AERATION OF VOC'S IN WASTEWATER BY USING GAS DISPERSION IMPELLERS

A DISSERTATION

Submitted in partial fulfilment of the
requirements for the award of the degree
of
MASTER OF TECHNOLOGY
in
CHEMICAL ENGINEERING
(With Specialization in Industrial Pollution Abatement)

By

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CANDIDATE'S DECLARATION

I here by declare that the work which is being presented in this dissertation entitled **"Aeration of VOC'S in Wastewater by Using Gas Dispersion Impellers"** in partial fulfillment of the requirements for the award of degree, Master of Technology in Chemical Engineering with specialization in Industrial Pollution Abatement (IPA) submitted in the Department of Chemical Engineering, Indian Institute of Technology Roorkee, is an authentic record of my work under the supervision of **Dr. C. Balomajumder**, Assistant Professor, Department of Chemical Engineering, Indian Institute of Technology Roorkee, Roorkee, during the period July-04 to June-05.

The matter presented in this dissertation has not been submitted by me for the award of any other degree of this or any other Institute/University.

Place: IIT Roorkee

Date: June 30. 2005

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CERTIFICATE

This is to certify that the above statements made by the candidate are correct to the best of my knowledge and belief.

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ABSTRACT

A number of Volatile Organic Compounds (VOCs) found in the wastewater and some of these VOCs are very harmful for the human health as well as environment. Although there are several methods which are being used for the removal of VOCs, but the Air Stripping process is the low energy usage, low preventive and maintenance cost and high efficiency process which can stripes VOCs from wastewater.

The present dissertation work consists of aeration system for the removal of VOCs. The aeration of VOC based on the mass transfer rate of VOCs from the liquid phase to the gaseous phase. Principle of air stripping involves the mass transfer of volatile organic contaminant from water to air. The system can be easily upgraded to strip greater amount of VOCs with relatively small increases in capital cost. Aeration tanks strip volatile compounds by bubbling air into tank through which contaminated water flows. The emission rate of VOCs during surface aeration can be estimated from the oxygen mass transfer coefficient $K_La_{O_2}$ and a modified coefficient Ψ_m. which incorporate the fraction of liquid phase mass transfer resistance to total resistance.

The present study shows that aeration of a VOC by using advanced designed gas dispersing radial impeller i.e. Rushton, CD-6 and BT-6 and the factors which affects the design of a aeration tank baffles,and the impeller used for best possible result. This study also shows the removal efficiencies of VOCs of these impellers and it compares the efficiencies of impeller used at different height of submergence. It also shows the effect of air supply on the removal efficiencies and wide study of the effects on mass transfer coefficient of VOCs at different operating condition.

A comparison of the result from experiment shows the emission rate of VOCs during aeration is a function of mass transfer coefficient of air and it increases with increase of submergence of height, by supply of air, and increase in impeller speed. Air supply can increase the removal efficiency up to 8-12%. Best aeration result can be obtained at the 2/3rd height of the submergence of the total depth of water for impeller used. Study also shows the gas dispersion impeller BT-6 impeller larger removal efficiency (up to 96%, with air supply at 4 hrs run) compare to Rushton and CD-6 impeller.

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CHAPTER-1 INTRODUCTION

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NOMENCLATURE

P_G.	Gas phase pressure, atm.
P_T	Total operating pressure, atm
Pi	Partial pressure at interface, atm
H	Henry's constant, atm m^3/mol
Hc	Henry's constant (dimensionless)
C_s	Gas phase concentration in equilibrium
C_L	Liquid phase concentration in equilibrium
M	Molecular weight of solute (g/mol)
K_La	Mass transfer coefficient, 1/hr
η	Removal efficiency, %
B	Tank baffle width, m
T	Tank diameter, m
C_S	Sparger clearance, m
D	Impeller diameter, m
D_D	Impeller central disk diameter, m
W	Impeller blade width, m
L	Impeller blade length, m

INTRODUCTION

1.1 General

Organic compound that have boiling point less than or equal to 100°C and/or vapor pressure greater than 1 mm Hg at 25^0C are generally considered to be Volatile Organic Compounds (VOCs). According to EPA section 51.00 (revised) volatile organic compound (VOC) means any compound of carbon, excluding carbon mono oxide, carbon dioxide, carbonic acid, metallic carbides or carbonates, and ammonium carbonate, which participates in atmospheric photochemical reactions. Volatile organic compounds are of great concern because:

- Such compounds are in the vapor state they are much more mobile and therefore more likely to be to be released to the environment.
- The presence of some of these compounds in the atmosphere may cause a significant public health risk.
- They contribute to a general increase in reactive hydrocarbons in the atmosphere, which can lead to the formation of photochemical oxidant.

VOCs include very wide wide range of individual substances, such as hydrocarbons (for example benzene and toluene), halocarbons and oxygenates. Hydrocarbon VOCs are usually grouped into methane and other no methane VOCs. Methane is an important component of VOCs, its environmental impact principally related to its contribution to global warming and to the production of ground level or lower atmospheric ozone.

VOCs are among the most common pollutant emitted by the chemical process industries (CPI). Talking about the health effect from VOC can be divided into two: one is from chlorinated solvent and other is from fuel components. Chlorinated solvents are easily absorbed through the digestive tract and the lungs (if breathed in). Once absorbed they moved throughout the body in the blood. For a short time, they collected in the lever, kidneys, brain or fatty tissues. In the lever, chlorinated solvents changes into other substances and eventually pass out the body. In general most of these substances are eliminated from the body in a matter of days after the exposure has ended. High amount of chlorinated solvents were found to cause dizziness, reduce the ability to concentrate and remember, damage the nervous system and produce an irregular heartbeat. Some chlorinated solvents (trichloroethylene, tetrachloroethylene, methylene chloride, carbon tetrachloride, vinyl chloride and 1, 2-dichloroethane) at high dose have cause cancer in laboratory animals.

Fuel components are easily absorbed through the lungs (if breathed in) and the digestive tract (if swallowed). These chemicals are carried rapidly throughout the body by blood, mostly to the brain and nervous system. Fuel component can also build up temporarily in the fatty tissues, bone narrow, liver and kidneys. Fuel component can cause drowsiness, dizziness, and headache at high doses. Long term exposure to high levels of toluene or xylene may lead to liver and kidney damage.

Reduction of VOC emission in area that exceed the current national ambient air quality standard for ozone of 0.12 ppm is mandated under title I of the clean air amendments requires reduction of the emission of 189 hazardous air pollutants, most of which are included under the definition of VOCs as well. The control of VOCs can take many forms. The least costly is usually modification of the process to eliminate the use of VOC containing materials.

1.1.1 Some Common Compound Group of VOCs [3]

Group 1: Volatile and degradable compounds: These compounds are relative volatile and are readily degradable. Examples include benzene, toluene and xylenes. The emission of these compounds is almost always liquid controlled.

Group 2: Volatile and no degradable compounds: These compounds have the same volatilization characteristics as group 1, but will not significantly degrade in biological treatment system. Example includes most of the chlorinated hydrocarbons, such as chloroform, trichloroethane, tetrachloroethane and methylene chloride.

Group 3: Nonvolatile and degradable compounds: With the exception of tri-methyl benzene, the vast majority of compounds associated with hydrocarbon emission fits category. Typical compounds include acetone and alcohols.

Group 4: Non volatile and non degradable compounds: About 10% of the influent hydrocarbons meet this category. At this time, compounds include in this group and their specific properties are unknown.

Group 5: Total hydrocarbons: Little is known about the behavior of the bulk hydrocarbon fraction.

1.1.2 Occurrence [3]

Volatile Organic Compounds (VOCs) are found in everything from paints and coating to underarm deodorant and cleaning fluids. They are major concern of the Environmental Protection Agency (EPA) and state air quality board all over. VOCs have been found to be major contributing factor to ozone, a common air pollutant that has been proven to be a public health hazard.

While ozone in the upper atmosphere is beneficial, ozone at ground level is quite the possible. The atmospheric ozone layer helps protect us from suns dangerous ultraviolet rays. Ground level ozone, however, is a highly reactive gas that according to EPA studies it affects the normal function of the lung in many healthy humans.

Ozone has been a difficult pollutant to control because it is not emitted into the air, but actually formed in atmosphere through a photochemical process. It is in this process that VOCs play a significant role. VOCs in air react with oxides of nitrogen and sunlight to form ozone. For this reason, environmental agencies have determined that controlling VOCs is an effective method for minimizing ozone levels.

1.1.3 VOCs in Air

- **Outdoor air pollution**

Emission of traffic contributing to a large extent to the occurrence of VOCs in air. Large quantities of volatile and semi volatile organic compounds are emitted into the atmosphere because of both natural and anthropogenic activities. These compounds then will interact through complex mechanism with other chemical compounds in the atmosphere, a process in which UV radiation from sunlight plays an important role. This will result in effect like for example photochemical air pollution, changes in stratospheric ozone and deposition.

- **Indoor air pollution**

Indoor air quality refers to the physical, chemical and biological characteristics of air in the indoor environment within a home, building, or an institution or commercial facility.

Indoor air pollution is a concern in the developed countries, where energy efficiency improvements sometimes make houses airtight, reducing ventilation and raising pollutant levels.

Volatile organic compounds are one of the major causes of indoor air pollution and originate mainly from solvent and chemicals. The main indoor sources are perfumes, hair sprays, furniture polish, glues, air fresher, moth repellents, wood preservatives, and many other products used in the house. The main health effect is the irritation of the eyes, nose and throat. In more severe cases there may be headache, nausea and loss of coordination. In the long term, some of the pollutants are suspected to damage to the liver and other parts of the body.

1.2 VOCs in Water and Industries [3]

The U.S. Environmental Protection Agency (EPA) estimates that VOCs are present in considerable amount in water supplies, especially the ground water and water discharge from industries as a wastewater. They can enter ground water from a variety of sources. Benzene, for example, may enter ground water from gasoline or oil spills on the ground surface or from leaking underground fuel tanks. The examples of commonly detected VOCs are dichloromethane (methylene chloride), an industrial solvent; trichloroethylene, used in septic system cleaners; and tetrachloroethylene used in the dry cleaning industry.

Industries categories such as metal finishing, synthetic organic chemical manufacturing, textiles, petrochemicals, petroleum refining, plastics, semiconductor, glass manufacturing, pharmaceuticals, dyes, synthetic rubber, paint and pigment, electroplating and naturals and synthetic resins use a variety of VOCs.

EPA reported that for 81% of the total wastewater flows and receives 97% of the indirect discharge from industries. Estimates indicate that greater than 98% of the VOCs were discharged by 11 industrial categories for the following seven potential hazardous air pollutants:

1. Carbon tetrachloride
2. Trichloroethylene
3. Perchloroethylene

4. Methylene chloride
5. Ethylene dichloride
6. Chloroform
7. Acrylonitrile

Table 1.1: Some Common VOCs and Their Sources [4]

VOC	FOUND IN	SOURCE
Benzene	Ground water Waste water	Gasoline leaks Process drains and effluents
Toluene/xylene	Ground waters	Gasoline leaks
Trichloroethylene	• •	Solvent leaks into water table
Tetrachloroethylene	• •	• •
Trichloroethane	• •	• •
Dichloroethanes	• •	• •
Trihalomethanes	Source water Waste water	Chlorination/ozonation of Treated waters
Vinyl chloride	Waste water	Plastics manufacture
Carbon tetrachloride	Ground water	Solvent spills
Naphthalene	Ground water	Diesel spills
Acetone	Waste water Ground water	Solvent spills • •
Methyliso-butyl ketone	ground water	Gasoline leaks
Chlorobenzenes	Waste water Source water	Process spills Solvent spills

1.2.1 Some Common VOCs Found in Water

A very prevalent water pollution problem pertains to contamination by organic compounds that offer potentially very important health risks. These organic contaminants are called volatile organic compounds (VOCs) when they have a certain propensity to evaporate away from the water into air. Many of these VOCs are only partially miscible with water but in general they all present certain solubility. Table 1.1 lists some of the more common VOCs found in waters as well as some possible sources. The problem of reducing VOCs in water applies to ground waters, surface waters, and waste waters alike.

1.2.2 Major Sources of Volatile Organic Compounds

According to US EPA (1998), major contributing sources of volatile organic compounds:

- Industrial process - 51%
- Transportation - 5%
- Fuel combustion - 4%
- Miscellaneous - 40%

Table 1.2: Applicability of VOC Abatement System [2]

Abatement Technology	Waste Gas Flowrate (scfm)	VOC/HAP Concentration (ppmv)
Thermal Oxidation	< 10,000 (Thermal Afterburner) 250–100,000 (Recuperative) 2,000–500,000 (Regenerative)	60% of LEL (Thermal Afterburner)* 25% of LEL (Recuperative) 10% of LEL (Regenerative)
Catalytic Oxidation	< 75,000	25% of LEL
Adsorption	No practical limit	100–5,000
Absorption	< 100,000	> 200
Condensation	< 3,000	> 1,000
Flare	No practical limit	No practical limit
Biofiltration	< 100,000	< 1,000
Membrane Separation	< 500	> 5,000

* Special safety considerations apply when the waste stream concentration is 25% of the lower explosive limit (LEL) or higher.

1.3 Selecting Abatement Technology [2, 3]

To select best VOC/HAP control device according to need is main concern for any treatment plant. Fortunately, there are only a few main criteria for selecting an appropriate control device. One of those criteria may be regulation that mandates a specific type of control equipment. However, most regulations impose a level of control (*e.g.*, MACT or BACT) but do not prescribe a specific control device. The main selection criteria for VOC abatement technologies are costs, VOC concentration, vent-gas flow rate and the required control level.

Table 1.2 shows the selection of abatement technology according to waste gas flow rate and VOC concentration.

1.3.1 Steps to Select Best Available Control Technology (BACT)

It is also known BACT evaluation process, the top-down BACT procedure is currently used by local air district to evaluate and determine BACT from all available and potentially applicable emission control option. The purpose of this process is to ensure the selection of the most effective control option(s). it incorporates the following key steps:

Step 1: Identify all available control option: The first step is to identify all available and potentially applicable emission control technologies, i.e. technologies that have a practical potential for application to the emission sources in question. Processes that have lower emissions, product substitution, innovative technologies, pollution prevention by source control and operational changes are to be considered along with standard add-on control devices.

Step 2: Eliminate technically infeasible control options: After all potential control option has been identified; a case-by-case technical fesibility evaluation is performed. For a control option to be considered technically infeasible, it is necessary to demonstrate that specific technical difficulties that preclude the successful execution of the control option will occur.

Step 3: Rank the remaining control option bye control effectiveness: Each technical feasible control option is subsequently ranked according to its emission reduction potential, with the most effective control option at the top and effective control option at the bottom. A ranking hierarchy table that provides the expected emission rate, emission reduction and emission performance is typically prepared.

Step 4: Evaluate energy, environmental and economic impact of most effective control option: After ranking the technical feasible control option a complete economic, environmental and energy impact analysis is performed. As part of the economic impact analysis, sources and site-specific control system design parameters are identified and detailed cost estimate are made, primarily by using equipment manufacturer cost quotation. These cost data are compared with cost effectiveness data from previous control technology determination.

Step 5: Select BACT: In this final step, the results of the impact analysis are evaluated to select BACT. The control option with the highest level of control that does not have significant or adverse economic, environmental, or energy impact is selected as BACT.

1.4 In this Study VOCs Studied are

1. Acetone
2. Dichloromethane or Methylene chloride

1.4.1 Acetone (Environmental Health Criteria; 207)

1.4.1.1 Physical Properties

Acetone is a clear and colorless liquid with a strong "fruity" odor. It is miscible with water and organic solvents such as ether, methanol, ethanol and esters. The physical properties of acetone, such as high evaporation rate, low viscosity and miscibility, make it suitable for use as a solvent. The physical and chemical properties of acetone are shown in appendix, TableA1.

1.4.1.2 Uses and Emissions into the Environment

Acetone is used mainly as a solvent and intermediate in chemical production. Major uses are in the production of methyl methacrylate, methacrylic acid and higher methacrylates, bisphenol A, methyl isobutyl ketone, drug and pharmaceutical applications, and as a solvent for coatings and for cellulose acetate. There are also foods uses as an extraction solvent for fats and oils, and as a precipitation agent in sugar and starch purification.

Atmospheric emissions occur from consumer products including nail polish removers, particle board, carpet backing, some paint removers, and liquid/paste waxes or polishes. Certain detergents/cleansers, adhesives, and automobile carburetor and choke cleaners also contain acetone.

Acetone is released into surface water in wastewater effluents from a wide range of manufacturing processes and industries, such as paper, plastic, pharmaceuticals, specialty cleaning and polishing products, paint and allied products, gum and wood chemicals, cyclic intermediates, industrial organic chemicals, gypsum products, paper board products, and energy-related industries, such as coal-gasification and oil shale processing.

Sources of acetone release into soil include disposal of agricultural and food waste, animal waste, atmospheric wet deposition, household septic tank effluents and chemical waste disposal sites.

1.4.1.3 Effects on Humans

Acetone is relatively less toxic than many other industrial solvents; however, at high concentrations, acetone vapor can cause depression, cardio respiratory failure and death. Acute exposures of humans to atmospheric concentrations as high as approx. 4750 mg/m^3 (approx. 2000ppm) have been reported to produce either no gross toxic effects or minor transient effects, such as eye irritation. More severe transient effects (including vomiting and fainting) were reported for workers exposed to acetone vapor concentrations >25500 mg/m^3 (>12000ppm) for approx. 4 h. Acute exposures to acetone have also been reported to alter performance in neurobehavioral tests in humans at 595 mg/m^3 (250 ppm). Females exposed to atmospheric concentrations of 2370 mg/m^3 (1000 ppm) were reported to suffer menstrual irregularities.

1.4.1.4 Releases

(a) Air

Atmospheric emissions are likely from the many consumer products containing acetone. Such products include nail polish removers; some paint removers, a number of liquid/paste waxes or polishes, some detergents/cleansers, adhesives and carburetor and choke cleaners. Atmospheric emissions from the phenol/acetone production process are approximately 0.44 g per kg of acetone produced.

(b) Water

Acetone is released into surface water as wastewater from certain chemical manufacturing industries. It is also released in water from energy-related industries, such as coal-gasification and oil shale processing. It has been detected in effluents from various industrial production processes including paper, plastic, pharmaceutical, specialty cleaning and polishing products, paint and allied products, gum and wood chemicals, cyclic intermediates, industrial organic chemicals, gypsum products, and paper board products.

Acetone can be released to groundwater as a result of leaching from municipal and industrial landfills. It may also leach from solvent cement used in joining polyethylene and other plastic pipes used in drinking-water distribution and domestic plumbing .One of the sources of acetone in seawater is the sensitized photoreaction of dissolved organic matter.

(c) Soil

Sources of acetone release into soil include disposal of agricultural and food waste, animal wastes, and atmospheric wet deposition. Acetone was detected in 43% of the soil from designated waste disposal sites tested for acetone. Household septic tank effluents are another source of acetone in soil.

1.4.2 Dichloromethane

Dichloromethane is also known as Methylene Chloride and is commonly abbreviated to DCM. Another synonym which is used includes Methylene Dichloride. Chemical properties of dichloromethane are shown in appendix, Table A2.

1.4.2.1 Production and Uses (ECSA 1997)

Dichloromethane is mainly produced together with other chloromethanes e.g. methyl chloride and chloroform. The raw materials are methanol and chlorine and, to a lesser extent, methane and chlorine.

In the methanol hydro chlorination process, hydrogen chloride reacts with methanol to form methyl chloride. In a second step, methyl chloride is chlorinated to heavier chloromethane through thermal, catalytic, or photolytic chlorination. Direct chlorination either thermal or catalytic of methane is also used, but the methanol hydro chlorination process, where no net hydrogen chloride is generated, is usually favored, except when a near-by use of HCl is possible (e.g. vinyl chloride production).

Main Uses: According to the European Chlorinated Solvent Association (ECSA, 1997), the uses of dichloromethane are:

- **For the pharmaceutical industry (30%):** Where dichloromethane is used as solvent for chemical reactions, purification and isolation of intermediates or products.

In this area, dichloromethane has some good advantages:

- **For paint stripping (19%):** Dichloromethane based paint strippers normally consist of 70-90% dichloromethane along with other organic solvents, e.g. ethanol, surfactants, emulsifiers and alkaline and/or acid activators. These products have several crucial advantages over other coating removal methods, as example, non flammable, reasonable price, universally suitable for all types of coatings, fast acting at room temperature, etc.
- **For aerosols (9%):** This application began in the mid-1970 to replace CFC. Dichloromethane is not a propellant itself, but contributes to package homogeneity through its good solvency and reduces the flammability of the propellant hydrocarbon mixture.
- **For adhesives (10%):** This application uses dichloromethane as a replacement of 1,1,1-trichloroethane as a solvent.
- **For other applications (32%):** Including metal degreasing, foam blowing, chemical Processing (polyurethanes, polycarbonates), secondary refrigerant medium, etc.

1.4.2.2 Sources of Emissions: According to department of environment and heritage, Australia the main sources are

(a) Point Source

The primary stationary sources of dichloromethane are the industries that manufacture it or use it in production. Some of the industries that use it in production are plastic product manufactures, manufacturers of synthetics, urethane foam production, the electronics industry (electroplating, circuit board manufacturing, and metal degreasing) and the paint industry. This may result in emission to air:

(b) Natural Sources

Dichloromethane does not occur naturally in the environment.

(c) Mobile Sources

There are no known sources of mobile emission of dichloromethane

(d) Consumer Product Which May Contain DCM:

Aerosol paints, automotive and machinery refinish paints and primers, automotive body polish and cleaners, aerosol air fresheners and deodorants, furniture polish and cleaners, hairsprays, household hard surface cleaners (aerosol and liquid), household insecticides, household tints and dyes, lubricating greases and oils, automotive chemicals, paint and varnish removers and thinners, shoe polish and cleaners, pet flea and tick products, waterproofing compounds.

1.4.2.3 Health Effects (International Chemical Safety Card of Dichloromethane)

(a) Effect of Short Term Exposure

The substance irritates the eyes, the skin and the respiratory tract. Swallowing the liquid may cause aspiration into the lungs with the risk of chemical pneumonitis. The substance may cause effects on the blood, resulting in formation of methaemoglobin. Exposure could cause lowering of consciousness. Exposure could cause formation of carboxyhaemoglobin.

(b) Effect of Long Term Exposure

Repeated or prolonged contact with skin may cause dermatitis. The substance may have effects on the central nervous system and liver, resulting in degenerative brain disease and enlargement of the liver. This substance is possibly carcinogenic to humans.

1.5 AIMS AND OBJECTIVE OF THIS STUDY

Base on the literature search, it was found that the effect of the types of dispersion impeller, effect of impeller speed, effect of submergence of impeller and effect of air supply on the removal of VOCs from the wastewater has not been studied on detail. Therefore, the work under report was aimed at the studies of:

- To study the characteristics of dispersion impellers and factors which affects the efficiency of aeration tank.
- Removal of VOCs from wastewater by aeration.
- To see the effect of impeller speed on the removal of VOCs.
- To see the effect of submergence of impeller on the removal of VOCs.
- To see the effect of well designed dispersion impellers on the removal of VOCs.
- To see the effect of air supply on the removal of VOCs.

LITERATURE REVIEW

2.1 Treatment Technologies

This study deals with various sources of VOC in wastewater, various treatment technologies of gaseous VOCs and aqueous VOCs and comparison of these technologies.

2.2 Sources of VOC Containing Wastewater [3]

VOC containing wastewater stream are generated by direct contact water with volatile organic compounds and by contamination of indirect contact wastewater through equipment leaks in chemical processing.

