The Effect of Electrical Field on CO_2 Adsorption and Desorption Using Fixed Bed

by

Shahrul Anuar bin Saat

Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
(Chemical Engineering)

JUNE 2004

Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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Approved by,

(Mrs. Suriati Binti Sufian)
Main Supervisor

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
May 2004

CERTIFICATION OF ORIGINALITY

This is to verify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

SHAHRUL ANUAR SAAT

ABSTRACT

CO_2 removal can be conducted via adsorption process. This project concentrate on the effect of electrical field on CO_2 adsorption and desorption process using fixed bed at different voltage. The main objective of this project is to study the effect of different voltages towards the adsorption and desorption process using a bench scale experiment setup. Literature study on the effect of polarizability of CO_2 and activated carbon towards the adsorption and desorption process was done. Further improvement on the existing bench scale experiment setup and experimental method has also been made.

The scope of study shall be conducting the bench scale experiment and literature review on the microscopic view (i.e polarizability) of the electrical enhanced adsorption and desorption. This includes improvement of the method and setup of the existing lab apparatus. The experiments conducted for the adsorption/ desorption process were using 2.5 mm and 1.5 mm size granular activated carbon (GAC). The experiment was also done under a 20 kPa CO_2 and N_2 flow for all the experiment. The results shows that variation in voltage affects the maximum uptake, rate of adsorption and rate of desorption of the fixed bed activated carbon.

As voltage increased, the maximum uptake of CO_2 gas in activated carbon and the rate of adsorption decreased, but the rate of desorption increased. For all three observed factors, the graph trend of 2.5 mm size GAC shows a higher value than the 1.5 mm GAC.

ACKNOWLEDGEMENT

I would like to express my greatest attitude and thanks to my supervisor Mrs. Suriati Sufian for her invaluable advice and supervision throughout the progress of the research. Thanks for your time, guidance and patience.

I would also like to dedicate this appreciation to my co-supervisor, Mrs Anis Suhaila Shuaib for her valuable ideas and suggestions, which contribute greatly to the successfulness of my research study.

I wish to thanks all the technical staffs within Chemical Engineering Department especially Mr. Zaaba, Mr. Jailani, Mr. Yusoff, Mr. Fauzi, Mr. Jamal, Mr. Mahadzir and Mr. Hasnizam who have been very co-operative in helping and sharing their expertise throughout the experimental work.

I would like to thanks all my friends who have been together contributing ideas and knowledge throughout this research study.

Finally, I dedicate this work to my parents for their support, encouragement and understanding throughout the course of this work.

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ABBREVIATIONS

ESA	Electrical Swing Adsorption
PSA	Pressure Swing Adsorption
TSA	Temperature Swing Adsorption
CFCMS	Carbon Fiber Composite Molecular Sieve
BET	Brunauer-Emmet-Teller
GAC	Granular Activated Carbon
PVC	Poly Vinyl Chloride
DC	Direct Current

NOMENCLATURES

CO_2	Carbon Dioxide
kPa	kilo Pascal
atm	Atmosphere (= 101.325 kPa)
yds	yards
R	Resistance of the material through which the current is passing
V	Volts (J/C)
I	Amperes (C/s)
μ	Dipole moment
α	Electric Polarizability
Q	Quadrapole moment
P	Power (J/s)
Q_{ad}	Heat of adsorption
t	time

r	Distance between interacting particles
v	Electronic absorption frequency
$\boldsymbol{\varepsilon_o}$	Absolute permittivity ($\varepsilon_o \equiv 8.854$ x 10-12 $C^2\ J^{-1}\ m^{-1}$)
C	Coefficient in the atom-atom pair potential
D	The distance between the two atoms
ρi	Number of atoms per unit volume of each body
A	Hamaker constant
$\mathbf{R_A}$	Radius of sphere
B	Energy of adsorption
E_1	Average heat of adsorption of the first layer
E_2	Heat of condensation

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Fossil fuels such as natural gas, refinery gas or coal gas generates huge quantities of carbon dioxide (CO_2) when employed for industrial and other chemical processes. Emission of CO_2 from these sources is considered as the major contributor towards global warming. A number of options currently exist to reduce CO_2 emissions, which one of them is by separating/removing and capturing the CO_2 prior emission and concentrate it for utilization or disposal.

