a benefit and limitation analysis of the various methods. Based on the emissions inventory, an appropriate abatement technique is selected considering pollutants emitted species in the vent stream, cost, emission rates. existence of control equipment and regulatory frameworks. The applicability of VOCs abatement technologies is shown in Table I

Table I
VOCs ABATEMENT SYSTEMS APPLICABILITY

VOC abatement technology	waste gas flow rate	VOC concentration (ppm)
Thermal oxidation	0-10 000 (thermal after burner	60% of LEL (thermal afterburner
	250-100 000 (recuperative	25% of LEL (recuperative)
	2 000 - 500 000 (regenerative)	10% of LEL (regenerative)
Catalytic combustion	0-75 000	25% of LEL
Adsorption	No practical limit	100 5 000
Condensation	< 3 000	> 1 000
Flaring	No practical limit	No practical limit
Biofiltration	> 1 000	< 1 000
Membrane separation	< 500	> 5 000

II. METHODOLOGY

Volatile organic compounds abatement technologies were evaluated and analysed in terms of principle of operation, design criteria, removal efficiency, process characteristics, legislation, environmental impact as well as emission composition, characteristics and source. The overall technology comparison and selection was based on economics, operational flexibility and applicability.

III. General Discussions

A. Source Characteristics and Composition

The composition of the effluent stream influences the choice of control technique. For example streams containing halogenated hydrocarbons may poison catalysts in used in some abatement techniques and may also be oxidized to acidic forms. Hence corrosion resistance construction materials maybe required. Streams with a variety of contaminants are difficult to treat, this limits treatment options. Recovery techniques may require additional separation equipment.

B. Concentration

VOC concentration and pollutants form (i.e. vapor or particulate) are important in the consideration of control equipment selection. High flow rate streams with variable concentrations create equipment wear and tear challenges. This could have a detrimental effect on thermal energy, recovery efficiency, and possibly reduce destruction or removal efficiency of the device. Condensation requires high inlet concentrations to operate efficiently. Low concentration streams require pre-treatment to increase the concentration before introducing the effluent into the control device. Fig. 1 shows the general applicability of VOCs control systems for high concentration sources. The number of VOCs in the effluent stream and economic considerations influence the choice of the abatement technology. Thermal oxidizers are commonly used where recovery is not required and feasible. Catalytic oxidation may be applied in these situations provided the effluent does not contain any components which may poison, mask or foul the catalyst. For three or less mixture of organics adsorption would be suitable. Absorption may be applicable in this situation in an environmentally acceptable disposal route is available. Recovery and condensation are recommended when recovery is required but these technologies are limited to streams not containing more than three organic compounds to costs of separating the recovered organics. Fig. 2 shows the general applicability of low concentration sources. For more than 3 VOCs in the stream, it is usually uneconomical to recover the VOCs for re-use, hence thermal or catalytic oxidizers are employed to destroy the organics. Adsorption may be used for pre-concentration before the effluent is fed into oxidizers. For 3 or less organics in the gaseous stream, absorption or biological oxidation may be employed for treating the process effluent.

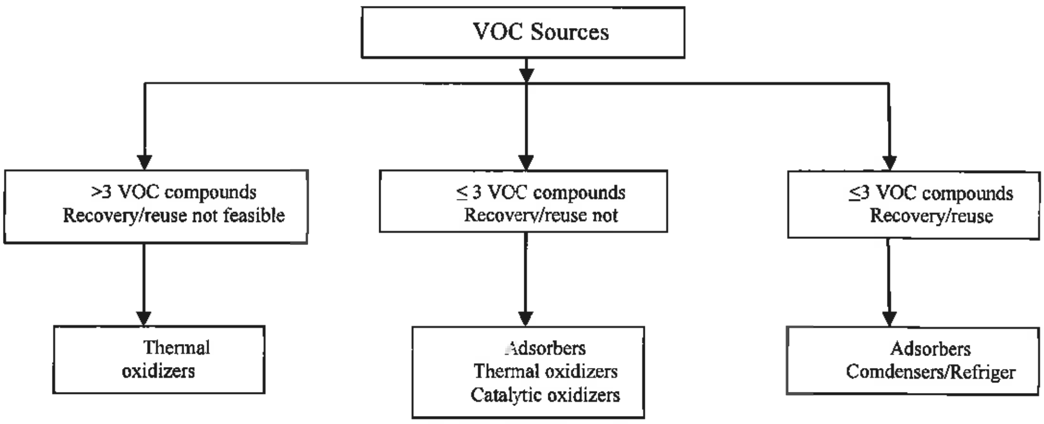

Fig. 1 General applicability of VOC control systems for high concentration sources [6]