- **Direct Contact Wastewater**

Water may come into direct contact with volatile organic compounds during a variety of different chemical processing steps, thus generating wastewater stream that must be discharged for treatment or disposal. Direct contact wastewater includes:

  - water used to wash impurities from organic compound product or reactants;
  - Water used to cool or quench organic compound product vapor stream;
  - Condensed stream from jet educator system pulling vacuum.

Direct contact wastewater is also generated when water is used in equipment washes and spill cleanups. This wastewater is normally more variable in flow and concentration and may be in a way that is different in from process wastewater.

- **Indirect Contact Wastewater**

Wastewater stream generated by unintentional contact with organic compounds through equipment leaks are defined as indirect contact wastewater. Indirect contact wastewater may become contaminated as a result of leaks from heat exchangers, condenser and pumps. This indirect contact wastewater may be collected and treated differently from direct contact wastewater. This wastewater is then combines with direct contact wastewater and transported to the wastewater treatment plant. Table 2.1 shows the use and adverse health effect of some common VOCs.

2.3 VOC Control: Current and Future Trends [22]

Researchers found in their study found that following technologies were identified as existing VOC abatement controls:

A) **Control Technology for Gaseous VOC**

- Thermal Oxidation
- Catalytic Oxididation
- Flares
- Condensation
- Absorbers
- Adsorber
- Boiler/process heaters
- Biofilters
- Ultraviolet Oxidizers
- Corona Destruction Reactors
- Plasma technology Devices

B) **Control Technology for Aqueous VOC**

- Membrane Separation
- Air Stripping
- Steam Stripping
- Carbon Adsorption
- Reverse Osmosis
- Pervaporation
- Liquid-Liquid Extraction

2.3.1 Current Practice

Because of their broad applicability to a wide to a wide variety of VOC emission streams, thermal and catalytic oxidizers, flares, condensation, and adsorber are the most effective gaseous VOC controls in use today, oxidizer and flares are destruction devices, where

VOC are combusted, reduced, or otherwise destroyed without being recovered. Adsorber and condensers, on the other hand, are recovery devices, where VOCs are recovered and often reused. The selection of destruction v/s a recovery device is usually based on the economic benefit of recovering VOC in the waste gas stream.

Absorbers and boilers / process heater are used less effective than other abatement technologies and are most commonly used to recover inorganic compounds. Boilers and heaters are not used solely for VOC abatement. However existing boilers or process heaters may be used to destroy VOCs as long as the safety and reliability of the primary process is not adversely affected.

Three of the technologies identified by survey participant; biofiltration, membrane separation and ultraviolet (UV) oxidation, have only recently become commercially available for VOC control. Biofiltration involves the use of soil or compost beds containing microorganisms to convert VOC into carbon dioxide. Water and mineral salts. Membrane separation refers to the use of a semi permeable polymeric membrane. To separate VOCs from a waste gas stream. UV uses oxygen-based oxidants, such as ozone, peroxide and OH and O radicals to convert VOC in to carbon dioxide and water in the presence of light.

Two of the technologies identified, corona destruction and plasma technology are not yet commercially available. In corona destruction, energetic electrons are generated in high intensity reactor, where they collide with VOC to produce non reactive compounds such as carbon dioxide and water.

The exact mechanism by which the excited electrons react with VOCs is not well known at this time. Early results indicate that corona destruction appears to be effective for lean VOC streams. It does not appear to produce intermediate hazardous compounds that would require disposal as hazardous waste. It operates at ambient temperature, does not require auxiliary fuel, and can treat halogenated and non-halogenated compounds.
Plasma technology is not yet well known as a VOC abatement technology depends upon factors such as the environmental, economic and energy impact of installing, operating and maintaining the equipment. While the priority of these selection criteria may vary among companies or even individual process units process units within the same company or plant, the fundamental decision making philosophy remains the same.

2.3.1.1 Some Common VOCs

- Benzene
- Toluene
- Xylene
- Isopropyl alcohol
- Methylene chloride
- Glycol ethers
- Petroleum distillate, naphthas & mineral salts
- Methyl ethyl ketone (MEK)
- Acetone
- Paraffin
- Olefins
- Aromatics

VOCs are carbon compounds that react with nitrogen oxide and other airborne chemicals, in the presence of sunlight (photo chemically), to form ozone, which is a primary component of smog. VOCs include most solvent thinners, degreasers, cleaners, lubricants, and liquid fuels. Above list shows the brief list of common VOCs. The list is not complete. Note that the last three items are basic categories of organic chemically encompassing thousands of individual compounds. [22]

The U.S. environmental protection agency (EPA) will not regulate, under the clean air acts ozone provisions, organic compounds that do not contribute to ground level ozone such compounds include methane, ethane, carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates, ammonium carbonate, 1,1,1-trichloroethane, methylene chloride and various chloro-fluorocarbons and per fluorocarbons.

The first task in evaluating VOC control techniques is to prepare a comprehensive emission inventory. The emission inventory provides the basis for planning, determining the applicability of regulation, permitting and the selection of control options for further consideration.

The inventory should cover the entire source by source. Each piece of equipment within the facility should be characterized base on:

- Pollutant emitted
- The individual chemical species within each vent stream (to identify any non VOC materials that may have detrimental effects on particular type of control equipment).
- Hourly, annual, average, and worst-case emission rates.
- Equipment status.
- Existence and condition of current pollution control equipment.
- Regulatory status.

2.3.1.2 Selection Issue

- Process modification
- Equipment modification

Process modification are usually the preferred alternative for reducing emissions modification include the substitution of materials to reduce VOC input to process, changes in operating condition to minimize the formation or volatilization of VOCs, and the modification of the equipment to reduce opportunities for escape into the environment. Equipment modification can take many forms, but objective is always to prevent the escape of VOCs.

2.3.1.3 Equipment Selection Consideration:

- Recycling potential
- Variability of loading
- Average loading
- Diversity of VOCs present
- Lower explosive limit
- Upper explosive limit
- High discharge temperature
- Non VOCs
- Location
- Maintenance

Table 2.1: Summary of VOC Control Technologies [22]

Technology	**Emission source**	**VOC category**	**Emission stream flow rate, scfm**	**VOC concentration ppmv**
Thermal oxidation	PV, ST, TO, WW	AHC, HHC, A, K	<20,000 without heat recovery ≥20,000 with heat recovery	20-1000 without heat recovery ≥1,000 with heat recovery
Catalytic oxidation	PV, ST, TO, WW	AHC*, A, K	Unlimited	50-10,000
Flaring	F, PV, ST, TO, WW	AHC, A, K	-	-
Condensation	PV, ST, TO	AHC, A, K, HHC*	≤2,000	5000-12,000
Adsorption	PV, ST	AHC, HHC, A	≥300	20-20,000
Absorption	PV, ST, TO	A, K	≥1,000	1,000-20,000
Boiler and process heaters	PV	AHC, A, K	-	-
Biofiltration	PV, WW	AHC, HHC*, A, K	Unlimited	500-2,000
Membrane separation	PV, TO	AHC, HHC, A, K	-	0-1,000
Ultraviolet oxidation	PV	AHC, HHC, A, K	-	-

Emission sources:

F= Fugitives, PV= Process Vent, ST= Storage Tanks, TO= Transfer Operation, WW= Wastewater Operation

VOC Category:

AHC = Aliphatic & Aromatic Hydrocarbon, HHC = Halogenated Hydrocarbons (* = Limited application) A = Alcohols, Glycols, Ethers, Epoxides and Phenols, K= Ketones & Aldehydes

2.4 Controlling Technology Used for Gaseous VOC

2.4.1 Thermal Oxidation

Thermal oxidation systems are known as fume incinerators, are no longer simple flares or afterburners. The modern thermal oxidizer is designed to accomplish from 95% to 99% destruction of virtually all VOCs. These systems can be designed to handle a capacity of

1,000 to 5,000 cfm and VOC concentration ranges from 100 to 2000ppm with normal residence time is 0.5 to 1.0 sec. available with thermal energy recovery option to reduce operating costs, thermal oxidizers are very popular.

Thermal oxidation system combust VOC at temperature from 1,300°F - 1,800°F. actual operating temperature is a function of the type and concentration of materials in the vent streams and the desired DRE. Compounds that are difficult to combust or that are present at low inlet concentration will require greater heat input (greater fuel cost) and retention time in the combustion zone to ensure that the desired DRE is accomplished. High DRE requirements will also require higher temperature and longer retention times. Inlet concentration in excess of 25% of the LEL is generally avoided by oxidizer manufacturers because of potential explosion hazards.

Operating temperatures near 1,800 F can produce elevated levels of nitrogen oxide (from nitrogen in the air) a secondary pollutant that may, in turn, require further treatment, such as selective catalytic reduction. Halogenated compounds in the vent stream are converted to their acidic counterpart. Two types of thermal energy recovery system are in common use today, regenerative and recuperative both use the heat content of the combustion exhaust stream to the incoming gas stream prior to entering the combustion zone.

Regenerative system, use ceramic (or other dense inert materials) 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 thermal energy inputs to the system as fuel and the heat content of the combust VOCs. Where the incoming gas stream contains sufficient thermal energy potential from VOC combustion, regenerative system can operate without external fuel.

The efficiency of the thermal recovery system depends on 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 compatible with regenerative oxidation systems. The absorbed heat is lost to the environment during periods of low activity (that is, when air flow or VOC content is reduced). Operation with insufficient VOC content to supply thermal input requirements necessitates the use of external fuel sources.

Recuperative thermal oxidation system oxidation system, 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 regenerative system comes from the relatively short system. The advantage over 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 to start up. Recuperative system are best suited to cyclic operations where the versatility of an oxidation system is required along with the ability to respond to cyclic operation where the versatility of an oxidation system is required along with the ability to respond to cyclic operating conditions.

2.4.2 Catalytic Oxidation

Wilson and Hassan, studied that Catalytic Oxidation system directly combust VOCs in a manner similar to thermal oxidizers. The major difference is that the catalytic system operates at a lower temperature typically about 700F-900F. this made possible by the use of catalyst that reduces the combustion energy requirement. The incoming gas stream is heated, most often in a recuperative heat exchanger followed by additional input from burners if needed and passed through a honeycomb or monolithic support structure coated with catalyst.

Catalytic system can be designed to handle a capacity of 1,000 to 100,000 cfm and VOC concentration ranges from 100 to 2000 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 VOC content are variable. Destruction efficiencies in excess of 90% are common with a maximum DRE 95%. High concentration vent streams can also be treated with catalytic technology. However as with thermal oxidation, vendors are generally unwilling to touch concentration in excess of 25% of the LEL. Lower operating temperature combined with a recuperative heat exchanger; reduces the start up fuel requirement. Large catalytic system has been installed, but is not as popular as direct thermal oxidation systems at this time due to high costs of catalyst replacement.

Catalytic system like thermal oxidizers can produce secondary combustion wastes. Halogen and sulfur compounds are converted to acidic species by the catalytic combustion process; using acid gas scrubbers treats these. Also the spent catalyst materials can require disposal as a hazardous waste if they are not recyclable. However the lower operating temperatures preclude the formation of significant quantities of nitrogen oxides. Catalyst material can be sensitive to poisoning by non VOC material such as sulfur, chlorides and silicon. Many catalyst manufacturers have overcome sensitivity to one ore more of these substances, but every catalyst has susceptibility that must be considered in the process selection stage. For example some catalysts are sensitive to deactivation by high molecular weight hydrocarbon or polymerizing materials. Also, the catalyst support may become deformed in high temperature, high concentration situations.

2.4.3 Absorption [22, 34]

Researchers found in their study found that absorption can be used to remove VOC 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 on an absorber tower designed to provide the liquid-vapor contact area necessary to facilitate mass transfer. This contact can be provided by using tower packing or trays, as well as liquid atomization. Absorber system can be designed to handle a capacity of 2,000 to 100,000 cfm and VOC concentration ranges from 500 to 5,000 ppm. Absorber can achieve VOC removal efficiencies of 95% to 98%. The design of absorption system for control is design of absorber for process application using vapor-liquid equilibrium (VLE) data, liquid and vapor flux rate equipment liquid and vapor-handling information and material balance.

Packed bed scrubbing uses packing material to improve liquid – vapor contact. Packing can be randomly dumped or stacked in the tower. Packing varies widely it must be considered in the process selection stage. For example some catalysts are sensitive to deactivation by high molecular weight hydrocarbon or polymerizing materials. Also the catalyst support may become deformed in high temperature, high concentration situations.

2.4.4 Condensation [6, 7]

The driving force for condensation is over-saturation, which is achieved by chilling or pressurization (or both) of the waste gas stream. Condensation is the most efficient for VOCs with boiling points above 100F at relatively high concentration above 500ppm, low boiling VOCs can require extensive cooling or pressurization, which sharply increases operating cost.

Exceeding the 25% LEL threshold is more common with condensation system. In fact, some systems begin operation above the UFL. This is dangerous, however, because the concentration will likely fall through the explosive range during the condensation process. Inert gas blanketing of vessels or unmanned process enclosure can avoid the explosion hazard associated with high VOC concentration, but cause additional operating cost. Polymerizing materials should also be avoided in condensation system due to potential for fouling heat transfer surfaces. Best suited monosolvent 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 solvent during equipment cleanup, burned as an alternative boiler fuel, shipped off site for disposal, or resold for reuse by others.

2.4.5 Wet Pulse Corona Discharge [5]

A novel VOC removal system consisting of a combined pulse corona discharge and scrubber are used to remove VOCs from a waste gas stream. Thus the term "wet" corona discharge.

Volatile Organic Compounds (VOCs) in a waste gas stream are partially oxidized (i.e., not destroyed) by corona discharge to increase their solubility in water and then scrubbed into an aqueous waste stream. The aqueous waste stream is then treated in the facility's wastewater treatment plant to destroy the partially oxidized VOCs. This process is economically applicable to both relatively high and dilute VOC concentrations. It uses only a small fraction of the energy required to destroy the VOCs and has a minimal additional loading on the wastewater treatment plants of most industrial facilities. Water from the facility's wastewater treatment plant is satisfactory for use in the scrubber. A schematic representation of the technology follows.

2.5 VOC Separation Systems for Aqueous Wastes

Several technologies exist that can be used for recovering VOC's from aqueous wastes. The most widely used technologies are air stripping, steam stripping and activated carbon adsorption; however, several emerging membrane-based technologies, such as reverse osmosis and pervaporation, have also shown potential for use in recovering VOC's from wastewater. The following is a summary of these technologies, a description of the technology, and some advantages and disadvantages of these technologies.

2.5.1 Air Stripping [1, 8, 9, 10, 18, 28, 29, 35]

Researchers in their experiments and studies found that many VOCs have high solubility in water. Thus chemical process industries (CPI) plants wastewater streams frequently may contain VOCs in concentration up to several thousand ppm. Air stripping to remove VOCs from groundwater remediation that can be effective applied to CPI plants.

Air stripping is a method of treating contaminated water for the removal of volatile organic contaminants. The air stripping process involves the aeration of contaminated water with sufficient volume of air that will allow the removal of volatile organic contaminants by volatilization from water into the passing air. Air stripping involves the mass transfer of volatile organic contaminant from water to air. A key advantage of air stripping is its low energy usage. In addition, the system can be easily upgraded to strip greater amount of VOCs with relatively small increases in capital cost.

Preventive maintenance requirements are also low, provided careful consideration has been given to the fouling characteristics of the system.

Aeration tanks strip volatile compounds by bubbling air into tank through which contaminated water flows. A forced air blower and a distribution manifold are designed to ensure air-water contact without the need for any packing materials. The baffles and multiple units ensure adequate residence time for stripping to occur. Air stripper can be operated continuously or in a batch mode where the strippers intermittently fed from a collection tank. The batch mode ensures consistent air stripper performance and greater energy efficiency than continuous operated units, because mixing in the storage tanks eliminates any inconsistencies in feed water composition.

Air stripping is of two types: **Diffused aeration and Surface aeration [35]**

- Mass transfer in a diffused aeration system is a dynamic process in which a local equilibrium concentrations (the driving force) changes as bubbles rise through the liquid column. The relationship between VOCs in the gas and liquid phase in a rising bubble was described by Matter-Muller [37], their development included the following assumption: the overall mass transfer coefficient K_La is constant during an experiment; equilibrium holds at the interface and is described by Henry's law; gas flow rate and temperature are constant; the rising bubbles are distributed uniformly across the column; pressure and volume changes within the air bubble are negligible; the liquid phase is well mixed (homogenous); the liquid phase concentration is time dependent but remains constant during the residence time of a single bubble; and gas phase concentration is dependent on bubble-residence time and vertical position.
- Researchers conducted experiment and found that the emission rate of VOCs during surface aeration can be estimated from the oxygen mass transfer coefficient $K_La_{O_2}$ and a modified coefficient Ψ_m. Which incorporate the fraction of liquid phase mass transfer resistance to total resistance. Indirect emission of VOC from the aeration basin using oxygen as a surrogate is a valuable and cost effective approach for engineering applications. Based upon the proportionality of mass transfer coefficient, previous researchers [37] have defined the ratio of mass transfer coefficient for VOC to oxygen as Ψ. this ratio along with the oxygen transfer coefficient $K_La_{O_2}$ is now widely used to

estimate VOC emission from quiescent and aerated water surfaces. The approach is popular because of its case of use the availability of oxygen transfer information.

Description

- Wastewater flows into the top of a packed column and is distributed throughout the packing.
- Air flows into the bottom of the column and the VOC is transferred from the wastewater to the air via direct contact.
- The VOC-laden air exits the top of the column and the VOC is subsequently condensed from this gas stream prior to emitting the stream to the environment.
- "VOC-free" wastewater exits the bottom of the column.

Advantages

- More effective for VOC's with higher volatility (lower boiling point).
- Preventive maintenance costs are typically low.
- System can usually be easily upgraded to strip greater amounts of VOC's with relatively small increases in capital costs.

2.5.2 Steam Stripping [9, 11]

- Wastewater flows into the top of a packed or tray column and is distributed throughout the column.
- Steam flows into the bottom of the column and the VOC is transferred from the wastewater to the steam via direct contact.
- The VOC-laden steam exits the top of the column and the VOC is subsequently condensed with the steam. If the VOC is immiscible in water, the condensate will form an aqueous layer and a solvent layer that can be separated using a decanter. If the VOC is miscible in water, additional distillation can be used to further separate the VOC and water.
- "VOC-free" wastewater exits the bottom of the column.

Advantages

- A widely used technology with well known operating characteristics.
- Operating temperatures are higher than air stripping, which presents a generally more favorable equilibrium relationship.
- More effective for VOC's with lower volatility (higher boiling point).
- Can remove a wider range of VOC's.
- Allows a wider range of removal levels.

Disadvantages

- Higher operating temperatures than air stripping may accelerate equipment and/or compound degradation.
- Some steam will condense and add to the hydraulic load of the system.

2.5.3 Reverse Osmosis [12]

Reverse Osmosis is a membrane-based process that operates on the principle of selective permeation of a VOC through the membrane. Unlike Pervaporation, no phase change occurs across the membrane and the water permeates from the feed side of the membrane to the permeate side of the membrane. Wastewater streams fed to reverse osmosis membranes enter the membrane housing at a high pressure and the water (and some VOC) preferentially permeates to the low pressure side of the membrane. "VOC-free" wastewater (referred to as the permeate) exits the low pressure side of the membrane. The "reject" stream exits the high pressure side of the module and contains a higher concentration of VOC than the initial wastewater stream. This stream can be disposed of or distilled for further VOC recovery.

Generally compact in size; therefore, a reverse osmosis system can be easily added to existing plant operations. Flexibility of adding modules or bypassing modules can accommodate surges in wastewater loads and/or concentrations.

2.5.4 Pervaporation [13]

- Pervaporation (a technology that combines permeation and evaporation) is a membrane-based process that operates on the principle of selective permeation of a VOC through the membrane.
- For VOC removal from wastewater, a hydrophobic (organophilic) membrane (typically a rubbery polymer) is required.
- Feed streams to Pervaporation membranes are typically preheated. The warm wastewater feed enters the membrane housing at a high pressure and the VOC (and some water) preferentially permeates to the low pressure side of the membrane. As the VOC (referred to as the permeate) goes from high pressure to low pressure it flashes to the vapor state and a condensation process (typically using chilled water) is used to condense the VOC.
- "VOC-free" wastewater (referred to as the retentive) exits the high pressure side of the membrane.

2.5.5 Liquid-Liquid Extraction [14, 15]

- Liquid-liquid extraction involves the separation of VOC's by contact with another liquid (solvent) in which the VOC's are more soluble.
- Extraction solvent selection is based on:

  - selectivity (ability of the solvent to extract much of the VOC but very little of the water)
  - ease of regeneration (ability to separate the VOC from the extraction solvent, typically using distillation)
  - low miscibility with the feed solution (the extraction solvent should not transfer to the exiting wastewater stream)
  - significant density difference between the extraction solvent and the wastewater feed (aqueous and organic phases are generally separated by settling)
  - moderate interfacial tension (impacts mixing capabilities)
  - low viscosity (<10 cps minimizes resistance to mass transfer)

  - low flammability and toxicity
  - low cost and ready availability
- Separation of the solvent-VOC waste can be handled via air stripping, steam stripping, distillation, or additional liquid-liquid extraction.
- Separation of the exiting wastewater stream can occur via air stripping, steam stripping, activated carbon adsorption or biological treatment.
- Process efficiency can be increased by increasing the flow rate of solvent to wastewater or by increasing the number of extraction stages..

2.5.6 Activated Carbon Adsorption [8, 24, 37]

Researchers in their study have found that 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 carbon. Variable flow rates and VOC concentration are not disruptive to carbon absorber. These systems can be designed to handle a capacity of 100 to 60,000 cfm and VOC concentration ranging from 20 to 5,000 ppm. They can easily handle VOC concentration in excess of the 25%LEL threshold mentioned earlier. The system is sized according to the maximum flow and concentration 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. Typically, a carbon adsorption system consists of two parallel adsorption trains. While one carbon bed is on-line, other is being regenerated. The carbon supplier may retrieve the saturation carbon and either replaces it with fresh carbon or regenerates it off-site and returns it to the facility. Replacement and off-site regeneration are expensive and result in wastes being generated it at another facility with the generator's name attached. Alternatively, regeneration can be done on-site with steam, hot air, or hot nitrogen. Which method is chosen depends upon process condition and available local utilities.

- Wastewater flows into the top or bottom of an adsorption column, filled with porous activated carbon, and is distributed throughout the carbon bed.

- Carbon adsorption beds can be fixed or moving, with respect to the carbon. For moving beds, the flow of activated carbon is countercurrent to the flow of the wastewater; however, fixed beds are more common in industry.
- The VOC is adsorbed onto the surface of the activated carbon and onto the surface of the pores. At some point the carbon becomes saturated with VOC and loses its capacity for additional adsorption. When this occurs the carbon must be regenerated for re-use or replaced with virgin carbon.
- Multiple fixed beds are generally employed so that as one or more beds are adsorbing at least one bed can be regenerating. Regenerating a bed of activated carbon typically involves the direct injection of steam, hot nitrogen or hot air to the bed which causes the VOC to release from the carbon and exit the bed via a vapor or steam condensate stream. The regenerated stream, containing a higher concentration of the VOC than the original wastewater stream, is subsequently condensed. If the VOC is immiscible in water, the condensate will form an aqueous layer and a solvent layer that can be separated using a decanter. If the VOC is miscible in water, additional distillation can be used to further separate the VOC and water.
- "VOC-free" wastewater exits the absorber after the contact with the activated carbon.