One of the techniques proposed for the capture and removal of CO_2 includes physical adsorption. Currently, under the physical adsorption technology, two generic adsorptive process schemes for CO_2 removal have been developed. They include thermal swing adsorption (TSA) and pressure swing adsorption (PSA).

These process schemes has their own deficiencies and majorly based on two factors, which are operating cost via energy consumption and cycle rate. TSA and PSA prove to consume relatively high amount of operating cost as both technologies possess the need for interchangeable parameter of temperature or pressure throughout their process. The cycle rate for the temperature and pressure swing cycles are also relatively slow, thus impeding their capability for large amount of CO_2 removal when accounted per day.

A newly developed swing adsorption technology for CO_2 removal by using Carbon Fiber Composite Molecular Sieve (CFCMS) or activated carbon, which is still in the research phase, is called Electrical Swing Adsorption (ESA). It is foreseeable that ESA possesses the capability of reducing the operating cost for the swing adsorption process by not applying any form of heating and pressurizing. It also practically reduces the cycle period by reducing the desorption rate via applying a low voltage across the adsorbent. ESA releases the adsorbate by an electric current without heating. This mechanism may be due to Ohmic heating or disruption of the Van Der Waals attractive forces between the adsorbent and adsorbate. Further development on ESA is essential to produce a more effective and reliable process for CO_2 removal through swing adsorption. An internal preliminary study and experiment was done on the ESA emphasizing on the electrical enhanced adsorption and desorption. This study emphasize on the effect of electrical field on CO_2 adsorption and desorption using fixed bed at different voltages

1.2 Problem Statement

A study had been done on the CO_2 removal through electrical enhanced adsorption and desorption, but the experiment was only done based on a constant voltage value as its electrical source. No theoretical explanation or experiment had been developed pertaining the effect of various voltages towards the adsorption and desorption process. Thus, auxiliary study must be done in order to review the effect of different voltage towards the CO_2 adsorption and desorption process.

Parallel to this, literature study must also be done in order to theoretically explain how does electricity affect the adsorption and desorption process. This project is significant in order to attain the potential of electrical enhanced adsorption and desorption as to apply it in the electrical swing adsorption (ESA) process. The process is seen as a potential in the CO_2 removal and swing adsorption technology.

1.3 Objective and Scope of Study

The main objectives of the project are:

1.3.1 To study the effect of different voltage source towards the CO_2 removal in the Electrical Swing Adsorption (ESA) process. The study shall focus on the effect on adsorption and desorption rate of the CO_2, and the maximum CO_2 uptake by the activated carbon whilst using different set of voltage. A graph trend shall be produced to compare the result of the findings in the end of the study.

1.3.2 To study the effect of adsorbent's particle size towards the adsorption and desorption rate of the CO_2, and the maximum CO_2 uptake by the activated carbon when using electrical enhanced adsorption and desorption process.

The scope of the study will be limited to:

1.3.3 Conducting literature review on the polarizability of the adsorbent (activated carbon) and adsorbate (CO_2) and its effect towards the electrical adsorption and desorption process.

1.3.4 Conducting the experiment on the effect of different voltages towards the CO_2 adsorption and desorption rate and electrical swing adsorption and desorption cycle rate, and further enhance the existing laboratory scale ESA.

The timeframe given to for the project is 14 weeks. The scope of work have been distributed within this time and may be referred to the project's Gantt's Chart. Appendix 5.