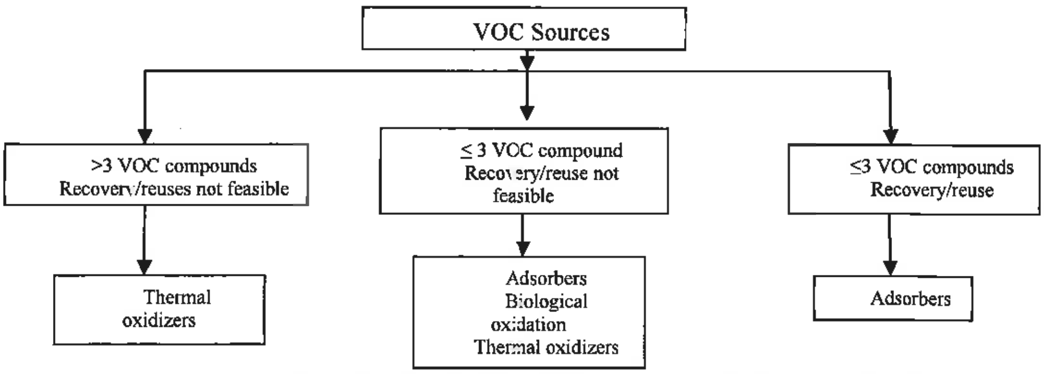

Fig. 2 - General applicability of VOC control systems for low concentration [6]

C. Fire and Explosion Hazards

Volatile organic compound are fire hazards, require precaution and safe handling methods. Chemical process industries handling bulk storage and operations at extreme conditions of temperature and pressure require control techniques to reduce hazards.

D. Recycle Probability

When there are large quantities of VOCs in the process effluent streams, recovery is the preferred option. This can also contribute towards capital and operating costs of the control equipment.

E. Maintenance

Maintenance is an important consideration when selecting the abatement technique. In certain situations, using wrong techniques could increase facility costs, downtime, and/or maintenance. If maintenance is not sophisticated and minimum quantities of VOCs are present in the process effluent streams, it is not necessary to choose a control technique that requires significant maintenance resources and continuous monitoring.

F. Discharge Temperature

Condensation and adsorption are not applicable to high temperature waste gas streams. This is because the cooling requirement could increase operating costs. Such process effluent streams may be suitably treated using thermal or catalytic oxidation which would not require any pre-treatment.

G. Removal Efficiencies

Combustion can achieve higher removal efficiencies compared to other abatement techniques.

H. VOCs Control Techniques Analysis

Table II shows an analysis of VOC control techniques with regards to annual operating cost, removal efficiency, and secondary waste generated as well as advantages and limitations.

Table II
ANALYSIS OF VARIOUS VOC CONTROL TECHNIQUES

Techniques	Annual operating cost $/cfm	Removal efficiency %	Secondary waste generated	Positive remarks	Negative remarks
Thermal oxidation	15-90 for recuperative, 20-150 for regenerative	95-99	Combustion products	Energy recovery is possible (maximum up to 85%)	Hallogenated and other compounds may require additional control equipment downstream
Catalytic oxidation	15-90	90-98	Combustion products	Energy recovery is possible (maximum up to 70%)	Efficiency is sensitive to operating conditions. Certain compounds can poison the catalyst. May require addition control equipment downstream
Bio-filtration	15-75	60-95	Biomass	Require less initial investment, less non-harmful secondary waste and non-hazardous	Slow, and selective microbes decomposes selective organics, thus requires a mixed culture of microbes (which is difficult). No recovery of material.
Condensation	20-120	70-85	Condensate	Product recovery can offset annual operating costs	Requires rigorous maintenance. Not recommended for the materials having boiling points above 33°C
Absorption	25-120	90-98	Wastewater	Product recovery can offset annual operating costs.	Requires rigorous maintenance. May require pre-treatment of the VOCs. Design could be difficult due to lack of equilibrium data.
Adsorption Activated carbon	10-35	80-90	Spent carbon and collected organics	Recovery of compounds, which may offset annual operating costs	Susceptible to moisture and some compounds (ketones, aldehydes and esters) can clog the pores, thus decreasing the efficiency
Zeolite	15-40	90-96	Collected organic, spent zeolite after several cycles	Effective in more than 90% RH. Recovery of compounds offsets annual operating costs	High cost of zeolite, restricted availability.
Membrane separation	15-30	90-99	Exhausted membranes	No further treatment, recovery of solvent may offset the operating cost	Membranes are rare and costly.