Table 2.2: Comparison Between Some VOC Control Strategies [22]

Control technologies	**Applicable concentration range, ppm**	**Capacities range cfm**	**Removal efficiencies %**	**Annual operating cost**	**Secondary waste**	**Advantages**
Thermal oxidation	11-2000	1,000-500,000	95-99	Recup:$15-19/cfm	Combustion products	Upto 95% recovery of energy is possible
Catalytic Oxidation	100-2,000	1,000-100,000	90-95	Fixed:$10-75/cfm Fluid:$15-90/cfm	Combustion product	Upto70% recovery of energy is possible
Condensation	>5,000	100-20,000	50-90	$20-120/cfm	Condensate	Product recovery can offset annual operating cost
Carbon adsorption	20-5,000	100-60,000	90-98	$10-35/cfm	Spent carbon, collected organic	Product recovery can offset annual operating cost
Adsorption	500-5,000	2,000-100,000	95-98	$25-120/cfm	Wastewater captured particulate	Product recovery can offset annual operating cost

AERATION FUNDAMENTAL AND DESIGN FACTORS FOR AERATION TANK

3.1 Basic Concept of Aeration

Basic concept of aeration is the mass transfer of the material at the interface. Common operation and processes in wastewater treatment involving mass transfer. The most important mass transfer in wastewater treatment involves:

- The transfer of material across gas-liquid interface as in aeration and in the removal unwanted gaseous constituents found in wastewater by air stripping.
- The removal of unwanted constituents from wastewater by adsorption on to solid surface such as activated carbon and ion exchange.

3.2 Oxygen Transfer

Oxygen transfer is the process by which oxygen is transferred from the gaseous to the liquid phase, is a vital part of oxygen that are needed, additional interface must be formed. Either air or oxygen can be introduced in to the liquid, or the liquid in the form of droplets can be exposed to the atmosphere.

Oxygen can be supplied by means of air or pure oxygen bubbles introduced to the water to create additional gas-water interfaces. In wastewater treatment plants. Submerged bubble aeration is most frequently accomplished by dispersing air bubble in the liquid. Turbine mixer may be used to disperse air bubble introduced below the center of the turbine; they are designed both to mix the liquid in the basin and to expose it to the atmosphere in the form of small liquid droplets.

3.3 Selection of Aeration System

While evaluating aeration system a total performance and cost of operation analysis is critical. The components of this analysis should include an evaluation of initial capital cost of system installation, all operating and energy costs, and projected maintenance costs. Also included should be an analysis of how well the systems perform the four basic functions required for all the aerators.

1. Provide sufficient oxygen transfer.
2. Provide sufficient mixing to ensure homogeneity of mixed liquor.
3. Respond to varying process conditions to maximize energy efficiency.
4. Provide reliable service, without costly maintenance and downtime, and without reduction in oxygen transfer capability.

3.4 Removal of VOC by Aeration

The principal mechanism governing the release of VOCs in wastewater collection and treatment facilities are:

a) Volatilization
b) Gas stripping

a) Volatilization

The release of VOCs from the wastewater surface to the atmosphere is termed volatilization. Volatile organic compounds are released because they partition between the gas and water phase until equilibrium concentration are reached. The mass transfer (movement) of a constituent between these two phases is a function of the constituent concentration in each phase relative to the equilibrium concentration. Thus, the transfer of a constituent between phases is greatest when the concentration in one of the phases is far from equilibrium. Because the concentration of VOCs in the atmosphere is extremely low, the mass transfer of VOCs usually occurs from wastewater to the atmosphere.

b) Gas Stripping

Gas stripping of VOCs occurs when a gas (usually air) is temporarily entrained in wastewater or is introduced to achieve a treatment objective. When gas is introduced into a wastewater, VOCs are transferred from the wastewater to gas. The forces governing the transfer between phases are the same as described above. For this reason, gas (air) stripping is most effective when contaminated wastewater is exposed to contaminated free air. In wastewater treatment, air stripping occurs most commonly in biological treatment processes and aerated transfer channels.

3.5 Mass Transfer Coefficient for Gas-Liquid mass Transfer [28, 43, 44]

3.5.1 Principle of Mass Transfer: Basic principle of mass transfer is given by Fick's First law of diffusion.

Fick's First Law of Diffusion:

Under no flow conditions, the mass transfer of material is brought about by ``molecular diffusion``. The transfer of mass by molecular diffusion in stationary system can be represented as a function of the concentration gradient as follows:

$$r = -D_m \frac{\partial C}{\partial x} \tag{3.1}$$

The negative sign denotes fact that diffusion takes place in the direction of decreasing concentration, [47].

3.5.2 Henry's Law for Dissolved Gases.

The equilibrium or saturation concentration of gas dissolved in a liquid is a function of type of gas and the partial pressure of the gas in contact with the liquid. Henry's law is given by

$$P_g = (H/P_T)x_g \tag{3.2}$$

3.5.3 Gas-Liquid Mass Transfer: A number of mass transfer theories have been proposed to explain the mechanism of gas transfer across gas liquid interfaces. The simplest and most commonly used is the two-film theory proposed by Lewis and Whitman [43], and the penetration model proposed by Higbin [44]. The two-film theory is more than 95% of the situations the result obtained are essentially the same as those obtained with the more complex theories.

3.5.3.1 Two-Film Theory: The two film theory is based on a physical model in which two film exist at the gas-liquid interface, as shown in fig. 3.1. Two conditions are shown in the figure:

(a) ``absorption``, in which a gas is transferred from the gas phase to the liquid phase.

(b) ''desorption''. in which gas is transferred out of the liquid phase in to the gas phase.

The two films. one liquid and one gas, provide the resistance to passage of gas molecules between the bulk-liquid and bulk-gaseous phases.

Assumptions made in the two-film theory: Mainly two assumptions were made.

(a) Concentration and the partial pressure in both the bulk-liquid and bulk-gas phase are uniform (i.e., mixed completely).

(b) All the resistance to mass transfer is caused by the liquid film.

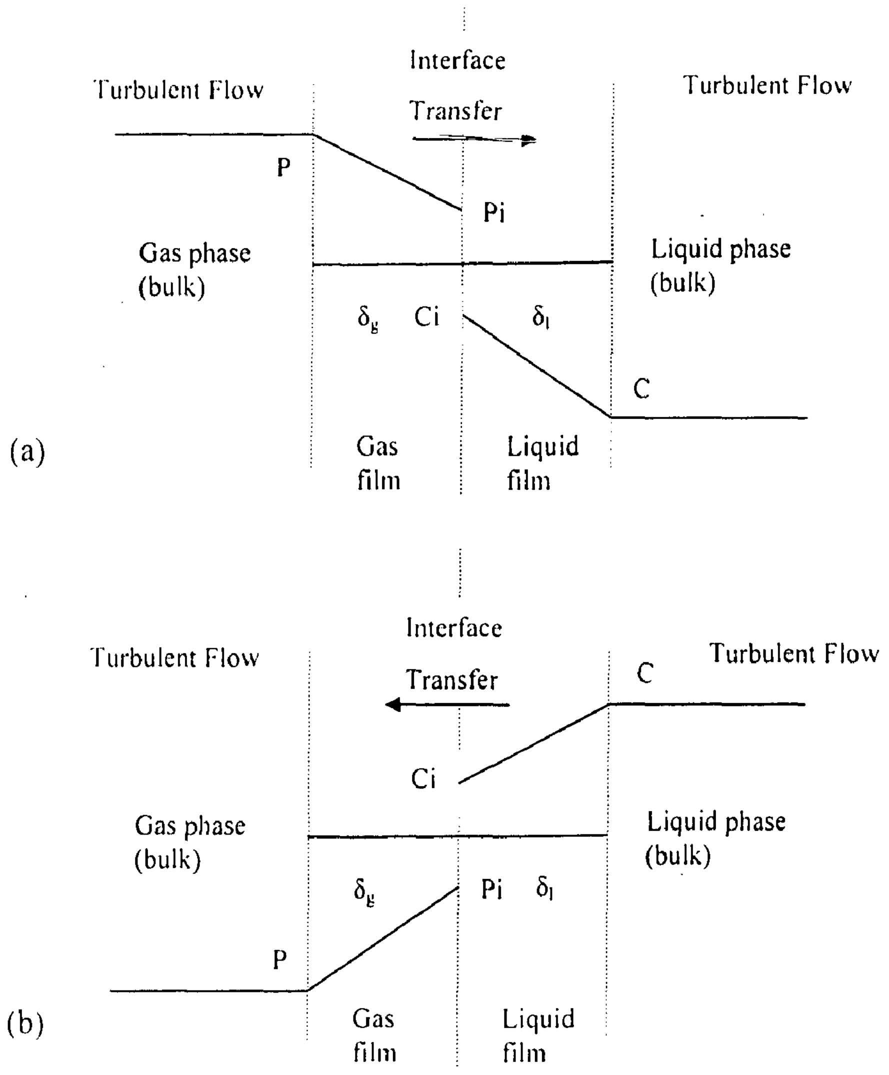


Fig. 3.1 Definition Sketch for the two film theory of gas transfer: (a) absorption (b) desorption.

Under the steady state conditions, the rate of mass transfer of gas through gas film must be equal to rate transfer through liquid. Using Fick's first law (Eq. 3.1)

$$r = k_G(P_G - P_i) = k_L(C_i - C_L) \tag{3.3}$$

According to assumption (b), the overall liquid mass transfer coefficient:

$$r = K_L(C_s - C_L) = k_G(P_G - P_i) = k_L(C_i - C_L) \tag{3.4}$$

Absorption of Gases: [28]

$$\frac{dC}{dt} = K_L a(C_s - C_t) \tag{3.5}$$

$$\frac{Cs - Ct}{Cs - Co} = e^{-(KLa)t} \tag{3.6}$$

Where $\frac{dC}{dt}$ = change in concentration with time,

Cs = gas phase concentration in the bulk gas phase

C_0 and C_t = Concentration at time t = 0 and t = t respectively

K_{La} = overall mass transfer coefficient of the constituent

Efficiency of the system is given by

$$\eta = \left[(1 - \frac{C_o}{C_i} \right] * 100\% \tag{3.7}$$

3.5.4 Relationship of Mass-Transfer Coefficient to Diffusivity and Ψ_M, [25, 43, 44, 45]:

The development of the Ψ concept is based upon the two-resistance mass transfer model and the assumption that gas-phase resistance is negligible.

The major resistance to mass transfer at the gas-liquid interface is the diffusion resistance in each phase. The best known models are based on Fick's law, and predict that mass-transfer coefficient k is proportional to some power of the molecular diffusivity, D

$$k \alpha D^n \tag{3.8}$$

n = 1.0 for the two-film theory [43], and 0.5 for the penetration theory [44], Dobbins [45] proposed a combined film surface renewal theory, with n varying from 0.5 to 1 .0 depending on the turbulence in the system. Under sufficiently turbulent conditions, n approaches 0.5 (surface renewal or penetration theory); under laminar, or less turbulent, conditions n approaches 1 .0 (film theory).

Ψ_m is the product of Ψ-value and the fraction of liquid-phase to total resistance. Equation (1) which was derived from two-resistance model can be used to estimate emission rates of SVOC. [43]

$$\Psi_m = \frac{K_{LaVOC}}{K_{LaO2}} = (D_{LVOC}/D_{LaO2})^n \frac{R_L}{R_T} = \Psi \frac{R_L}{R_T} \qquad (3.9)$$

$\Psi = k_{LaVOC}/k_{LaO2} = (D_{LVOC}/D_{LO2})^n$ [dimensionless];

n = between 0.5 and 1, according to the mixing condition of water.

3.6 Factors Affecting Mass Transfer Rate [38]

The oxygen mass transfer in a stirred tank depends on several factors, such as the type and geometry of the vessel, sparger and stirrer design, physical properties of the liquid (density, viscosity, surface tension, oxygen solubility and diffusivity), the presence of antifoam agents and the dissipated energy. The latter is also affected by the air flow rate (*G*), stirrer speed (*N*) etc.

Air flow rate: Different effects of air flow rate on mass transfer rate have been reported .Some studies show the volumetric mass transfer coefficient (KLa) increases almost linearly with air flow rates. Because most diffusers produce larger bubbles at a higher air flow rate, the ratio of bubble surface area to volume decreases per unit air flow rate.

Liquid depth: Because of different surface renewal properties that occur when bubbles form, rise, and burst at the surface, the value of the mass transfer coefficient is affected by liquid depth. Cumulate there to form a "cap." A surface tension gradient, which opposes the tangential shear stress, reduces surface flow over the rear portion of the bubble surface. This cap grows with increasing surfactant concentration until it reaches the maximum size that the surface tension gradient can support

3.7 Design of Perfect Stirred Tank and Impeller Selection [40]

To design an effective stirred tank, an effective impeller should be chosen for the process duty. Sizing of the impeller is done in conjunctions with mixer speed to achieve the desired process result. The approximate size and wall baffle must be selected to create an effective flow pattern. The mixer power is than estimated from available data on impeller characteristics, and the drive size is determined.

3.7.1 Geometry

A conventional stirred tank consists of a vessel equipped with a rotating mixer. The vessel is generally a vertical cylindrical tank. Non standard vessels such as those with square or rectangular cross section, or horizontal cylinder vessels are sometimes are used. The rotating mixer has several components: an impeller, shaft, shaft seal and a variable speed motor drive. Wall baffle are generally installed for transitional and turbulent mixing to prevent solid body rotation (sometimes called fluid swirl) and cause axial between the top and bottom of the tank.

In tall tanks, the mixer may be installed from the bottom to reduce the shaft length and provide mechanical stability. The mixer can be side entering for large product storage. In horizontal cylinder tanks, the mixer can be installed on the side from top.

3.7.2 Impeller Types

The typical impeller used in transitional and turbulent mixing are listed in table. These have been divided in to different general classes, based on flow pattern, applications and special geometries. The classification also defines application types for which these impellers are used. For example, axial flow impellers are efficient for liquid blending and solid suspension, while radial flow impellers are best used for gas dispersion. Up/down impellers can be disks and plates, are considered low-shear impellers, and commonly used in extraction columns. The pitched blade turbine, although classified as an axial flow impeller, is sometimes referred to as a mixed flow impeller due to the flow generated in doth radial and axial direction

Table 3.1 Impeller Classes and Specific Types [41]

Impeller classes	**Specific types**
Axial flow	Propeller, pitched blade turbine, hydrofoils
Radial flow	Flat-blade impeller, disk turbine(Rushton), hollow blade turbine, CD6, BT6
High shear	Cowls, disk, bar, pointed blade impeller
Up/down	Disks, plate circles

3.7.3 Impeller Selection

There are hundreds of impeller types in commercial use. Determination of most effective impeller should be based on the understanding of the process requirements and knowledge of physical properties.

There are four types of turbine impellers, which are characterized by the flow patterns and the level of shear they create: axial flow, radial flow, radial flow, hydrofoil, and high shear impellers. They have the widest use in low and medium viscosity liquid applications, solid suspension, liquid-liquid emulsification, and gas dispersion. Turbine impellers can have blades varying from 2 to 12 in number. Two blades are normally unstable mechanically, while it is difficult to install more than six blades on a hub. Axial flow impellers generally have three or four blades, and radial flow are designed with six blades.

Axial Flow Impellers: Axial flow impellers are used for blending, solid suspension or draw down, gas inducement and heat transfer. The oldest axial flow impeller design is the marine propeller, which is after used for side entering mixer in large tank and as a top entering mixer in small tanks.

Radial Flow Impellers: Like axial flow turbine impellers, radial flow impellers are commonly used for low to medium viscosity fluids. Although they can be used for any type of single and multiple phase nixing duty, they are most effective for gas-liquid and liquid-liquid dispersion. Compare to axial flow impellers they provide higher shear and turbulence levels with lower pumping. Radial flow impellers discharge fluid radially outward to the vessel wall. With suitable baffles these flows are converted to strong top-to-bottom flow both above and below the impeller.

Radial flow impellers may either have a disk (Rushton turbine) or be open or may have either flat or curved blades. Impellers without the disk do not normally pump do not normally pump in true radial direction since there is pressure difference between each side of the impeller. The disk is a baffle on the impeller, which prevents gas from rising along the mixer shaft.

The Rushton turbine is constructed with six vertical blades on the disk. Standard relative dimension consist of blade length of D/4, blade width of D/5, and the disk diameters of 0.66 and 0.75D.

The recently developed hollow blade impellers e.g. CD6 and BT6, provides better gas dispersion and higher gas holding capacity than the Rushton turbine. The impeller blades are semicircular or parabolic in cross section. This general shape allows for much higher power level to be obtained in the process than that obtained by the Rushton turbine during gas dispersion.

Hydrofoil Impellers: Hydrofoil impellers were developed for application where axial flow is important and low shear is desired.

High Shear Impellers: High shear impellers are operated at high speed and are used for the addition of a second phase in grinding dispersing pigments, and making emulsion.

Table 3.2: impeller selection guide [Chemineer Inc. England]

Impeller selection guide					
Application	Miscible Fluids Blending	Solids Suspension	Three Phase Process	Immiscible Fluids Blending	High Viscosity
Impeller types	High Efficiency (HE-3, SC-3)	High Efficiency (HE-3, SC-3, Maxflo W)	Gas Dispersion (BT-6, Maxflo W)	ChemShear, Dispersion, P-4	Helix, Anchor, Screw

3.7.4 In this study gas dispersion impellers e.g. D-6 or Rushton, CD-6, and BT-6 impellers were used. [38]

3.7.4.1 D-6 or Rushton Impeller (Gas Dispersion Impellers: 1950's)

Rushton turbine was the standard impeller for gas dispersion applications. It features six flat blades mounted on a disk. John M. Smith and coworkers introduced the concept of using concave blades. They explained the improved performance of the concave blades compared to flat blades in terms of reduced cavity formation behind the blades. Impellers with a semi-circular blade shape are now common in the industry.

Relatively recent, new blade designs with a deeper concavity have been proposed by other researchers. Under most conditions with these deeper blades the gas is being dispersed from the inside of the blade, instead of from large cavities behind the blade. All of the disk-style gas dispersion impellers studied in the literature so far has blades that are symmetric with respect to the plane of the disk. This is not necessarily optimal, as the gas usually enters from the bottom, causing a distinctly asymmetric flow pattern.

- Radial flow impeller
- Six flat blades on a disk
- Suitable for gas dispersion and liquid-liquid dispersion
- Turbulent power number range: 4.5-6.2
- Trailing vortices in single-phase flow

3.7.4.2 CD-6 (Gas Dispersion Impellers: 1980's)

- Radial flow impeller with six concave blades on a disk.
- 2 times more efficient than D-6 impeller
- Design based on prior research by Smith and co-workers.
- Turbulent power number range: 2.8-3.2.

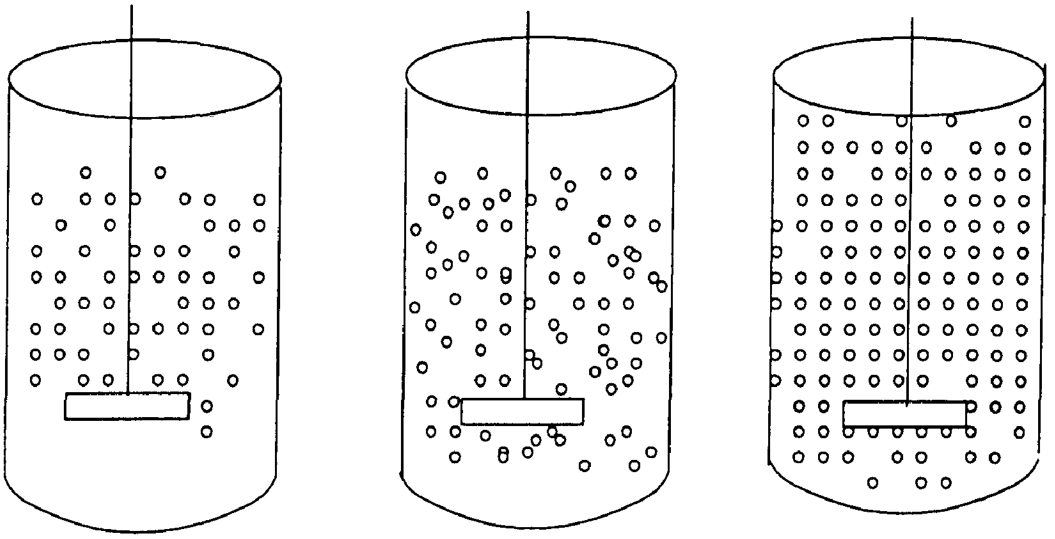
3.7.4.3 BT-6 (Gas Dispersion Impellers: 1998)

- Asymmetric blade technology: Gas flow is asymmetric so why would blade shape be symmetric.
- Blade curvature is different on top and bottom and the blade is longer on top.

- About 6 times more efficient than D-6 impeller.
- Rising gas is captured by longer upper portion of blade and dispersed from inside the deep blades.
- Low turbulent power number Po = 2.3.
- Power number is constant for impeller
- Reynolds numbers greater than 1,000.
- Flat power draw curve under gassed conditions.
- Superior gas dispersion capabilities.

Study shows the flow pattern in the vessel developed by the gas dispersion impeller; BT-6 develops more uniform dispersion of gas in the entire vessel. Fig. 3.1 shows the dispersion of gases inside the aeration tank by the impeller used and it shows that the BT-6 impeller gives the best and uniform gas dispersion throughout the whole tank.

Similarly Fig. 3.2 shows the plot between superficial gas velocity and mass transfer coefficient it shows that mass transfer coefficient changes or increases more frequently in the case of CD-6 and BT-6 impeller compare to D-6 impeller and BT-6 impeller having larger value.



D-6 CD-6 BT-6

Fig. 3.2 Flow Pattern in vessel

(a) Mass Transfer Coefficient [38]: Superficial gas velocity is the ratio of gas supplied (volume per unit time) to the area of pipe by which gas is supplied. Graph shows that mass transfer rate increases rapidly when gas superficial velocity increases 0 to .02 m/s. and it shows that RT-6 impeller has large mass transfer coefficient compare to CD-6 and D-6 for the same superficial gas velocity.

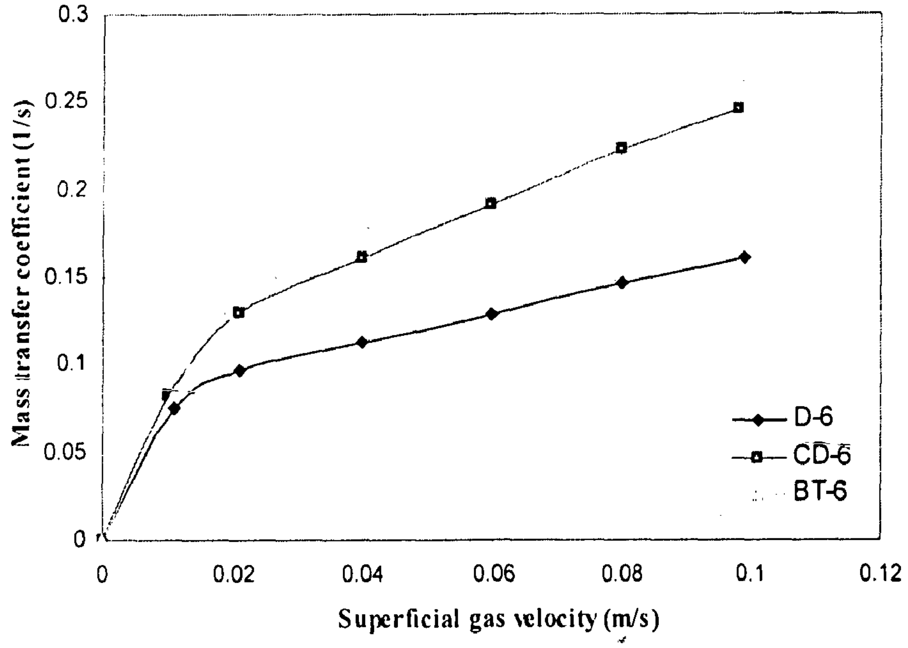


Fig. 3.3 Plot of superficial gas velocity Vs mass transfer coefficient

(b) Gas Holdup [46]

Gas holdup, є is a measure of the gas void fraction in a dispersion, and is defined as (Vg – V)/Vg, where Vg and V are the gassed and ungassed dispersion volumes, respectively. The amount of gas held within the fluid plays an important role in gas-liquid mass transfer operations. Invariably, the more gas held within the tank the higher the mass transfer rate. Comparing the gas holdup, є, against the gas flow number, F*l*, at the same impeller speed of 4 s^{-1} (Figure 3.3), a minor difference in holdup values for the three impellers is found, prior to flooding. The CD6 impeller obtains the highest gas holdup value, e = 1.8%, before flooding. CD-6 generates 2.5 times the gas holdup of the Rushton, while the value for the BT-6 is above 2.

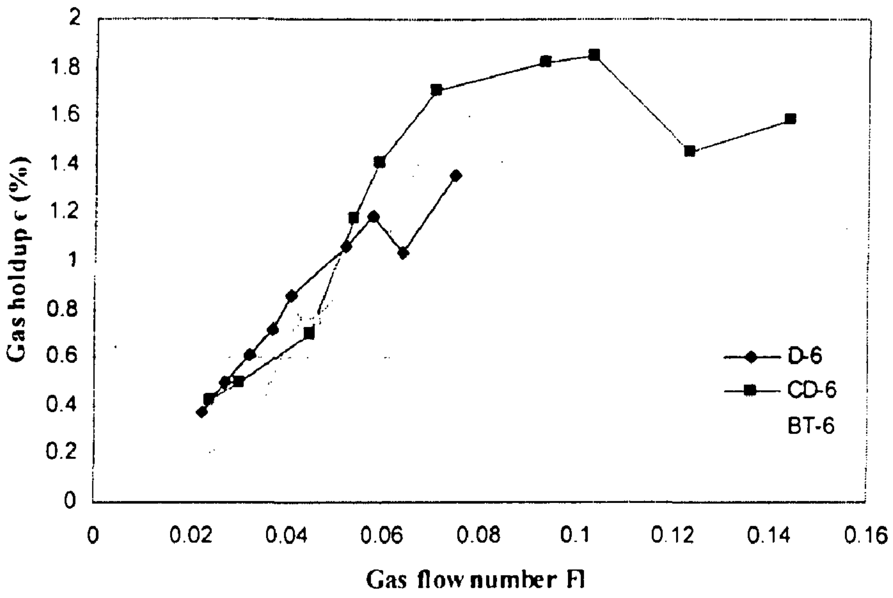


Fig. 3.4 Gas holdup generated at 250rpm (fall in holdup due to flooding

3.7.5 Selection and Importance of Baffles [42]: It is common knowledge that baffles promote better flow in an agitated vessel, but how to apply them and what kind to use take some ingenuity. In addition, most agitated vessels are baffled, and the design of the baffle system must also economically satisfy process objectives. Baffles are needed to stop the swirl in a mixing tank. Almost all impellers rotate in the clockwise or counter-clockwise direction. Without baffles, the tangential velocities coming from any impeller(s) causes the entire fluid mass to spin. It may look good from the surface seeing that vortex all the way down to the impeller, but this is the worst kind of mixing. There is very little shear and the particles go around and around like in a Merry-Go-Round. This is more like a centrifuge than a mixer.

3.7.5.1 Use of Baffling: During agitation of a low-viscosity liquid, the rotating impeller imparts tangential motion to the liquid. Without baffling, this swirling motion approximates solid-body rotation in which little mixing actually occurs. Think about stirring a cup of coffee or a bowl of soup: The majority of the mixing occurs when the spoon is stopped or the direction of stirring is reversed. The primary purpose of baffling is to convert swirling motion into a preferred flow pattern to accomplish process objectives. The most common flow patterns are axial flow, typically used for blending and solids suspension, and radial flow, used for dispersion. However, baffling also has some other effects, such as suppressing vortex formation, increasing the power input and improving mechanical stability.

3.7.5.2 Standard Baffling

Many agitated vessels. use standard baffling, which consists of four flat vertical plates, radially-directed (*i.e.*, normal to the vessel all), spaced at 90 deg. around the vessel periphery, and running the length of the vessel's straight side. Standard baffle width is 1/10 or 1/12 of the vessel dia. Sometimes, baffles are flush with the vessel wall and base, but, more often, gaps are left to permit the flow to clean the baffles. Recommended gaps are equal to 1/72 of the vessel dia. between the baffles and the vessel wall, and ¼ to one full baffle width between the bottom of the baffles and the vessel base.

3.7.5.3 Types of Baffles: Beavertail baffle, concave baffle and flat plate baffle

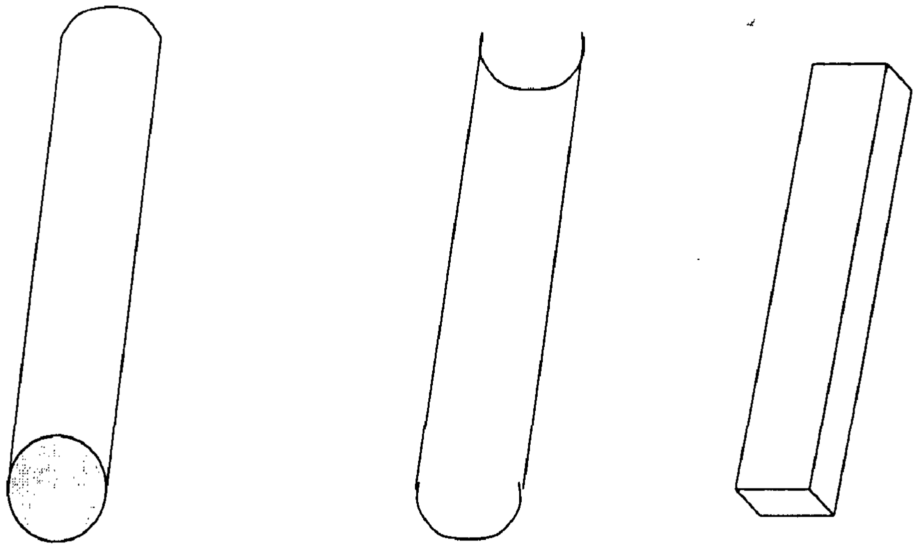


Fig. 3.3 Common baffle Style are the Beavertail Baffle (left), Concave Baffle and the Flat Plate (right)

Table 3.3: Baffle Configuration and Relative Power Number [42]

Baffle configuration	**Relative power number**
One beavertail	0.67
One concave	0.80
Two concave	0.86
Four standard	1.00

3.8 The Effect of Surfactants on Industrial Aeration Systems [40]

Oxygen transfer is one of the most energy-intensive operations of industrial wastewater treatment. and in many wastewater treatment plants it consumes more energy than all other plant operations combined. Efficient and reliable oxygen transfer systems are needed for economical wastewater treatment. There are many factors which affect oxygen transfer rate and efficiency. Prominent among these factors are aeration method, dissolved oxygen concentration, geometry and wastewater characteristics.

The concentration of surface active agents can have profound effects on aeration rates, and has been noted previously by a number of investigators. In some instances, the presence of surfactants may reduce the oxygen transfer rate by as much as 80%. In other cases, it has been reported that oxygen transfer rate is enhanced by the presence of surfactants. The large variation in transfer rate requires that the effects of surfactants be included in aeration system design. The alpha factor, calculated as the ratio of "dirty" clean" water mass transfer coefficients, is most often used to quantify the effects of surfactants on oxygen transfer rate.

Typical Alpha Values: The relative rate of oxygen transfer in wastewater compared to clean water must be established (alpha value). Table 3.5 shows the typical Alpha values for different types of aeration system.

Table 3.4: Alpha Values for Different Aeration System [28]

Aeration System	Typical Alpha
Course Bubble Diffusers	0.80
Fine Bubble Diffusers	0.45
Jet Aeration	0.75
Surface Mechanical Aerators	0.85
Submerged Turbines	0.85

EXPERIMENTAL STUDY

4.1 Experimental Set Up

4.1.1 Aeration Tank

A flat bottom, cylindrical tank with a diameter of T=30 cm, and height of 35 cm. the reactor has a total working volume of 24.74 L and the working volume of water is 16 L and the water height in the tank is 22.6 cm. Figure 1 shows the schematic set, was used in this study. The four equi-spaced baffles, B=0.1T, arranged at the 90^0 around the circumference and were fitted to the wall 0.3 cm of gap between baffle and the wall of tank is provided for better cleaning of baffle. The vessel was constructed of MS sheet. The working fluid was filtered tap water. Air was introduced, via air pump, through 3mm diameter copper tube and multiple holes are provided at the end of the pipe for better dispersion of air with a clearance of Cs=T/5.

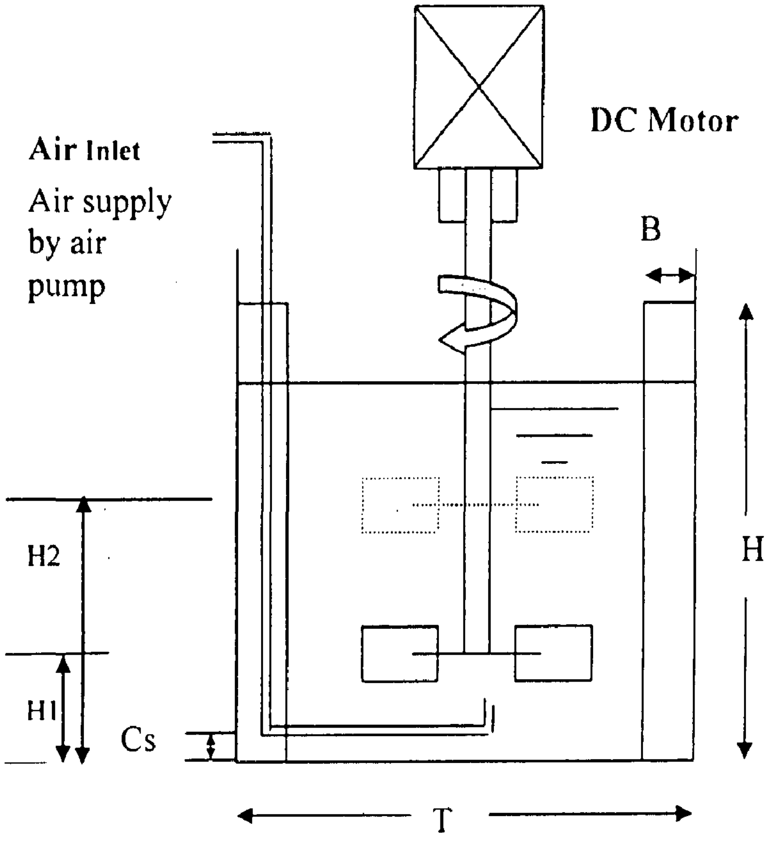


Fig. 4.1: Experimental set up

4.1.2 Agitator Motor

A single phase. D.C. shunt motor was used to drive the impeller in the wastewater. Motor was installed on an iron frame over the tank. For variable speed of the motor, a variable speed controller was used. The agitator speed was controlled by an electric variable speed controller, which was calibrated with a tachometer. The main functions of variable speed controller were:

- To feed 220 volts D.C.fixed voltage to series field winding of D.C. variable speed motor.
- To feed variable D.C. volts, 220 volts, with a load capacity of 2.5 amp as desired by D.C. motor series field and armature windings.

4.1.3 Impeller Used in the Experiment

The CD-6, the BT-6 and a standard Rushton turbine are illustrated in Figure 2. The hollow blade impellers are essentially identical to the Rushton turbine in terms of the dimensions and the presence of the central disc, except for the blade design. Whereas the Rushton turbine has flat blades, the CD6 and the BT6 have semi-circular and parabolic hollow blades, respectively. Both the CD6 and BT6 are operated in the concave direction of rotation. All three impellers had a diameter of D=T/3, and a and operated at height H1=12 cm and H2=16 cm from the bottom of the tank to the impeller mid plane was maintained

Different types of radial impeller which is mostly used for gas dispersion has been used in the study of removal of VOCs by aeration:

Table 4.1 Impeller Used in the Study

Impeller no.	Impeller type	Diameter (cm)	Fig.
1	D6 (Rushton impeller	10 cm	4.2(a)
2	CD6 impeller (semicircular blade)	10 cm	4.2(b)
3	BT6 impeller (parabolic blade)	10 cm	4.2(c)

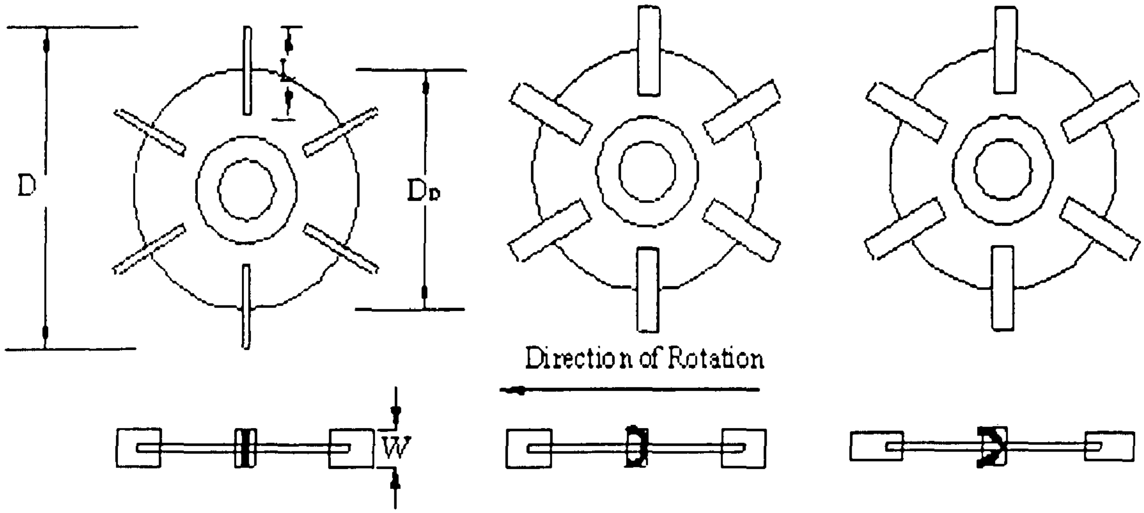


Fig. 4.2 Impeller Used in the Study

(a) D-6	**(b) CD-6**	**(c) BT-6**
D = 0.1m	D = 0 .1m	D = 0.11m
L = D/4	L = D/4	L = D/4
W = D/5	W = D/5	W = 2D/13
D_D = 7D/10	D_D = D/10	D_D = 2D/3

4.1.4 Wastewater

The wastewater selected for the experimental work is prepared in the laboratory by dissolving VOCs in the tap water for the study. Water containing 10 mg/L concentration of VOCs was prepared.

4.2 VOCs STUDIED

Two types of VOCs have been studied in the experiment:

1. Acetone
2. Dichloromethane or methylene chloride

Chemical physical properties of these VOCs are given in appendix A1 and A2.

4.3 EXPERIMENTAL PROCEDURE

The experimental setup which is shown in fig 4.1 was used for experiments. All the electric connection was made. The reactor was thoroughly washed and cleaned for every set of readings. Laboratory made wastewater was then poured in to the reactor. Prior to start of each run, the content of the tank were thoroughly mixed to ascertain the homogeneity of the wastewater under study. Dissolved oxygen (DO) was removed using sodium sulfite with a cobalt chloride catalyst. The cobalt chloride dose was less than 0.5 mg/L. Theoretically, 7.9 mg/L of sodium sulfite is required for each milligram per liter of DO present. Since it is common practice to add 1 .5-2 .0 times of this amount to ensure complete deoxygenation, approximately 14 mg/L per mg of DO was added. After adjusting the impeller height from the bottom of the tank the impeller speed was adjusted by using the tachometer to the desired value began each experiment. Sample were taken after every 20 min, each experiment run was 4 hrs for both types of VOCs.

4.3.1 Effect of Different Types of Impeller

In order to access the effect of surface aeration on the removal of VOCs. The experiment were carried out using three different type of gas dispersion radial impeller i.e. D6, CD6 and BT6 impeller.

4.3.2 Effect of Different Height of Submergence of Impeller

In order to access the effect of surface aeration on the removal of VOCs. Experiment were carried out at different height of submergence of impeller in the aeration tank i.e. H1 = 12 cm from the bottom of the tank and H2 = 16 cm from the bottom of the tank.

4.3.3 Effect of Impeller Speed

In order to access the effect of surface aeration on the removal of VOCs. Experiments were carried out at higher rpm at 250 rpm, 300 rpm and 350 rpm for each impeller and at each height.

4.3.4 Effect of Air Supply

In order to access the effect of surface aeration on the removal of VOCs. Experiment was carried out with and without air supply.

4.4 Estimation of Concentration of VOCs

Concentration of VOCs has been calculated using gas chromatography.

hydrogen and burned air, the extent of ionization depends upon the nature of the compound its quality and temperature of the flame. A collector D.C. potential applied is placed across the flame and measures the conductivity of the flame. It is a hydrocarbon selective and very high sensitivity detector.

In FID, nitrogen is used as carrier gas, hydrogen as fuel and oxygen to support combustion. The flow rate of carrier has to be determined by the requirement of analysis.

Qualitative Analysis

Qualitative analysis is base on the fact that each component has a characteristic retention time for a particular set of operating conditions. The retention time of the component is measured along the base line from the injection point to the apex of the component peak. Tentative identification can be made by comparing previously recorded chromatograms of known mixture with chromatograms of the sample mixture. The known mixture is prepared by including the components which assumed will be present in the sample mixture.

Quantitative Analysis

Quantitative analysis is based on the relationship between the peak parameters of height and area and the concentration of the component in the sample mixture. Most quantitative analysis is accomplished by using peak area measurement.

To utilize the peak area measurement efficiently for quantitative analysis, a calibration curve is necessary. The calibration curve is constructed using known component as a standard.

4.4.2 Acetone

To estimate the concentration of Acetone, the GC conditions are given below:

Injection temperature: 200^0C
Detector temperature: 200^0C
Oven temperature : 110^0C
Sample injection : 4μl

4.4.1 Gas Chromatograph (GC)

It comprises of the basic for a variety of Analytical and non analytical application. It comprises of the basic unit to which a broad range of optional modules may be added optional variable permit isotherm or temperature programmed operation, use of thermal conductivity or flame ionization detectors, syringe or valve sample introduction. A large oven with a removal front opening door is standard. Each heated zone–injector, detector, and column oven is insulated to minimize heat transfer between zones, the temperature of each one of which can be controlled and read independently.

Flow and pressure controls of the carrier gas, fuel and air are housed on top towards the back of the oven; top mounted injectors allow vertical sample injection.

Oven Column

Here column is maintained at the required temperature (should be greater than the boiling point of the component that is to be analyzed). It also houses the injectors, detectors, flow control valves and gas lines. The injector has independent heating systems. Only the detector in use is heated the oven interior contains the heater cage and the temperature-sensing element. The heater is a nichrome wire element. The sensor is a platinum resistance thermometer. The air inside the oven is stirred by means of blower for uniform temperature.

Injection Port

It consists of a stainless steel body, which fits into a universal base and accepts a removal glass insert. The injector design ensures that the entire injector is swept with carrier gas, giving narrow band injection into the column. Liquid injection requires a micro liter syringe. For liquid sample it is advice to use 2 or 4 micro liter of sample.

Detector

The Flame Ionization Detector (FID) yields excellent sensitivity and a wide linear dynamic range. This detector operates in principle that the electrical conductivity of the sample is directly proportional to the concentration of charged particles within the sample. The sample component contained in the effluent gas from column is mixed with

4.4.3 Dichloromethane

To estimate the concentration of Acetone, the GC conditions are given below:

Injection temperature: 200^0C
Detector temperature: 200^0C
Oven temperature : 100^0C
Sample injection : 4μl

4.5 Estimation of VOC Removal Efficiency

VOCs removal efficiency has been calculated by using the equation (3.7)

4.6 Estimation of K_La

In aeration open vessel were used, that allows the sufficient air volume to avoid significant gas phase saturation above the liquid surface, which allow us to assume $C_s = 0$ [25]. Therefore from the equation (3.7), the liquid concentration changes over time were used to estimate the mass transfer coefficient K_La using the equation below.

$$\ln\left(\frac{C_t}{C_o}\right) = -K_{La}(t - t_0) \qquad (4.1)$$

4.7 Estimation of Specific Power Input [25]

$$P/V = 2.05E\text{-}06\ (N)^{3.11} \qquad (4.2)$$

Where P/V is the specific power input in Watt/m^3 and N is the rotational speed of impeller in rpm.

RESULTS AND DISCUSSION

5.1 General

Aeration of VOCs means removal of VOCs by using aeration and the removal of VOCs by aeration mainly depends upon the mass transfer of VOCs from liquid phase to vapor phase. which is entirely dependent on the agitation of the wastewater to expose more interfacial area between air and water.

In this chapter, experimental results obtained on the effect of impeller speed, different heights of submergence of impeller, effect of supply of air in the aeration tank, and type of the impellers on the removal of VOCs are presented. In this chapter study of effect on mass transfer coefficient (K_La) of VOCs at different rpm and specific power input also presented.

5.2 Effect of Impeller Speed, Type of Impeller, Height of Submergence and Supply of Air on VOC Removal.

Table 5.1 to 5.3 shows the removal efficiency of three impellers used at various conditions.

Fig. 5.1 to 5.4 shows the removal of Acetone at height H1 and H2 with and without air supply by using Rushton impeller.

Fig. 5.5 to 5.8 shows the removal of Dichloromethane at height H1 and H2 with and without air supply by using Rushton impeller.

Fig. 5.9 to 5.12 shows the removal of Acetone at height H1 and H2 with and without air supply by using CD6 impeller.

Fig. 5.13 to 5.16 shows the removal of Dichloromethane at height H1 and H2 with and without air supply by using CD6 impeller.

Fig. 517 to 5.20 shows the removal of Acetone at height H1 and H2 with and without air supply by using BT6 impeller.

Fig. 5.21 to 5.24 shows the removal of Dichloromethane at height H1 and H2 with and without air supply by using BT6 impeller.

5.2.1 Effect of Impeller Speed on VOC Removal:

Experiment was studied at three higher rmp i.e. 250, 300 and 350rpm. Graph clearly shows that the removal efficiency of Acetone is a function of impeller speed and it increases with the increase in impeller speed, for both types of VOCs studied. Graph shows that initially rate of reduction of VOC is high (up to 2 hrs), because initially the VOC concentration were high and after sometime when the concentration reaches value about 4 mg/L, than its removal rate reduced because of low concentration. Graph clearly shows that best result obtained at 350rpm, although difference of removal efficiency is not more at 300 and 350rpm. Table 5.1 to 5.3 shows the efficiency obtained at varying operating condition.

5.2.2 Effect of Types of Impellers on VOC Removal:

In this study well designed gas dispersion radial impellers i.e. Rushton (D-6), CD-6 and BT-6 were selected. These impellers are efficient for gas dispersion application. Graph clearly shows that BT-6 impeller gives best result at all operating conditions (up to 95% removal efficiency can be obtained) because BT-6 impeller having higher mass transfer coefficient at the same superficial gas velocity compare to D-6 and CD-6.