İ. Industrial Application

- Thermal oxidizers: Are applied in various industrial processes including storing and loading/unloading of petroleum products and other volatile liquids, vessel cleaning, process vents, paint manufacturing, rubber products and polymer manufacturing, plywood manufacturing, surface coating operations, flexible vinyl and urethane coating, graphic arts industry and hazardous waste disposal facilities.
- Catalytic incinerators: They are mainly used to reduce emissions from solvent evaporation processes and are also applied in vanish cookers and foundries, filter paper processing ovens, plywood veneer dryers, gasoline bulk loading stations, rubber products and polymer manufacturing.
- Adsorption: Applied in dry cleaning operations, degreasing, paint spraying, solvent extraction, paper coating, printing and pharmaceuticals.

- Absorption: This abatement technique is preferred in chemical, food, agriculture, ferroalloy and chromium electroplating industries. The absorption process is influenced by availability of suitable solvent, desired removal efficiency, pollutant concentration, handling capacity, value of recovered pollutants and unrecoverable solvent disposable cost.
- Flares: Can handle large fluctuations in VOC concentration, flow rate and heating value. Flares are normally applied as control devices for process upsets.
- Condensation: Applied in the dry cleaning industry, degreasing operations and volatile organic liquid transfer operations.
- Bio-filtration: Is applied in chemical, food, ink, fertilizer and pulp and paper industries as well as water and waste water treatment plants.
- Membrane separation: Applied mainly in the chemical industries such as fertilizer, agrichemicals, ink, paints, explosives and pharmaceuticals.

IV. ECONOMIC CONSIDERATIONS

The total investment, net present value (NPV) and total annual costs are the main economic considerations when selecting a cost-effective abatement technology. The total investment includes the equipment, installation, site preparation and construction and land costs as well as working capital and offsite facilities. There are a number of ways of estimating NPV, investment and annual operating costs for abatement technologies. These range from simple computer-based spread sheets to sophisticated financial- management software. Table III shows a model for estimating investment costs for volatile organic compounds abatement devices based on Du Point's extensive work on evaluating control technologies [7]. Although investment cost are project specific, the models allows estimates for new and replacement equipment. Examples of cost factors used in NPV calculations are shown in

Table IV.

Table III
ESTIMATING INVESTMENT COSTS FOR VOC/HAP ABATEMENT [7]

A	Cost Element	Basis
1	Engineered Equipment	• Vendor estimate
2	Miscellaneous Engineered Equipment	• 0%–10% of Engineered Equipment
3	Equipment Installation	• 10%–40% of (Engineered Equipment + Miscellaneous Engineered Equipment)
4	Field-Erected Equipment	• Vendor estimate
5	Equipment Foundations, Supports, Platforms	• 5%–15% of (Engineered Equipment + Miscellaneous Engineered Equipment + Equipment Installation + Field-erected
B	**Installed Equipment**	• **Sum of first five cost elements**
1	Process and Service Piping, Instrumentation, and Electrical	• Usually based on a combination of historical values from previous projects and vendor estimates
2	Architectural and Civil Items (e.g., pipe supports, dikes, trenches, pilings, sanitary)	• Contractor estimate
3	Buildings and Structures (e.g., process buildings, silo supports, control rooms	• 5%–15% of (Installed Equipment +, Piping/Instrumentation/Electrical)
4	Dismantlement and Rearrangement (e.g., existing equipment, buildings, piping)	• 0%–10% of (Installed Equipment +, Piping/Instrumentation/Electrical +
5	Freight/Quality Assurance/Procurement	• 7% of Engineered Equipment
6	Sales Tax	• Varies by state. Some states exempt pollution abatement equipment from sales taxes.
7	Construction Contractor (e.g., payroll, taxes, benefits, tools and equipment, rentals,	• 20% of (Installed Equipment + Piping/Instrumentation/Electrical + overhead, profit) Architectural Civil + Buildings/Structures + Dismantlement/Rearrangement)
8	Other Identifiable Costs (e.g., fire protection, railcar/truck loading spots, waste treatment allowances, substations, cooling towers,	• Project-specific
C	**Direct Costs**	• **Sum of all previous costs**
1	Project Management	• 15%–22% of Direct Costs
2	Contracts Administration	• 2%–5% of Direct Costs
3	Contingencies	• 10%–30% of (Direct Costs + Project Management Costs + Contracts Administration)
	Total Investment	**Sum of A, B, C costs**