5.2.3 Effect of Height of Submergence on Removal of VOC

Graph shows the removal efficiency increases with the increase in height of submergence but at higher rpm and for BT-6 impeller, effect of height of submergence on removal efficiency is not significance. Table 5.1 to 5.3 shows the removal efficiencies were increased up to 3-8%. At higher rpm gas dispersion becomes uniform through out the aeration tank so height of submergence doesn't give significance improve on removal efficiency although best result were obtained at height of submergence at 2/3rd of total water height from the bottom of the tank.

5.2.4 Effect of Air Supply on Removal of VOC:

Graph clearly shows that supply of air gives significant effect on removal efficiencies for all three impeller used. Study performed only at 300rpm for without air supply to see the affect of air supply on the removal of VOC, and it is clear from graph that supply of air increases the removal efficiency, although it shows more effect in the case of D-6, it increases the removal efficiency up to 8% for Acetone and 12% for Dichloromethane. Table 5.1 to 5.3 shows the comparison of efficiency obtained.

Table 5.1: Estimated Removal Efficiency of Rushton Impeller

RUSHTON (D-6) IMPELLER								
RPM	Removal eff. With air supply (%)				Removal eff. Without air supply(%)			
	At height H1		At height H2		At height H1		At height H2	
	Acetone	**DCM**	**Acetone**	**DCM**	**Acetone**	**DCM**	**Acetone**	**DCM**
250	70.16	66.35	78.57	70.30				
300	79.47	78.23	82.14	80.34	72.16	66.65	79.79	69.81
350	81.79	81.05	82.09	84.76				

Table 5.2: Estimated Removal Efficiency of CD-6 Impeller

CD-6 IMPELLER								
RPM	Removal eff. With air supply (%)				Removal eff. Without air supply(%)			
	At height H1		At height H2		At height H1		At height H2	
	Acetone	**DCM**	**Acetone**	**DCM**	**Acetone**	**DCM**	**Acetone**	**DCM**
250	75.84	80.74	82.92	81.40				
300	84.53	84.97	87.82	85.18	82.91	78.42	81.61	81.45
350	83.79	86.81	89.63	88.56				

Table 5.3: Estimated Removal Efficiency of BT-6 Impeller

BT-6 IMPELLER								
RPM	Removal eff. With air supply (%)				Removal eff. Without air supply(%)			
	At height H1		At height H2		At height H1		At height H2	
	Acetone	**DCM**	**Acetone**	**DCM**	**Acetone**	**DCM**	**Acetone**	**DCM**
250	89.65	91.69	91.61	92.61				
300	93.58	92.26	95.84	93.91	89.68	81.90	91.14	85.03
350	94.91	93.71	95.87	94.05				

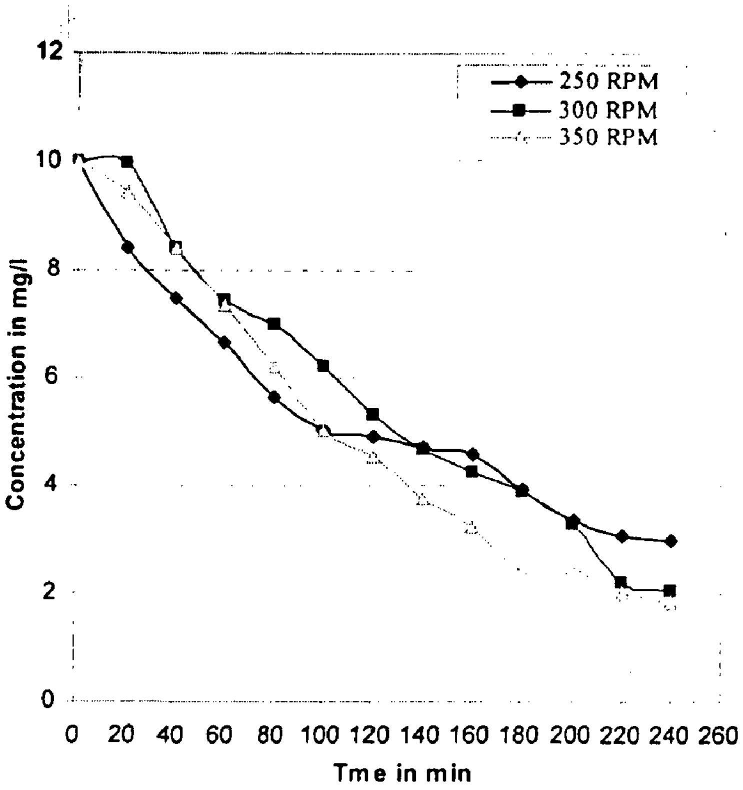


Fig 5.1 Plot of acetone concentration Vs time at three different rpm by Rushton Impeller at height H1

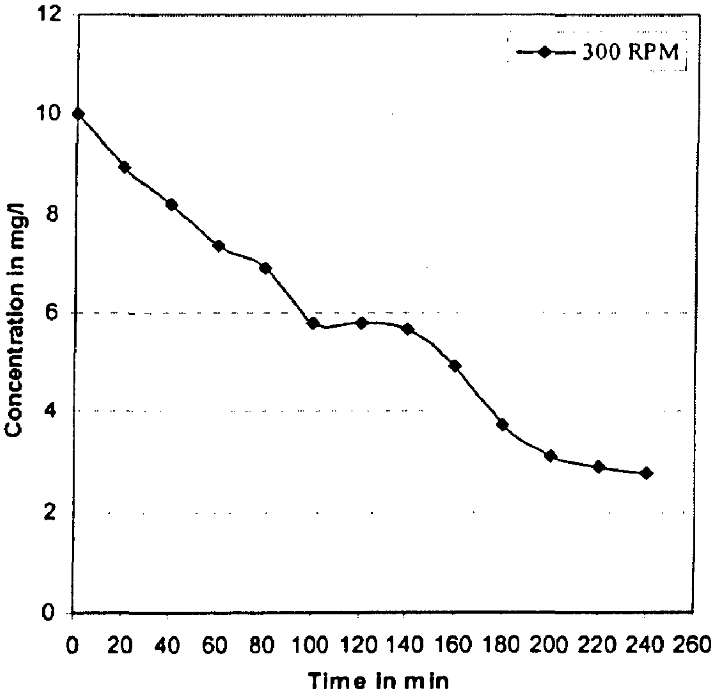


Fig. 5.2 Plot of acetone oncentration Vs time, without air supply at height H1 by Rushton Impeller

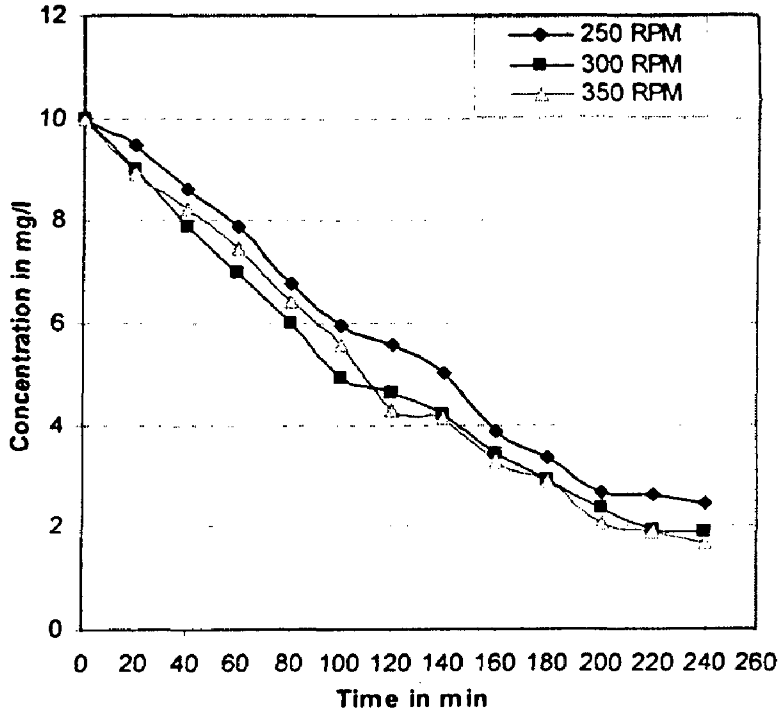


Fig. 5.3 Plot of acetone concentration Vs time at three diffrent rpm at height H2 by Rushton Impeller

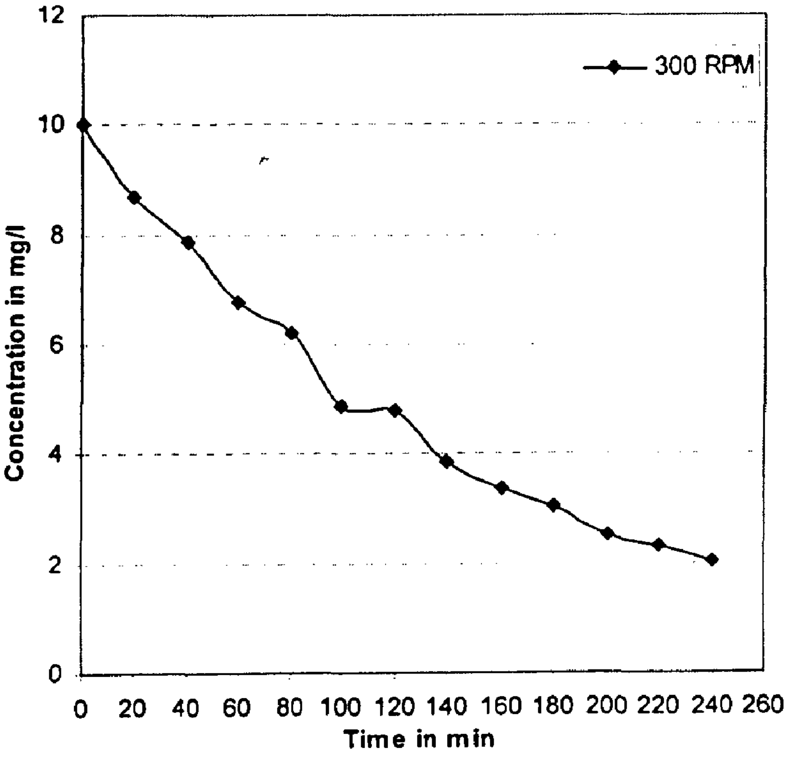


Fig. 5.4 Plot of acetone concentration Vs time at height H2, without air supply by Rushton Impeller

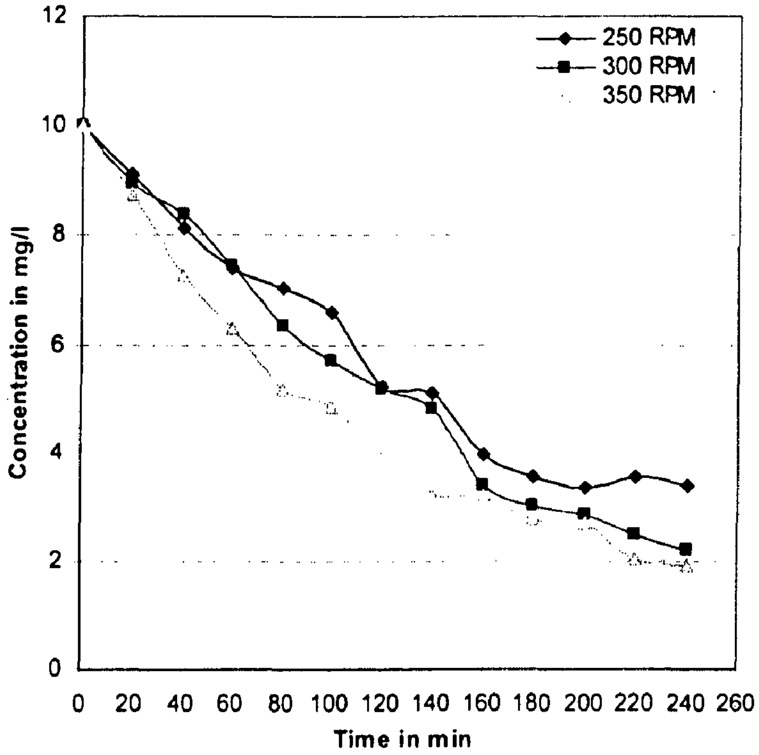


Fig. 5.5 Plot of dichloromethane concentration Vs time at three different rpm at height H1 by Rushton Impeller

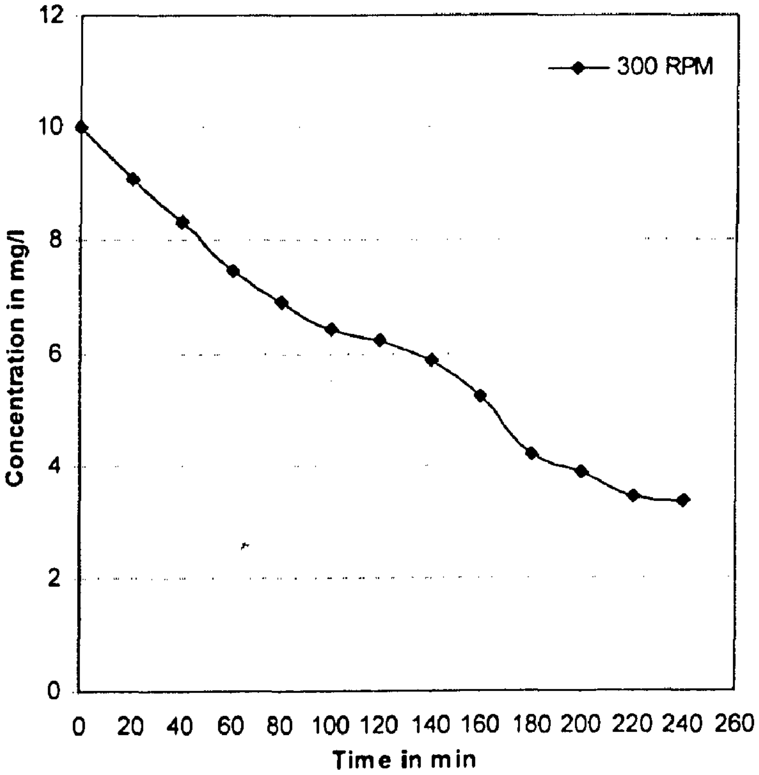


Fig. 5.6 Plot of dichloromethane concentration Vs time, without air supply at height H1 by Rushton Impeller

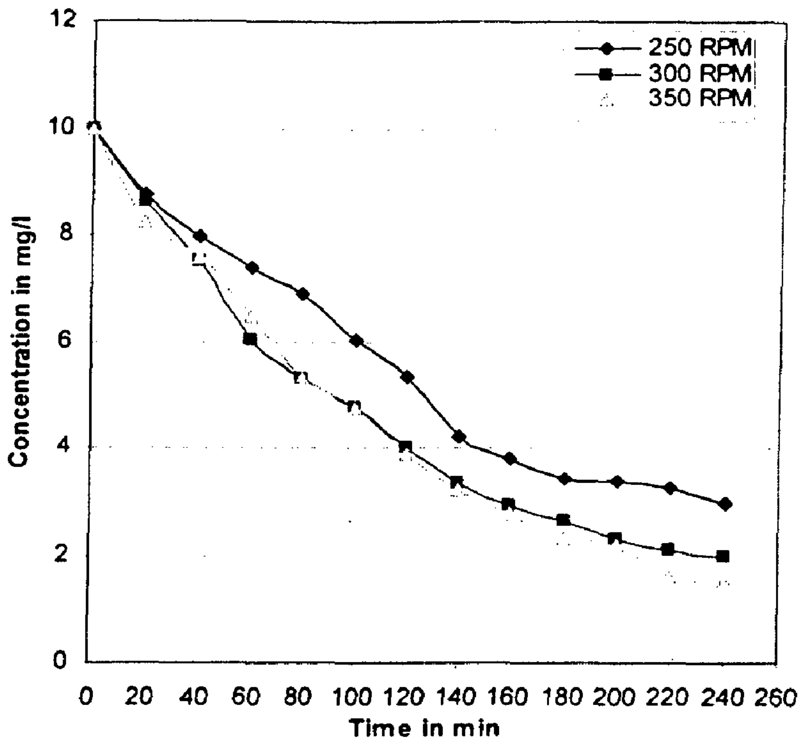


Fig. 5.7 Plot of dichloromethane concentration Vs time at three different rpm at height H2 by Rushton Impeller

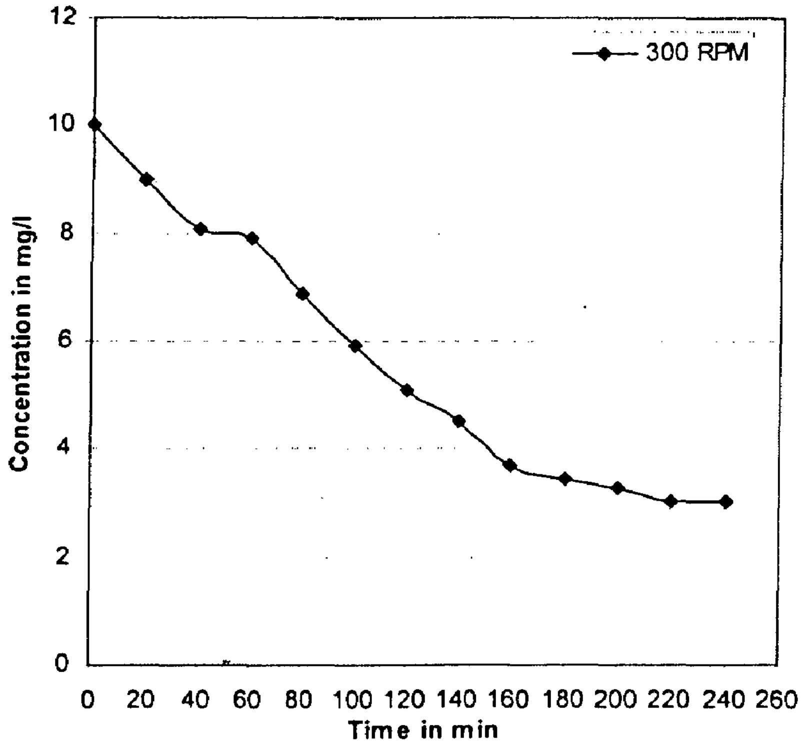


Fig. 5.8 Plot of dichloromethane concentration Vs time at height H2, without air supply by Rushton Impeller

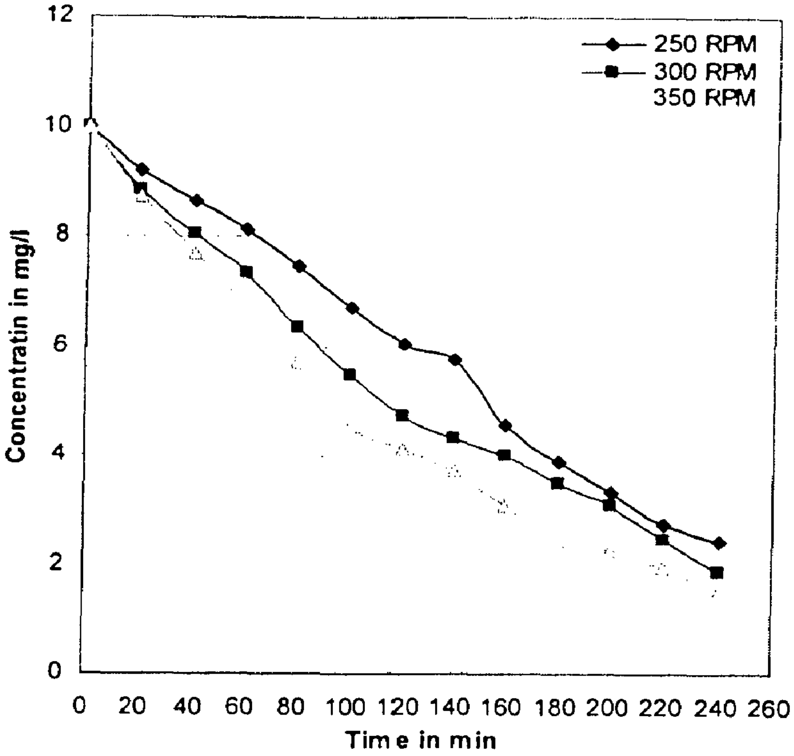


Fig 5.9 Plot of acetone concentration Vs time at three different rpm at height H1 by CD6 Impeller

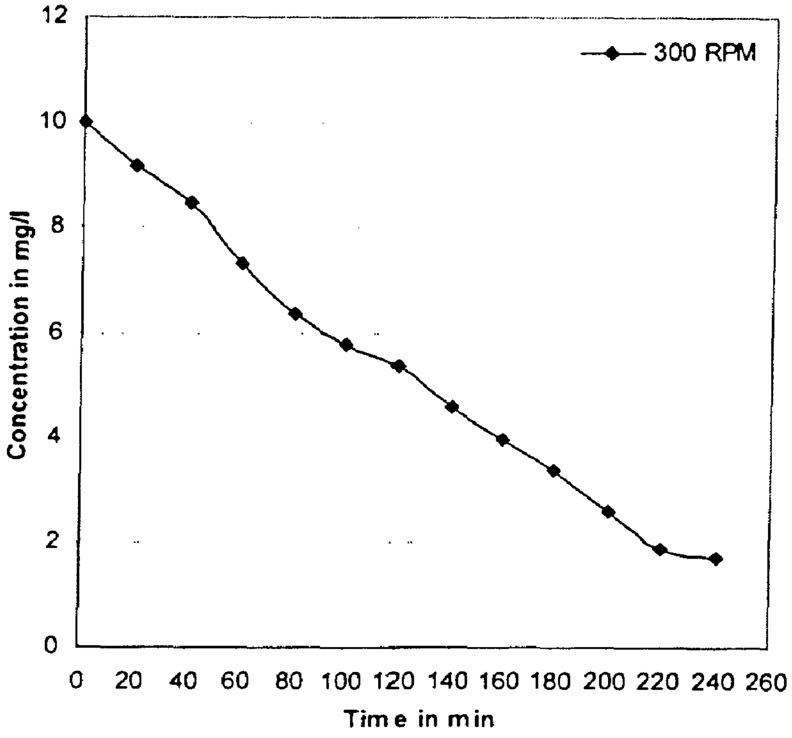


Fig. 5.10 Plot of acetone concentration Vs time at height H1 without air supply by CD6 Impeller

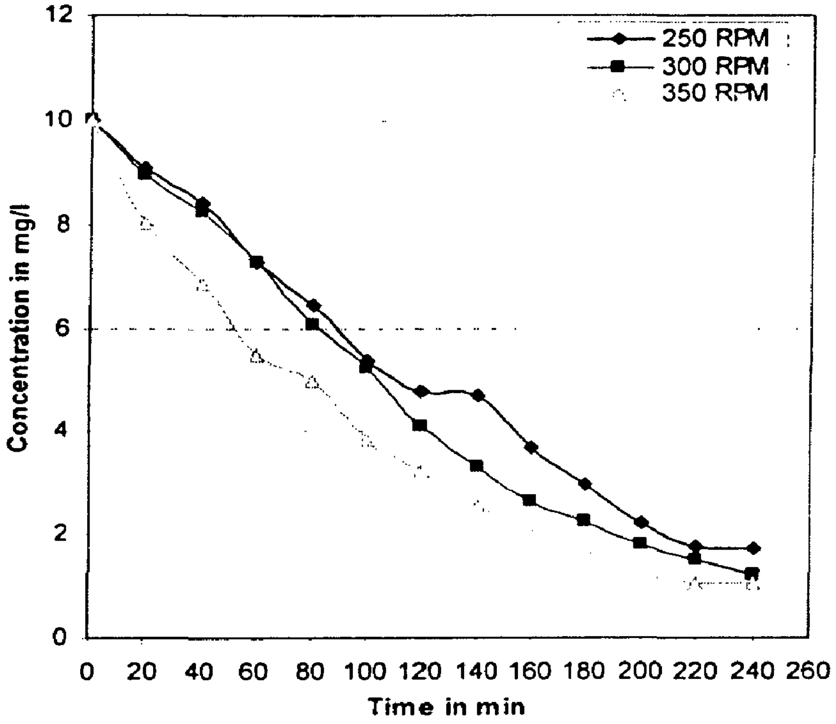


Fig. 5.11 Plot of acetone concentration Vs time at three different rpm at height H2 by CD6 impeller

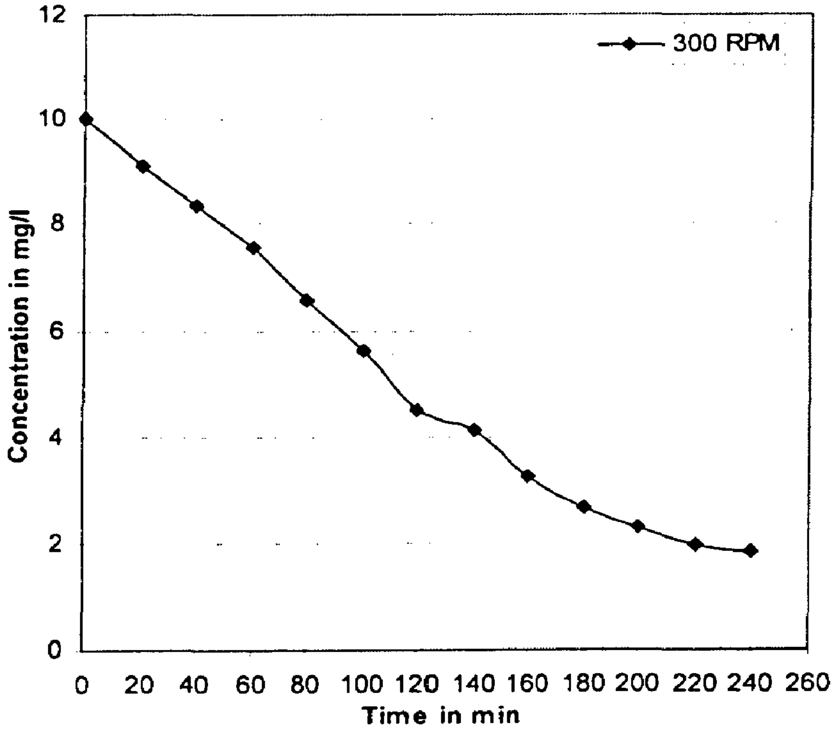


Fig 5.12 Plot of acetone concentration Vs time at height H2 without air supply by CD6 Impeller

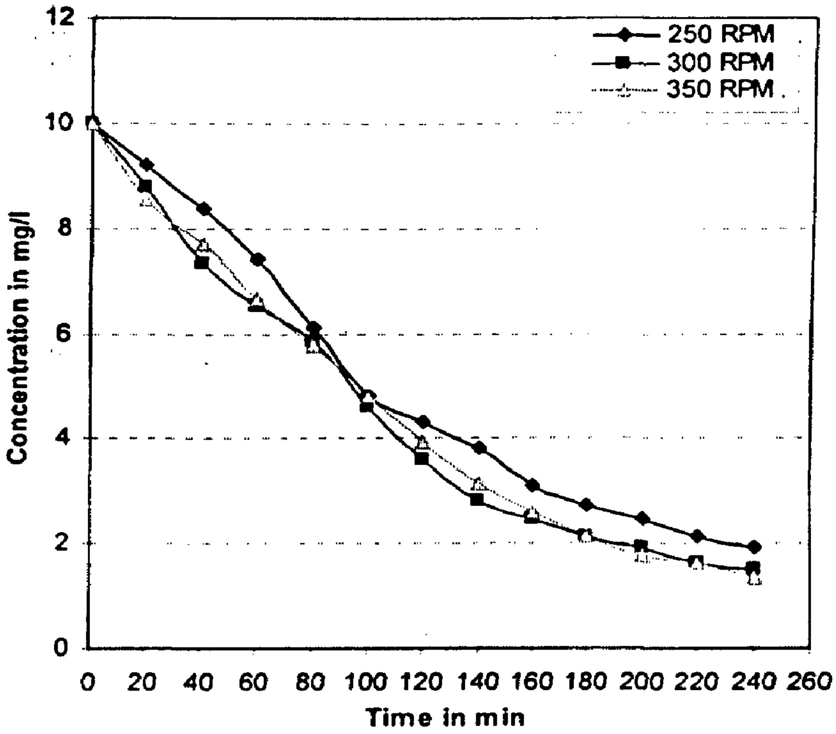
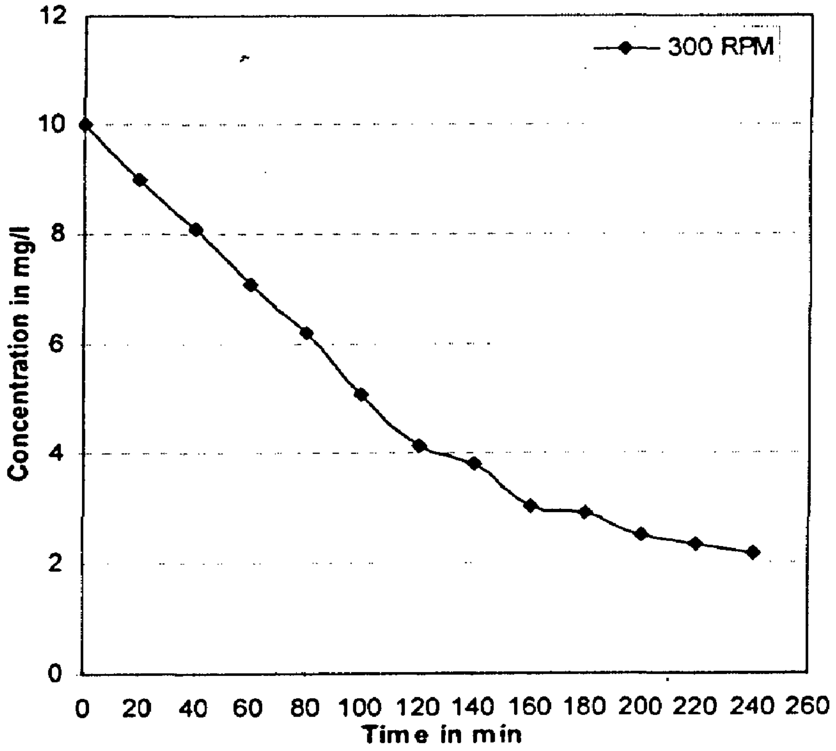


Fig. 5.13 Plot of dichloromethane concentration Vs time at three different rpm at height H1 by CD6 Impeller



5.14 Plot of dichloromethane concentration Vs time at height H1, without air supply by CD6 impeller

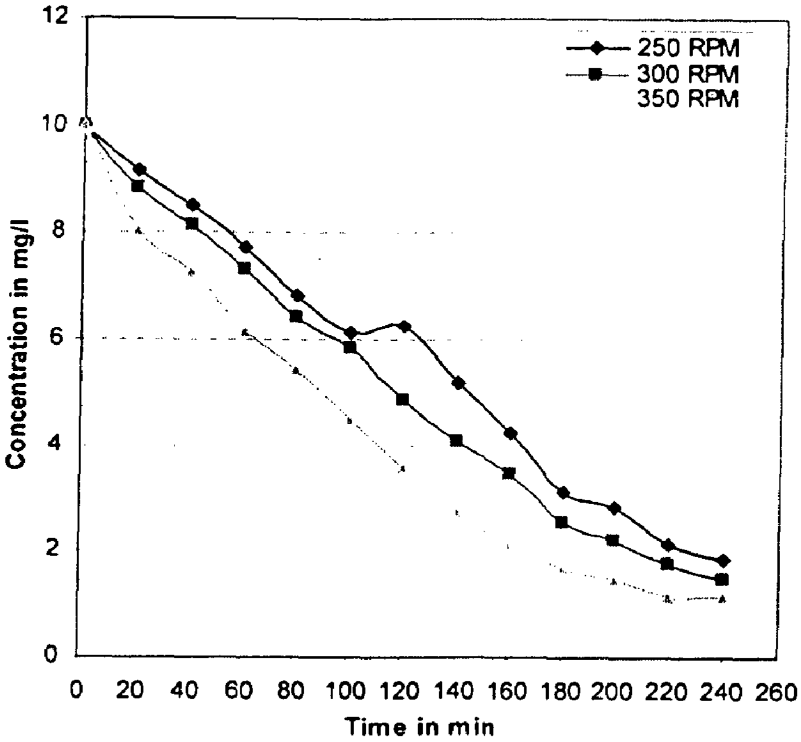


Fig. 5.15 Plot of dichloromethane concentration Vs time, at three different rpm at height H2 by CD6 Impeller

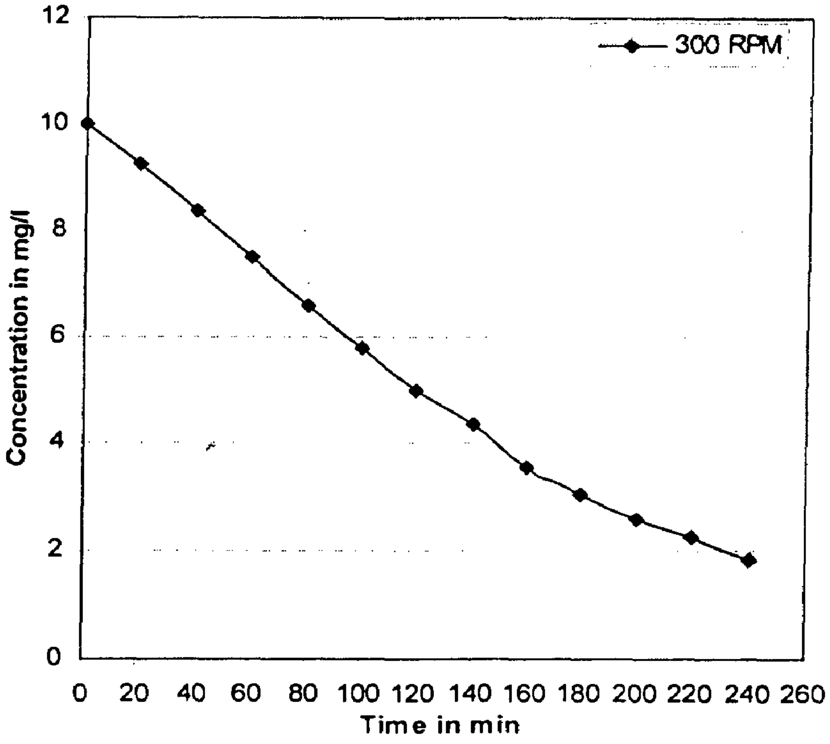


Fig. 5.16 Plot of dichloromethane concentration Vs time at height H2, without air supply by CD6 impeller

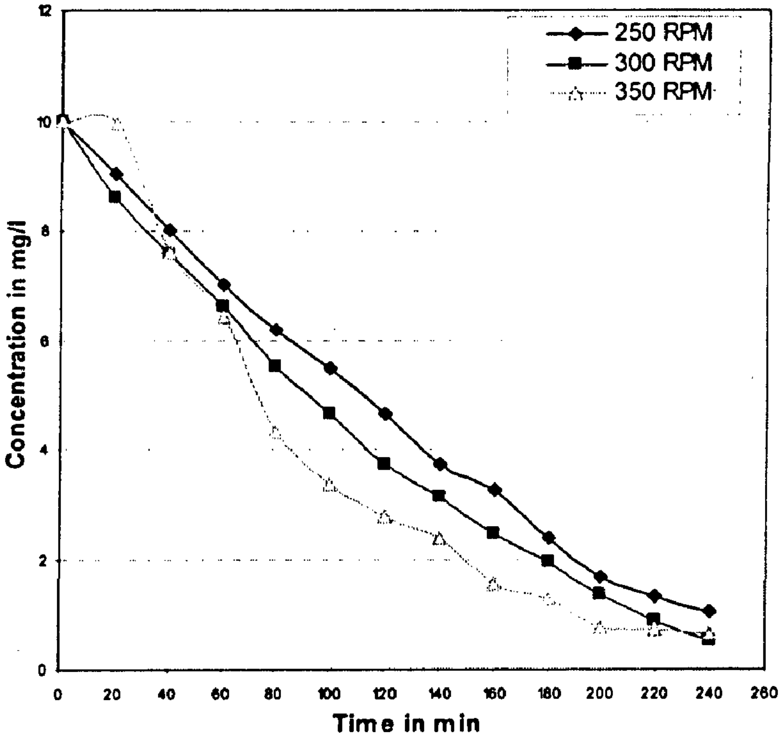


Fig 5.17 Plot of acetone concentration Vs time at three different rpm at height H1 by BT6 impeller

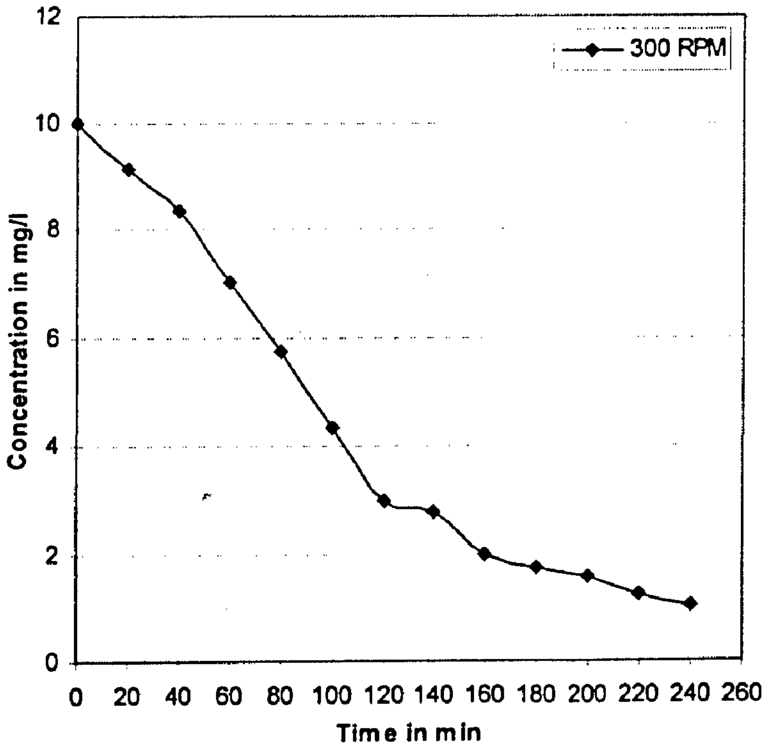


Fig. 5.18 Plot of acetone concentration Vs time at height H1, without air supply by BT6 Impeller

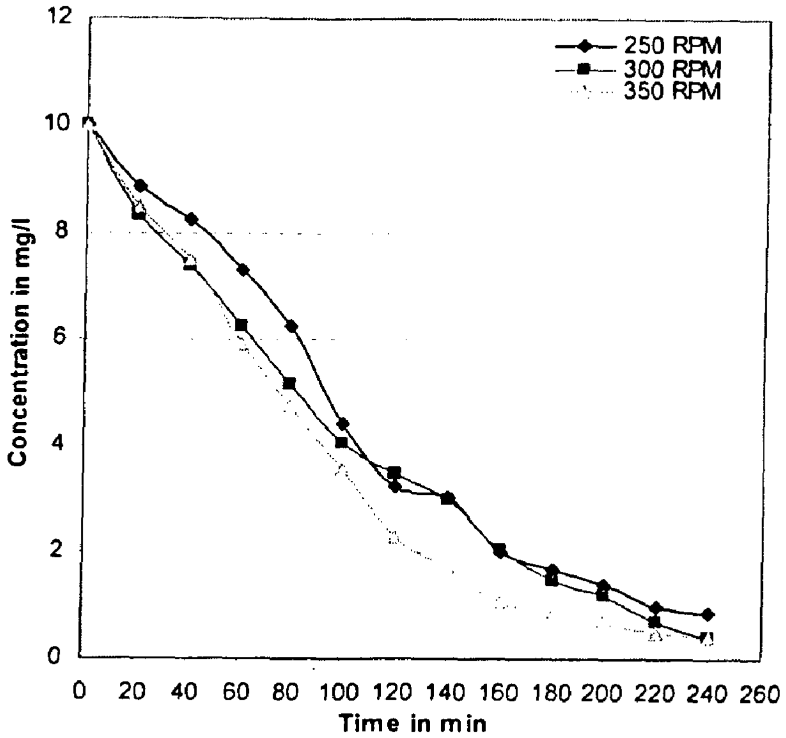


Fig. 5.19 Plot of acetone concentration Vs time at three different rpm at height H2 by BT6 impeller

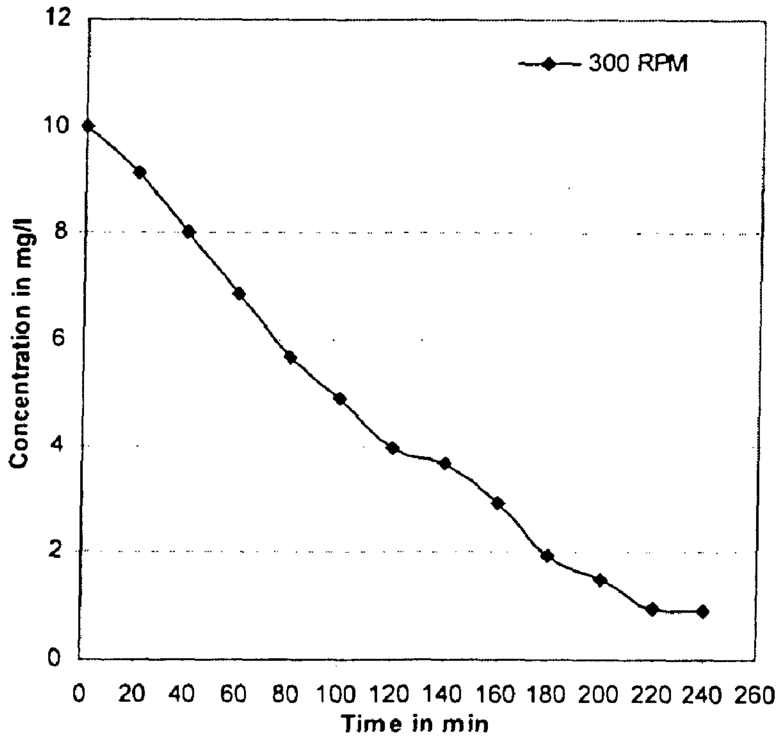


Fig. 5.20 Plot of acetone concentration Vs time at height H2, without air supply by BT6 impeller

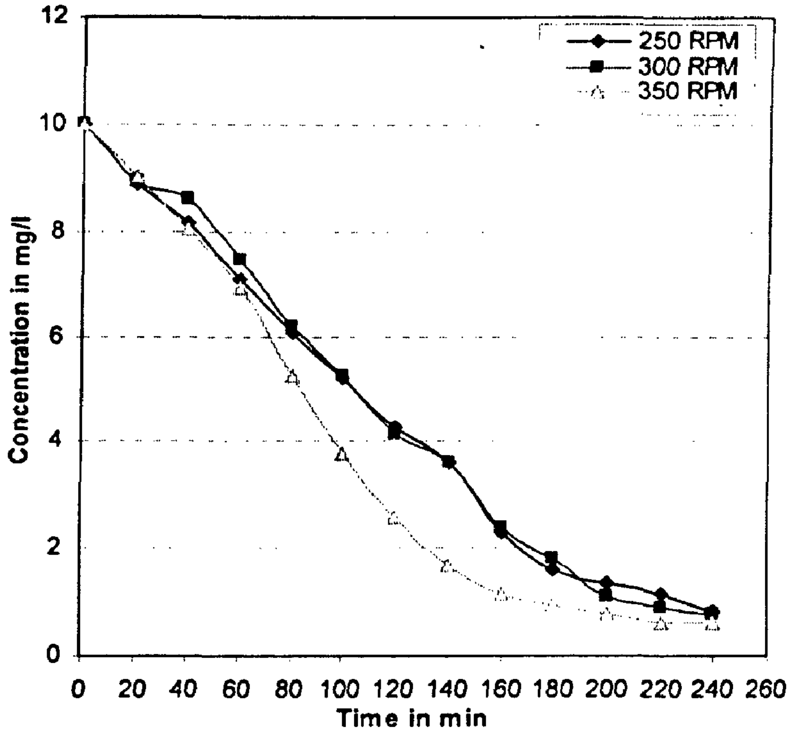


Fig. 5.21 Plot of dichloromethane concentration Vs time at three different rpm at height H1 by BT6 impeller

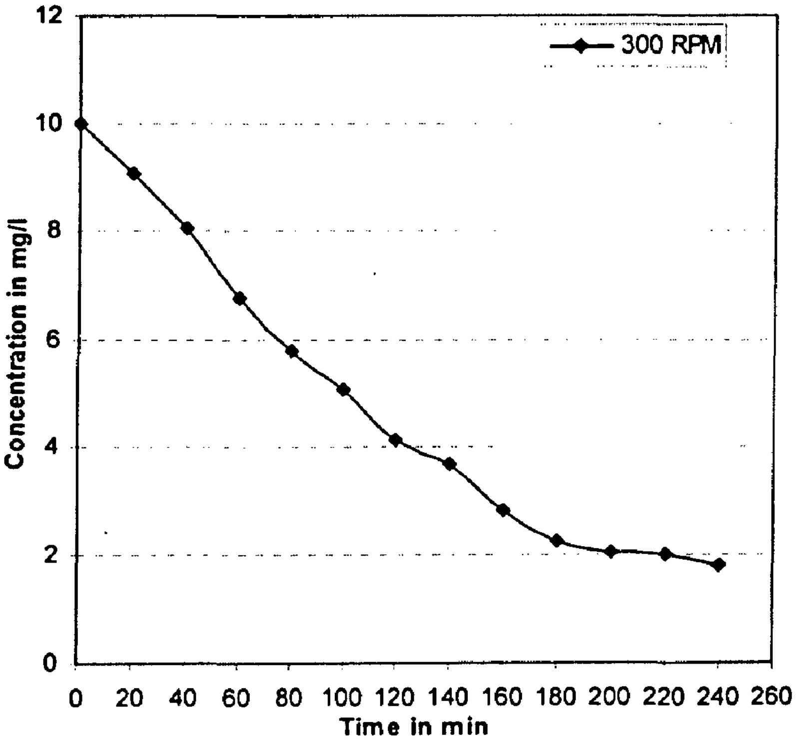


Fig. 5.22 Plot of dichloromethane concentration Vs time at height H1, without air supply by BT6 impeller