Table IV
ANNUAL OPERATING COST FACTORS [7]

Cost Element	Unit Cost Factor (U.S. Dollars)
Raw Materials	
Activated Carbon (5-yr life)	• $2.80/lb
Platinum Catalyst (5-yr life)	• $4,200/ft3
Membrane Module (3-yr life)	• $450/m2

Polymeric Adsorbent (5-yr life)	• $3.00/lb
Zeolite Honeycomb (5-yr life)	• $1,000/unit
Carbon Fiber Wheel (5-yr life)	• $1,000/unit
Compost Bed (3-yr life)	• $10/yd3
Utilities	
Electricity	• $0.04/kWh
Natural Gas	• $2.50/MMBtu
Cooling Water	• $0.05/Mgal
Filtered Water	• $0.15/Mgal
Steam	• $3.50/Mlb
Nitrogen	• $0.045/lb
Other	
Wastewater Treatment	• $0.35/lb organic
Cost Factors	
Technical Support	• $160,000/yr
Operations Labour	• $430,000/yr for 3-shift coverage
Maintenance	• 4% of total investment/ year
Taxes and Insurance	• 0.75% of total investment/ year
General Plant Overhead — Investment-related	• 0.5% of total investment/ year
General Plant Overhead — Labour-related	• 24% of (Operating + Maintenance Labour)/year
Project Liaison Costs (1 yr only)	• 2% of total investment
Start-up Costs (1 yr only)	• (1 yr only) 10% of total investment
Creep Investment	• 1.5% of total investment/yr
Working Capital	• 60 days of cash costs
Cash-Flow Bases	
Depreciation (6-yr accelerated)	• 20%, 32%, 19%, 12%, 12%, 5%
Income Tax Rate	• 40%
Discount Rate for Net Present Cost	• 12%
Capital Recovery	• 10% borrowing costs, 10-yr life

Figure **3** shows an overview of investment and net present costs for end-of-pipe treatment of VOC and HAP emissions based on a 12% discount rate and a 10-year equipment life [7]. The costs in Figure **3** assume the absence of halogenated compounds and particulates in the effluent streams as their presence would double the costs. Hidden costs of installing and operating VOC/HAZAP control devices such as permitting and compliance costs are not included. An example of an investment cost for a bio-filtration system is shown in Table V.

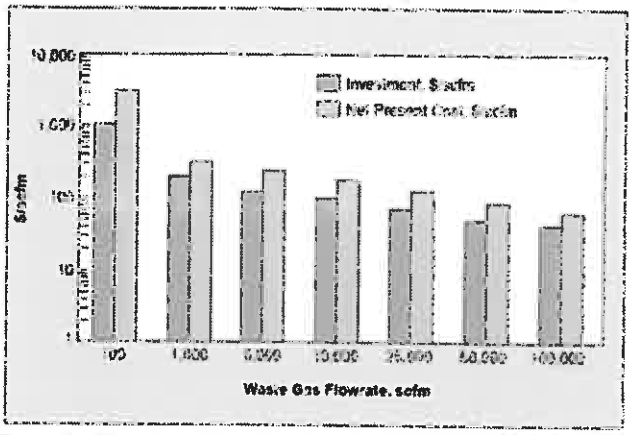

Figure 3 - Overview of investment and net present costs for end of pipe treatment technologies [7]

Table V
EVALUATION OF BIO FILTERS INVESTMENT COST BASED ON A SPECIFIC AIR FLOW RATE AND EMPTY BED RESIDENCE TIME (EBRT)

Air flow rate (m^3h^{-1})	EBRT (s)	Total investment cost (£)	Annualized investment cost (AIC) (£)
10 000	360	90 273.60	7 220.89
15 000	240	125 930.71	10 073.60
25 000	144	195 085.00	15 605.80
70 000	51	514 314.28	41 144.14
400 000	9	2 869 642.85	229 570.40

Basic design for each abatement technologies are required to determine the size and main operational requirements of the system. The size is used to obtain good estimate of the capital costs and operational requirements help in the estimation of annual operating costs. The basic design and the engineering economics can be used to determine an abatement system life cycle cost. Lifecycle costs calculations include capital, resource, labour and maintenance and anticipated major maintenance costs as well as anticipated lifespan.

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