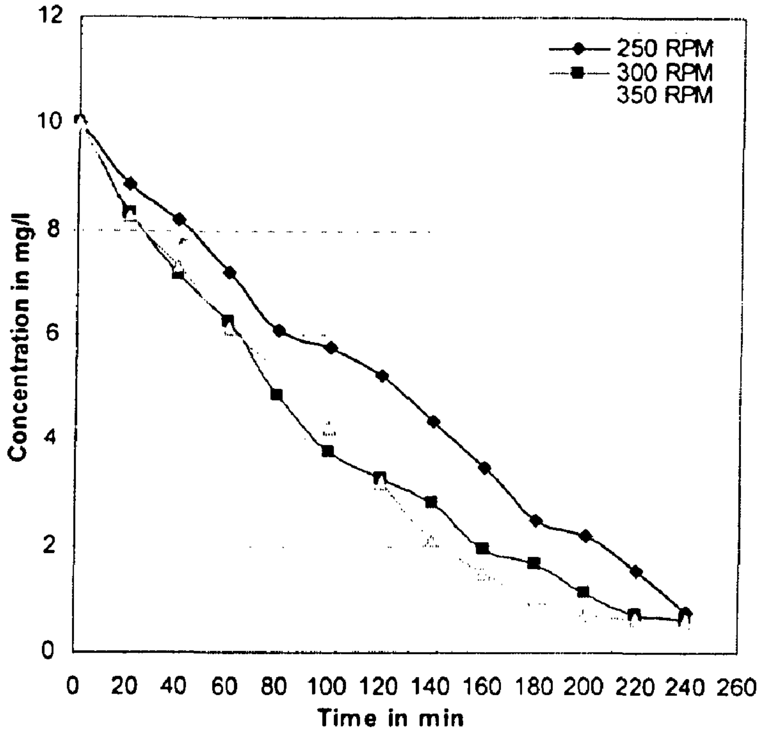


Fig. 5.23 Plot of dichloromethane concentration Vs time at three different rpm at height H2 by BT6 impeller

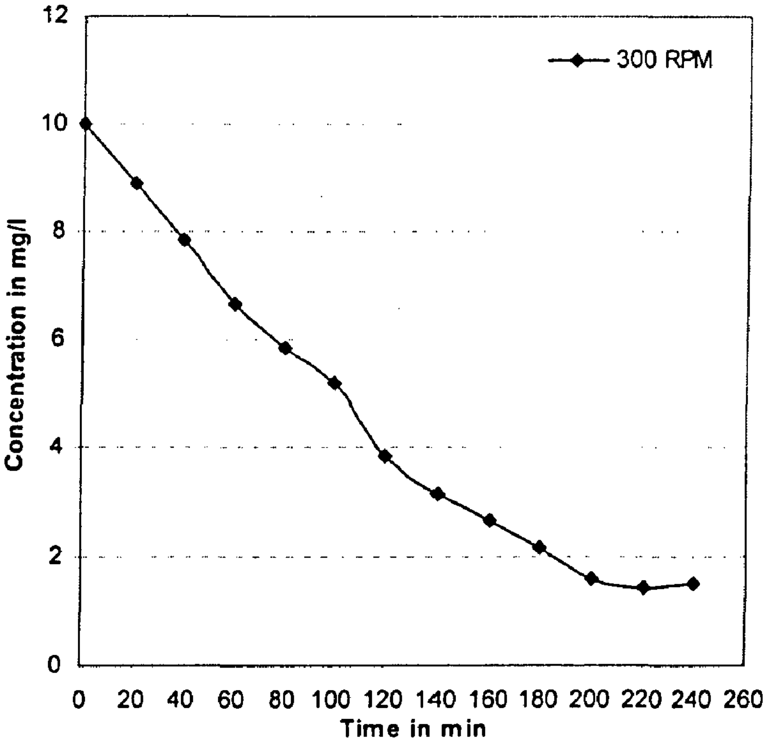


Fig 5.24 Plot of dichloromethane concentration Vs time, at height H2 without air supply by BT6 impeller

5.3 Effect of Specific Power Input on K_La

Mass transfer coefficient depends upon specific power input (as specific power input proportional to impeller speed) graph clearly shows that it increases with the increase of specific power input at both height of submergence H1 and H2. These graph shows that mass transfer coefficient increases with the increase in specific power input, and its value changes more frequently for BT- impeller, and it's having lower value for Rushton impeller. Value of K_La changes with increase in height of submergence.

Fig. 5.25 to 5.27 shows the effect on mass transfer coefficient of VOC1 and VOC2 for all three impellers at height H1.

Fig. 5.28 to 5.30 shows the effect on mass transfer coefficient of VOC1 and VOC2 for all three impellers at height H2.

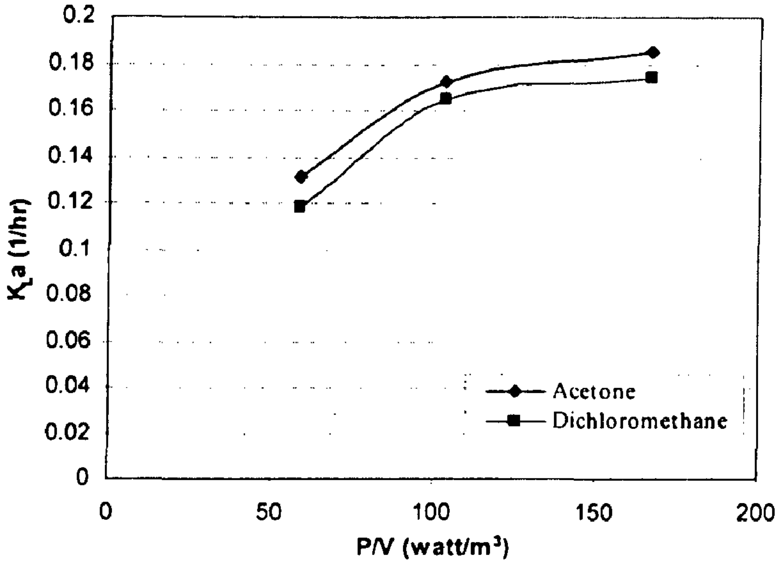


Fig. 5.25 Plot of mass transfer coefficient(KLa) Vs specific power input(P/V) by rushton impeller(height H1)

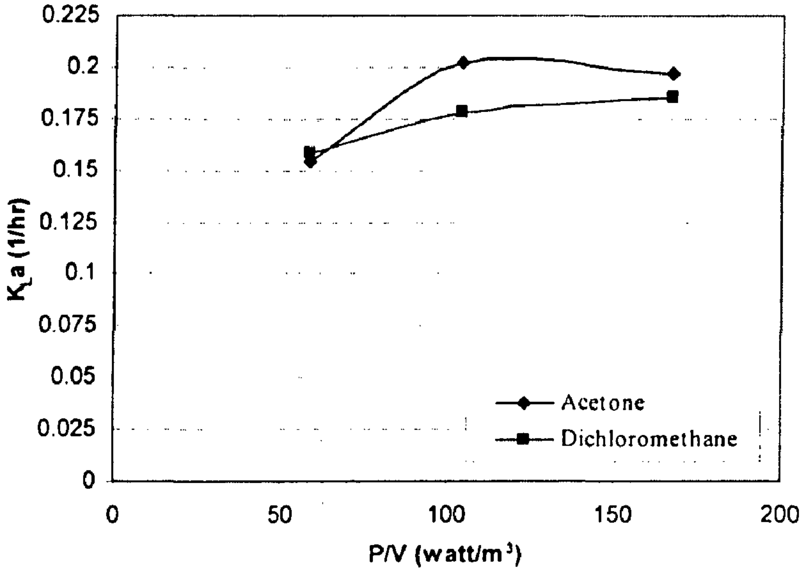


Fig. 5.26 Plot of mass transfer coefficient (KLa) Vs specific power input (P/V) by CD6 impeller at height H1

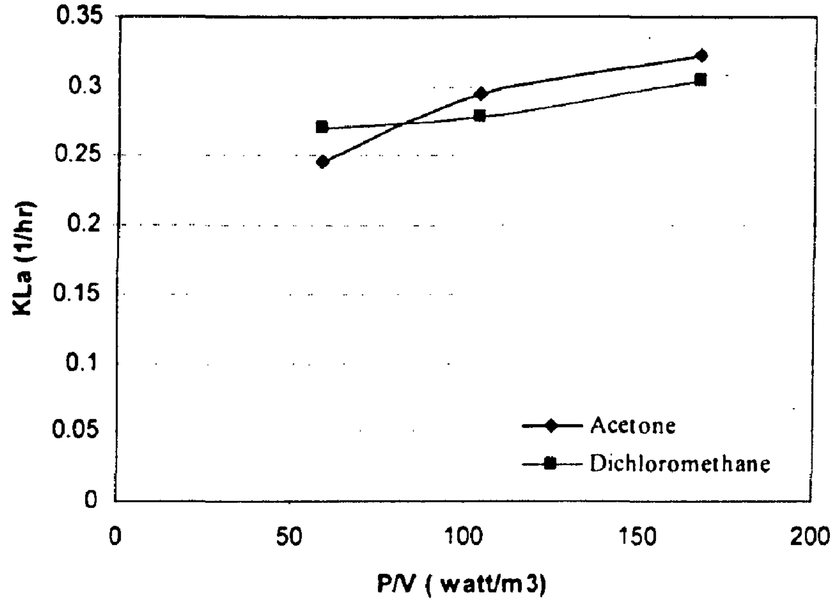


Fig. 5.27 Plot of mass transfer coefficient (KLa) Vs specific power input (P/V) by BT6 impeller at height H1

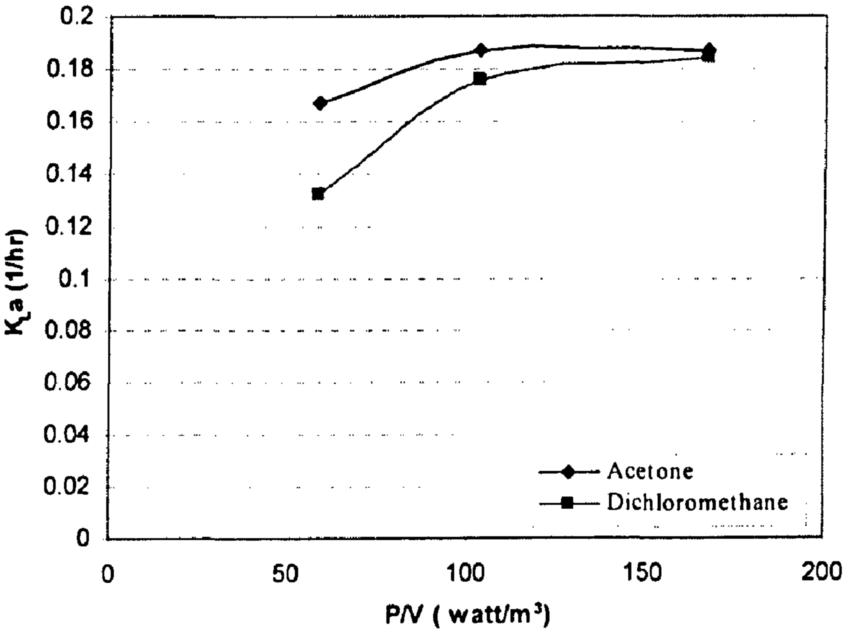


Fig. 5.28 Plot of mass transfer coefficient (KLa) and specific power input (P/V) by rushton impeller at height H2

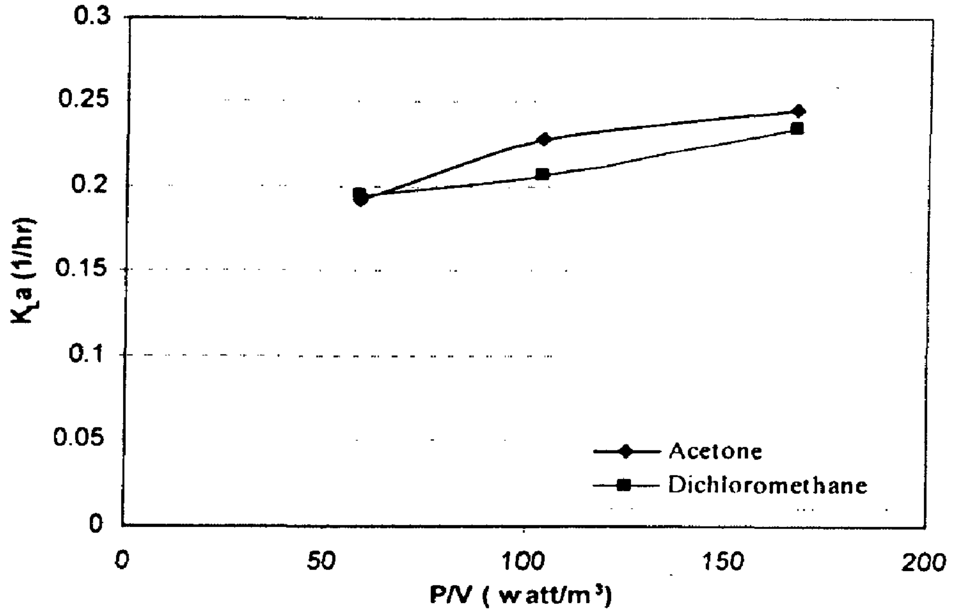


Fig. 5.29 Plot of mass transfer coefficient (KLa) Vs specific power input (P/V) by CD6 impeller at height H2

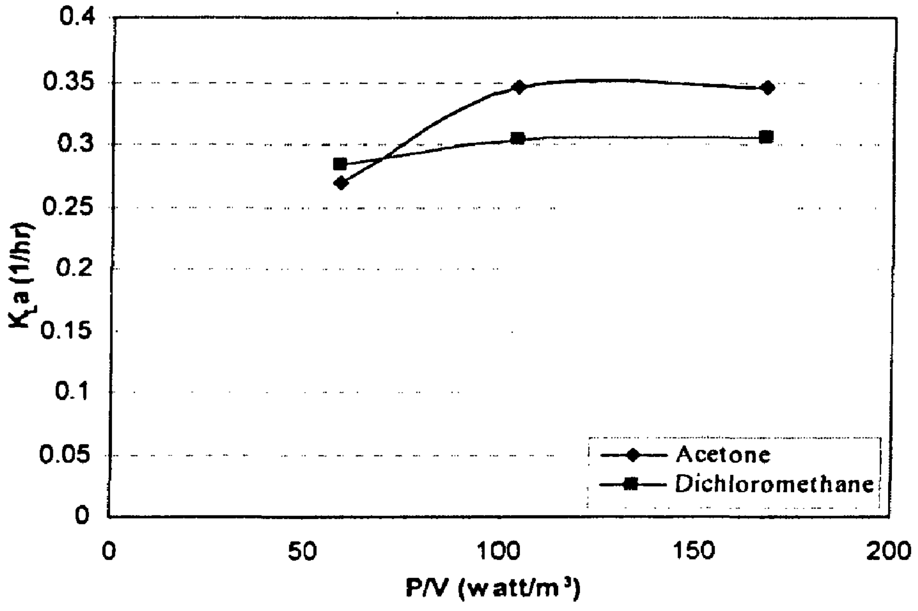


Fig. 5.30 Plot of mass transfer coefficient (KLa) Vs specific power input (P/V) by BT6 impeller at height H2

5.4 Effect of Types of Impeller on K_La

Graph clearly shows that mass transfer coefficient is high for BT6 impeller and Rushton impeller is having lower mass transfer coefficient and it also increases with increase in height of submergence of impeller.

Fig. 5.31 to 5.34 shows the effects of types of impeller on mass transfer coefficient at height of submergence H1 and H2 for VOC1 and VOC2

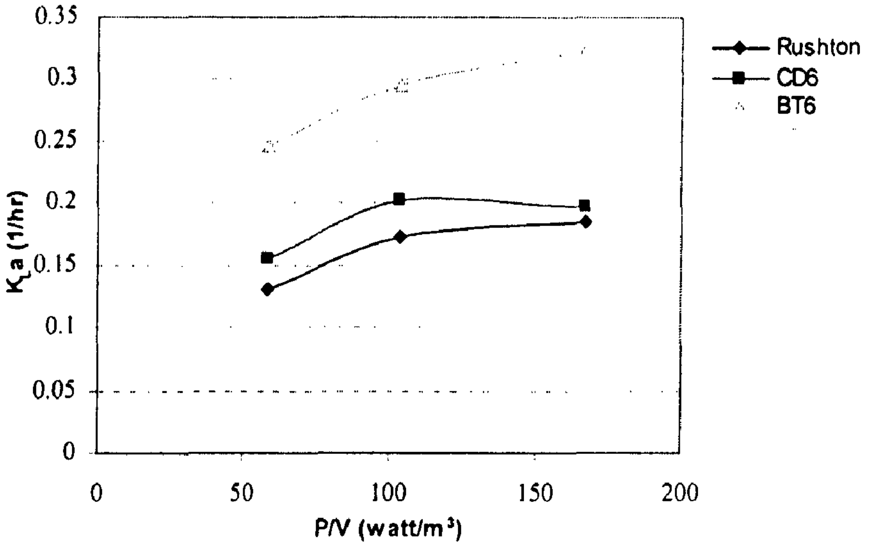


Fig. 5.31 Comparison of mass transfer coefficient of three different impellers for acetone at height H1

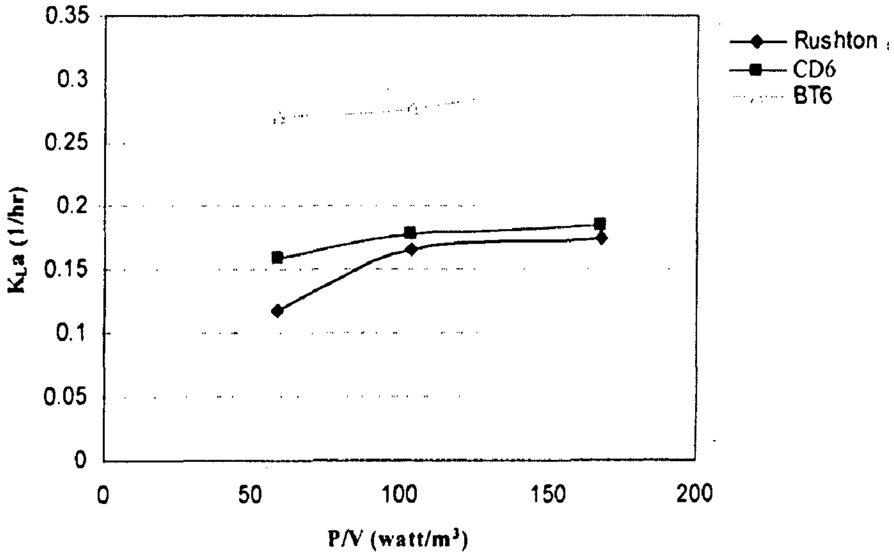


Fig. 5.32 Comparison of mass transfer coefficient of three different impeller for dichloromethane at H1

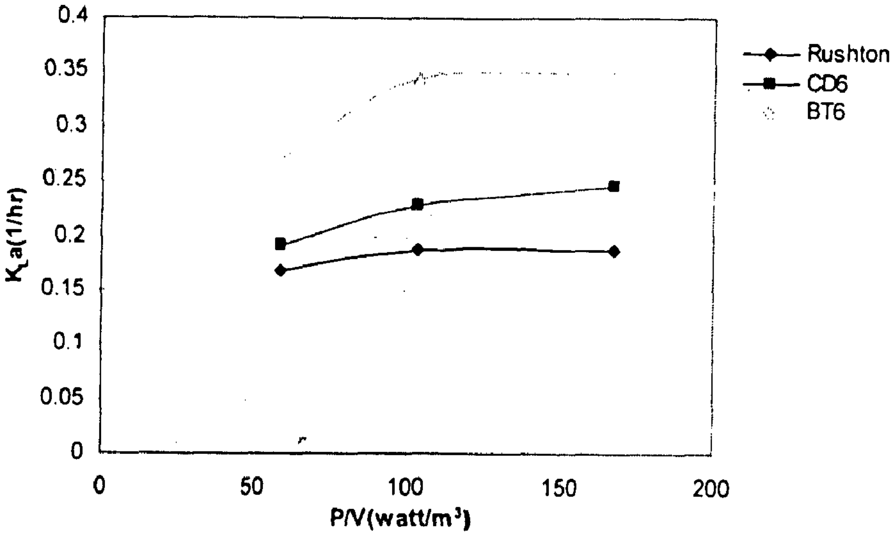


Fig. 5.33 Comarison of mass transfer coefficient of three different impeller at height H2 for acetone

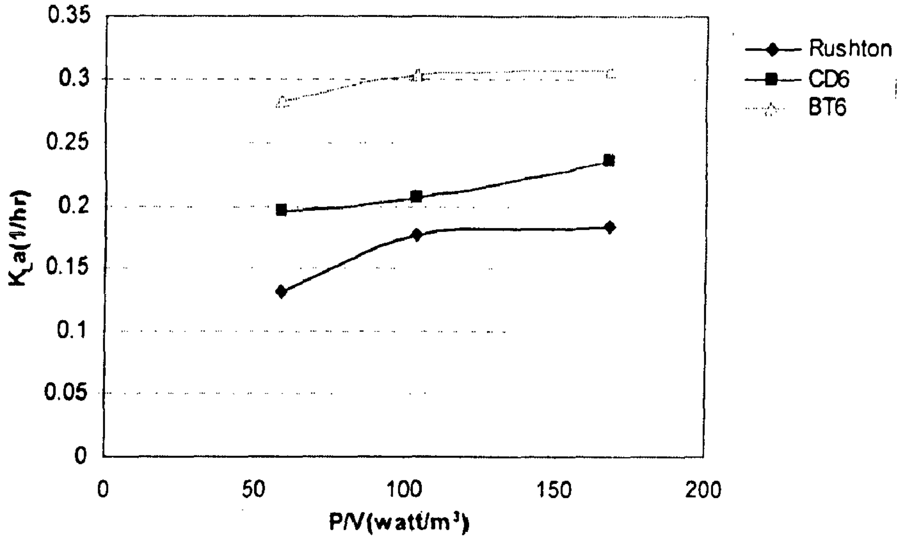


Fig. 5.34 Comarison of mass transfer coefficient of three different impeller at height H2 for dichloromethane

5.5 Effect of Impeller Speed on K_la for Types of Impellers.

Fig, 5.35 to 5.38 shows the effect of impeller speed on K_La, it clearly shows that it increases with increase in rpm and it changes rapidly in the case of BT6 impeller. Previously discussed in chapter 3, the BT-6 impeller has the excellent gas dispersion capacity.

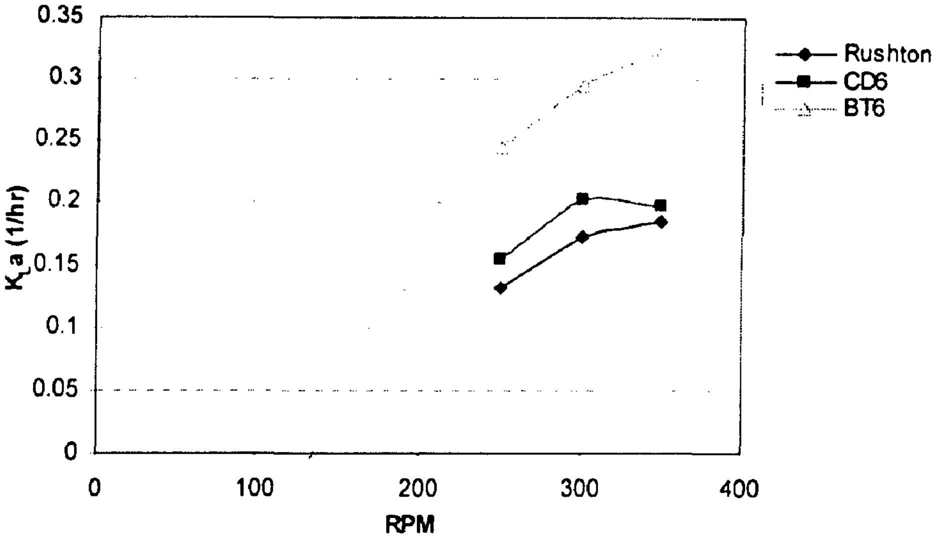


Fig. 5.35 Plot of mass transfer coefficient Vs RPM at height H1 for acetone by three different impeller

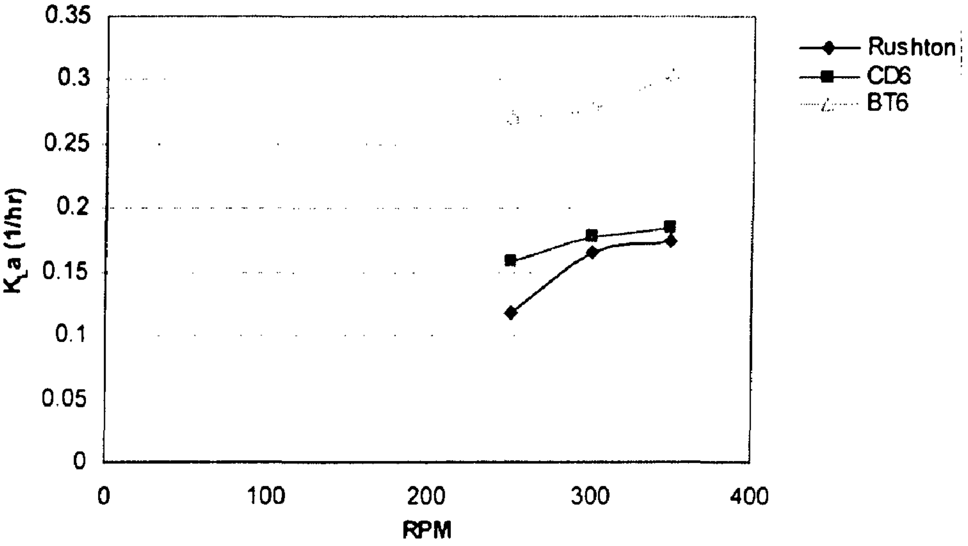


Fig. 5.36 Plot of mass transfer coefficient Vs RPM at height H1 for dichloromethane by three different impellers

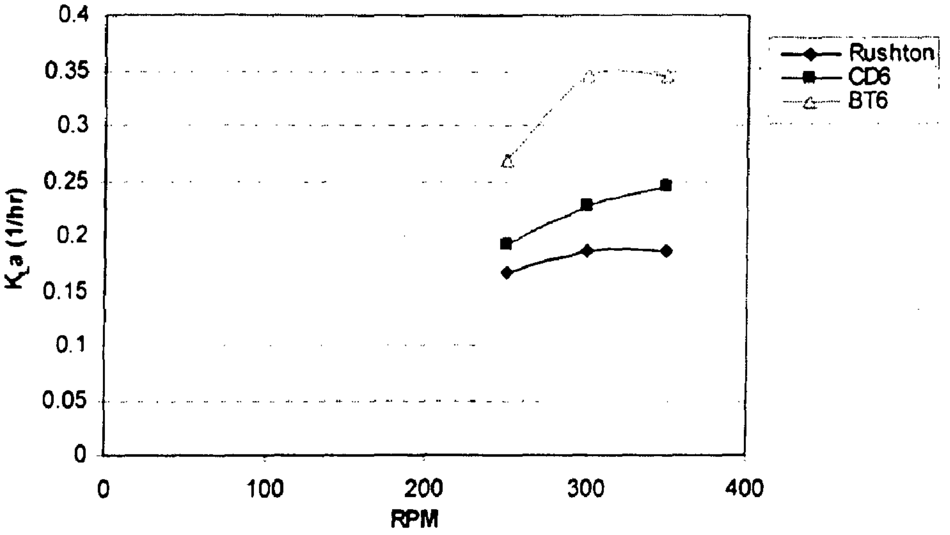


Fig. 5.37 Plot of mass transfer coefficient Vs RPM at height H2 of acetone by three different impeller

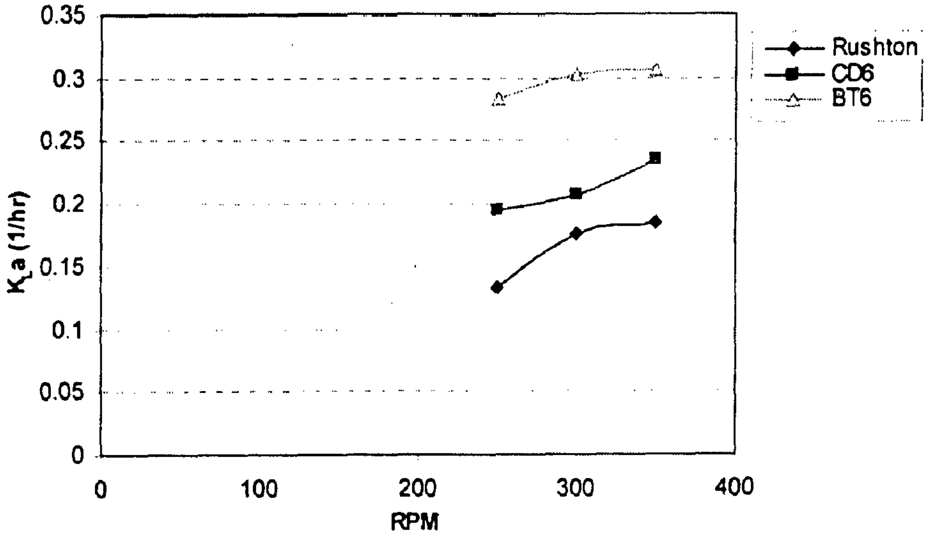


Fig. 5.38 Plot of mass transfer coefficient Vs RPM at height H2 for dichloromethane by three different impellers

Chapter 6

CONCLUSIONS AND RECOMONDATIONS

6.1 Conclusions

On the basis of the experiments conducted on the synthetic wastewater for studying the removal of VOCs (with impeller speed, impeller types, height of submergence of impeller, and supply as variable), following conclusions emerge:

1. Removal of VOCs as a function of time is exponential in nature. In graphs concentration of VOCs Vs time at any impeller speed, any impeller type and any height of submergence of impeller lie along an exponential curve.
2. Removal of VOCs by aeration largely depends upon the speed of the speed of the impeller. The graph shows that the VOCs removal increases with the increase in speed of the impeller because greater turbulence and consequently larger mass transfer at the surface, but energy consumption also increases with the increase in speed. Experiment shows that best results were obtained at 350 rpm.
3. Removal of VOCs by aeration also depends largely upon the type of the impeller, in the experiment special gas dispersion radial impellers were used. Graph shows that BT-6 impeller having greater removal efficiency than Rushton and CD-6 impeller.
4. Removal of VOCs by surface aeration depends upon the oxygen or air transfer hence removal efficiency also increased by the supply of air from external source. The graph shows that removal efficiency can be increased up to 8 to 12 % by supply of air bubble.
5. Removal of VOCs by aeration also depends upon the height of submergence of impeller from the bottom of the tank. As the graph shows that best result were obtained by the impeller having submergence height 2/3rd of the total water height from the bottom of the tank.

6.2 Recommendations

Based on the knowledge and experience during the course of experiments, following recommendations are suggested for further study:

1. Effect of temperature of the wastewater on the removal of VOCs should be studied.
2. It is clear that VOCs removal is very much function of type of impeller used. Similar investigation should be carried out using other modified latest designed impeller.
3. VOCs removal is also a function of speed of the impeller. Similar investigation should be carried out for higher speed of the impellers.
4. Effect of suspended solids on the removal of VOCs may be studied.
5. Effect of surfactant on removal of VOVs may be studied.

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APPENDIX

Table A1: Chemical identity and properties of Acetone

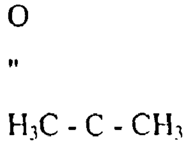
Chemical name	Acetone
Synonym(s)	dimethyl ketone; 2-propanone; beta-ketopropane
Chemical formula	C_3H_6O
Chemical structure	 $H_3C-\overset{\overset{O}{\parallel}}{C}-CH_3$
Rrelative molecular mass	58.08
Identification numbers: CAS registry	67-64-1
Flash point	-17°C closed cup, -9°C open cup
Flammability limits in air at 25°C	2.15-13% v/v
Vapor pressure	181.72 mmHg at 20°C
Viscosity	0.303 cP
Water solubility	miscible with water and organic solvents
Physical state	Liquid
Melting point	-95.35°C
Freezing point	-94.7°C at 1 atm
Boiling point	56.2°C at 1 atm
Density: at 20°C Riddick et al. (1986)	0.78996 g/ml

Table 2: Physical-chemical properties of Dichloromethane

Property	**Value**
Molecular weight	84.9 g
Aspect	liquid
Melting point	- 94.9 °C
Boiling point	39 - 40 °C at 1013 hPa
Decomposition temperature	120 °C
Density	1.33 at 20 °C
Vapour pressure	475 hPa at 20 °C
log Koc	1.68
Water solubility	13.7 g/l at 20 °C
Henry's Law constant	2.19E-03(atm-m3/mol)

Table A3: Estimated concentration of VOC1 using Rushton impeller at height H1

1.1 with air supply

250 RPM		300 RPM		350 RPM	
Time in min	Conc. (mg/l)	Time in min	Conc. (mg/l)	Time in min	Conc. (mg/l)
0	10	0	10	0	10
20	8.417	20	9.964	20	9.419
40	7.489	40	8.427	40	8.426
60	6.66	60	7.429	60	7.332
80	5.633	80	6.973	80	6.198
100	5.009	100	6.217	100	5.035
120	4.893	120	5.294	120	4.543
140	4.713	140	4.673	140	3.746
160	4.553	160	4.253	160	3.216
180	3.922	180	3.893	180	2.393
200	3.364	200	3.269	200	2.445
220	3.047	220	2.206	220	2.015
240	2.984	240	2.053	240	1.821

1.2 without air supply

300 RPM	
Time in min	Conc. (mg/l)
0	10
20	8.933
40	8.211
60	7.347
80	6.916
100	5.788
120	5.798
140	5.673
160	4.943
180	3.726
200	3.104
220	2.896
240	2.784

Table A4: Estimated concentration of VOC1 using Rushton impeller at height H2

2.1 With air supply

250 RPM		300 RPM		350 RPM	
Time in min	Conc. (mg/l)	Time in min	Conc. (mg/l)	Time in min	Conc. (mg/l)
0	10	0	10	0	10
20	9.461	20	8.981	20	8.917
40	8.620	40	7.894	40	8.218
60	7.876	60	6.979	60	7.445
80	6.762	80	5.991	80	6.424
100	5.975	100	4.910	100	5.553
120	6.256	120	4.642	120	4.291
140	5.033	140	4.202	140	4.097
160	3.839	160	3.432	160	3.257
180	3.361	180	2.926	180	2.882
200	2.652	200	2.340	200	2.066
220	2.87	220	1.943	220	1.896
240	2.143	240	1.786	240	1.791

2.2 Without air supply

300 RPM	
Time in min	Conc. (mg/l)
0	10
20	8.664
40	7.87
60	6.789
80	6.221
100	4.854
120	4.773
140	3.861
160	3.374
180	3.054
200	2.495
220	2.315
240	2.012

Table A5: Estimated concentration of VOC2 using Rushton impeller at height H1

3.1 With air supply

250 RPM		300 RPM		350 RPM	
Time in min	Conc. (mg/l)	Time in min	Conc. (mg/l)	Time in min	Conc. (mg/l)
0	10	0	10	0	10
20	9.126	20	8.766	20	8.957
40	8.126	40	7.278	40	8.386
60	7.402	60	6.294	60	7.448
80	7.057	80	5.179	80	6.341
100	6.583	100	4.861	100	7.36
120	5.225	120	3.861	120	5.183
140	5.084	140	3.218	140	4.792
160	3.940	160	3.169	160	3.36
180	3.549	180	2.776	180	3.012
200	3.327	200	2.685	200	2.835
220	3.523	220	2.037	220	2.485
240	3.365	240	2.175	240	2.013

3.2 Without air supply

300 RPM	
Time in min	Conc. (mg/l)
0	10
20	9.087
40	8.344
60	7.465
80	6.894
100	6.400
120	6.623
140	5.871
160	5.209
180	5.186
200	4.267
220	3.947
240	3.335

Table A6: Estimated concentration of VOC2 using Rushton impeller at height H2

4.1 with air supply

250 RPM		300 RPM		350 RPM	
Time in min	Conc. (mg/l)	Time in min	Conc. (mg/l)	Time in min	Conc. (mg/l)
0	10	0	10	0	10
20	8.724	20	8.628	20	8.247
40	7.939	40	7.496	40	7.585
60	7.366	60	6.018	60	6.473
80	6.901	80	5.275	80	5.304
100	6.023	100	4.758	100	4.746
120	5.334	120	4.013	120	3.89
140	4.200	140	3.324	140	3.235
160	4.788	160	3.346	160	2.778
180	4.411	180	3.321	180	2.315
200	3.673	200	3.324	200	2.192
220	3.255	220	2.121	220	1.616
240	2.97	240	1.966	240	1.524

4.2 without air supply

300 RPM	
Time in min	Conc. (mg/l)
0	10
20	8.972
40	8.082
60	7.915
80	6.885
100	5.898
120	5.098
140	4.531
160	3.682
180	3.433
200	3.274
220	3.025
240	3.019

Table A7: Estimated concentration of VOC1 using CD-6 impeller at height H1

5.1 With air supply

250 RPM		300 RPM		350 RPM	
Time in min	Conc. (mg/l)	Time in min	Conc. (mg/l)	Time in min	Conc. (mg/l)
0	10	0	10	0	10
20	9.196	20	8.834	20	8.725
40	8.648	40	8.033	40	7.67
60	8.1	60	7.339	60	6.724
80	7.445	80	6.353	80	5.703
100	6.678	100	5.476	100	4.499
120	6.021	120	4.715	120	5.119
140	5.758	140	4.308	140	3.733
160	4.556	160	4.012	160	3.073
180	3.896	180	3.498	180	2.377
200	3.343	200	3.093	200	2.26
220	2.752	220	2.466	220	1.924
240	2.416	240	1.547	240	1.621

5.2 Without air supply

300 RPM	
Time in min	Conc. (mg/l)
0	10
20	9.168
40	8.461
60	7.299
80	6.342
100	5.757
120	5.339
140	4.548
160	3.965
180	3.381
200	2.589
220	1.88
240	1.709

Table A8: Estimated concentration of VOC1 using CD-6 impeller at height H2

6.1 with air supply

250 RPM		300 RPM		350 RPM	
Time in min	Conc. (mg/l)	Time in min	Conc. (mg/l)	Time in min	Conc. (mg/l)
0	10	0	10	0	10
20	9.067	20	8.933	20	8.044
40	8.403	40	8.223	40	6.845
60	7.295	60	7.291	60	5.47
80	6.454	80	6.05	80	4.985
100	5.342	100	5.213	100	3.835
120	4.773	120	4.111	120	3.218
140	4.693	140	3.316	140	2.558
160	3.678	160	2.655	160	2.032
180	2.972	180	2.261	180	1.726
200	2.224	200	1.778	200	1.245
220	1.743	220	1.517	220	1.03
240	1.708	240	1.218	240	1.037

6.2 without air supply

300 RPM	
Time in min	Conc. (mg/l)
0	10
20	9.082
40	8.331
60	7.538
80	6.577
100	5.614
120	4.486
140	4.108
160	3.229
180	2.642
200	2.264
220	1.968
240	1.839

Table A9: Estimated concentration of VOC2 using CD-6 impeller at height H1

7.1 With air supply

250 RPM		300 RPM		350 RPM	
Time in min	Conc. (mg/l)	Time in min	Conc. (mg/l)	Time in min	Conc. (mg/l)
0	10	0	10	0	10
20	9.203	20	8.782	20	8.529
40	8.363	40	7.312	40	7.69
60	7.398	60	6.516	60	6.64
80	6.097	80	5.847	80	5.759
100	4.797	100	4.588	100	4.794
120	4.297	120	3.582	120	3.912
140	3.796	140	2.786	140	3.115
160	3.084	160	2.453	160	2.572
180	2.709	180	2.12	180	2.114
200	2.461	200	1.914	200	1.739
220	2.13	220	1.624	220	1.641
240	1.926	240	1.503	240	1.319

7.2 Without air supply

300 RPM	
Time in min	Conc. (mg/l)
0	10
20	8.97
40	8.102
60	7.075
80	6.167
100	5.053
120	4.108
140	3.797
160	3.016
180	2.87
200	2.478
220	2.334
240	2.158

Table A10: Estimated concentration of VOC2 using CD-6 impeller at height H2

8.1 with air supply

250 RPM		300 RPM		350 RPM	
Time in min	Conc. (mg/l)	Time in min	Conc. (mg/l)	Time in min	Conc. (mg/l)
0	10	0	10	0	10
20	9.16	20	8.82	20	8.063
40	8.493	40	8.146	40	7.263
60	7.732	60	7.304	60	6.17
80	6.81	80	6.431	80	5.423
100	6.103	100	5.853	100	4.46
120	6.246	120	4.853	120	3.579
140	5.196	140	4.054	140	2.741
160	4.234	160	3.433	160	2.121
180	3.105	180	2.559	180	1.672
200	2.829	200	2.238	200	1.481
220	2.14	220	1.753	220	1.165
240	1.66	240	1.482	240	1.144

8.2 without air supply

300 RPM	
Time in min	Conc. (mg/l)
0	10
20	9.231
40	8.377
60	7.484
80	6.544
100	5.777
120	4.967
140	4.363
160	3.552
180	3.033
200	2.599
220	2.248
240	1.855

Table A11: Estimated concentration of VOC1 using BT-6 impeller at height H1

9.1 With air supply

250 RPM		300 RPM		350 RPM	
Time in min	Conc. (mg/l)	Time in min	Conc. (mg/l)	Time in min	Conc. (mg/l)
0	10	0	10	0	10
20	9.043	20	9.955	20	8.605
40	7.999	40	7.605	40	7.559
60	7.002	60	6.431	60	6.6
80	6.182	80	4.302	80	5.512
100	5.452	100	3.354	100	4.641
120	4.633	120	2.754	120	3.731
140	3.723	140	2.375	140	3.126
160	3.253	160	1.556	160	2.437
180	2.391	180	1.262	180	1.926
200	1.661	200	0.749	200	1.333
220	1.325	220	0.718	220	0.866
240	1.035	240	0.642	240	0.509

9.2 Without air supply

300 RPM	
Time in min	Conc. (mg/l)
0	10
20	9.123
40	8.331
60	6.997
80	5.744
100	4.331
120	2.954
140	2.769
160	1.991
180	1.72
200	1.576
220	1.221
240	1.032

Table A12: Estimated concentration of VOC1 using BT-6 impeller at height H2

10.1 with air supply

250 RPM		300 RPM		350 RPM	
Time in min	Conc. (mg/l)	Time in min	Conc. (mg/l)	Time in min	Conc. (mg/l)
0	10	0	10	0	10
20	8.861	20	8.312	20	8.48
40	8.229	40	7.384	40	7.51
60	7.301	60	6.246	60	5.907
80	6.247	80	5.149	80	4.727
100	4.392	100	4.054	100	3.549
120	3.216	120	3.467	120	2.288
140	3.011	140	2.963	140	1.704
160	2.002	160	2.041	160	1.076
180	1.669	180	1.455	180	0.828
200	1.378	200	1.165	200	0.705
220	0.961	220	0.706	220	0.498
240	0.839	240	0.416	240	0.413

10.2 without air supply

300 RPM	
Time in min	Conc. (mg/l)
0	10
20	9.115
40	8.017
60	6.874
80	5.688
100	4.906
120	3.946
140	3.64
160	2.903
180	1.95
200	1.468
220	0.952
240	0.886

Table A13: Estimated concentration of VOC2 using BT-6 impeller at height H1

11.1 air supply

250 RPM		300 RPM		350 RPM	
Time in min	Conc. (mg/l)	Time in min	Conc. (mg/l)	Time in min	Conc. (mg/l)
0	10	0	10	0	10
20	8.883	20	8.927	20	9.028
40	8.139	40	8.617	40	8.02
60	7.081	60	7.446	60	6.927
80	6.077	80	6.173	80	5.246
100	5.204	100	5.241	100	3.766
120	4.248	120	4.149	120	2.591
140	3.588	140	3.585	140	1.67
160	2.289	160	2.369	160	1.142
180	1.601	180	1.803	180	0.926
200	1.369	200	1.107	200	0.783
220	1.14	220	0.893	220	0.61
240	0.831	240	0.774	240	0.603

11.2 without air supply

300 RPM	
Time in min	Conc. (mg/l)
0	10
20	9.071
40	8.06
60	6.756
80	5.788
100	5.028
120	4.102
140	3.642
160	2.803
180	2.217
200	2.053
220	1.974
240	1.81

Table A14: Estimated concentration of VOC2 using BT-6 impeller at height H2

12.1 air supply

250 RPM		300 RPM		350 RPM	
Time in min	Conc. (mg/l)	Time in min	Conc. (mg/l)	Time in min	Conc. (mg/l)
0	10	0	10	0	10
20	8.866	20	8.319	20	8.274
40	8.206	40	7.147	40	7.307
60	7.202	60	6.24	60	6.131
80	6.064	80	4.85	80	5.339
100	6.292	100	3.76	100	4.202
120	5.201	120	3.269	120	3.198
140	4.327	140	2.818	140	2.106
160	3.456	160	1.938	160	1.49
180	2.495	180	1.657	180	1.001
200	2.175	200	1.121	200	0.685
220	1.517	220	0.717	220	0.619
240	0.739	240	0.609	240	0.595

12.2 without air supply

300 RPM	
Time in min	Conc. (mg/l)
0	10
20	8.913
40	7.822
60	6.657
80	5.826
100	5.164
120	3.819
140	3.154
160	2.66
180	2.166
200	1.588
220	1.436
240	1.497

Table A15: Specific power input (P/V) and K_La_{VOC} at height H1 using Rushton impeller

RPM	P/V	K_La_{VOC1}	K_La_{VOC2}
250	58.79	0.131	0.118
300	103.65	0.172	0.165
350	167.42	0.185	0.174

Table A16: Specific power input (P/V) and K_La_{VOC} at height H1 using CD-6 impeller

RPM	P/V	K_La_{VOC1}	K_La_{VOC2}
250	58.79	0.154	0.178
300	103.65	0.202	0.205
350	167.42	0.197	0.220

Table A17: Specific power input (P/V) and K_La_{VOC} at height H1 using BT-6 impeller

RPM	P/V	K_La_{VOC1}	K_La_{VOC2}
250	58.79	0.246	0.270
300	103.65	0.295	0.278
350	167.42	0.323	0.305

Table A18: Specific power input (P/V) and K_La_{VOC} at height H2 using Rushton impeller

RPM	P/V	K_La_{VOC1}	K_La_{VOC2}
250	58.79	0.167	0.132
300	103.65	0.187	0.176
350	167.42	0.187	0.184

Table A19: Specific power input (P/V) and K_La_{VOC} at height H2 using CD-6 impeller

RPM	P/V	K_La_{VOC1}	K_La_{VOC2}
250	58.79	0.192	0.195
300	103.65	0.228	0.207
350	167.42	0.246	0.235

Table A20: Specific power input (P/V) and K_La_{VOC} at height H2 using BT-6 impeller

RPM	P/V	K_La_{VOC1}	K_La_{VOC2}
250	58.79	0.269	0.283
300	103.65	0.345	0.303
350	167.42	0.346	0.306