CHAPTER 2

LITERATURE REVIEW AND THEORY

The latest offspring of the adsorption technology is the Electrical Swing Adsorption for CO_2 removal using CFCMS (carbon-based adsorbent) initially researched at Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6088, USA, through a bench scale experiment. Emphasized in this study is that by using the characteristic of carbon-based material, through an electrical enhancement, the CO_2 desorption rate can be shorten. "CFCMS has a continuous carbon skeleton which imparts electrical conductivity to the material. We have utilized the electrical properties of CFCMS to effect a rapid desorption of adsorbed gases in our breakthrough apparatus. The process has been named electrically enhanced desorption. Clearly, the desorption of adsorbed CO_2 can be rapidly induced by the application of a DC electrical potential." [4]

2.1 Physical Adsorption (Physisorption)

In theory, the adsorption process revolves around intermolecular forces between adsorbate and adsorbent surface areas. "Certain components of mixture, in this case, CO_2 are concentrated at the surface due to differences in the intermolecular forces of attraction between the components of the fluid mixture and solid. Adsorption is merely contacting the fluid mixture with the solid. Energy is released (exothermic) during the process of adsorption. Energy must be supplied to the adsorbed phase (endothermic) for the desorption process." [1]

Physical adsorption or physisorption is discussed in this chapter due to the fact that the adsorption process of CO_2 in activated carbon is in a form of physical adsorption. Thus, to understand more on the CO_2 gas adsorption process, physisorption is emphasized in this particular chapter.

All solid surfaces are energetically heterogeneous. This means that they consists of sites which differ in the strength with which they can interact with impinging molecules. Upon gas adsorption, it is the strongest surface sites that are populated first; weaker adsorption sites can only be filled with adsorbate in excess of that required to populate the strongest sites. When the interaction between a surface and an adsorbate is relatively weak even in the strongest sites, only physisorption takes place. Adsorbed molecules generally tend to form a monolayer surface which can interact further, albeit weakly, with additional adsorbate molecules to form multilayer.

Physisorption occurs when an adsorbable gas (the adsorptive) is brought into the contact with the surface of a solid. The intermolecular forces involved are the same kind as those responsible for the imperfection of real gases and the condensation of vapors. In comparison with chemisorption, in physical adsorption, the forces are relatively weak with bonding energy between 50-500 meV/atom, involving mainly van Der Waals induced dipole-induced dipole interactions between adsorbate molecules. "In addition to the attractive dispersion forces and the short range repulsive forces, specific molecular interactions (e.g polarization, field-dipole, field gradient-quadrapole) usually occur as a result of particular geometric and electronic properties of the adsorbate and adsorptive" [7].

Physisorption, other than having weak bonding, also has the property of reversible binding, which is important in a gas adsorption and desorption process, as the adsorbate gas can easily be purged from the adsorbate for regeneration process. Physisorption process occur near or below the adsorbate's critical temperature, which in this case the activated carbon. Physisorption of CO_2 on activated carbon occur on a very low heat of adsorption of approximately 30 kJ/mol, near to its heat of condensation and it is also non-activated, which means it has less adsorption at higher temperatures. Physisorption has the advantage of having multilayer adsorption that helps the activated carbon to have a higher adsorption capacity in adsorbing gas molecules. During physical adsorption, the gas molecules do not lose their chemical identity during the separation process.

2.1.1 Van Der Waals Forces

Van Der Waals forces are essential in the physisorption process as it is the main bonding between the adsorbate and the adsorbent. Van Der Waals acts as the main bonding between two uncharged or non-polar particles. "This behaviour indicates attractive interparticle force. This attraction arises from dipolar interaction: local fluctuations in the polarization within one particle induces correlated response in the others via the propagation of electromagnetic waves. Molecules that do not possess permanent dipole posses a non-zero instantaneous dipole moment because of fluctuations caused for instance by electromagnetic radiation." [2]

The next diagrams and formulas give the main interaction formulas for charged and uncharged particles, with different condition between the interactive particles and surface :

a) General non polar – non polar London dispersion energy

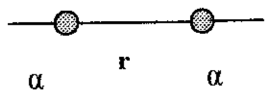

Figure 2.1 : Non polar – non polar molecule interaction

London dispersion energy = $-3hv\,\alpha^2/\,4(4\pi\varepsilon_o)^2\,r^6$

Where;

α = electric polarizability

r = distance between interacting particles

v = electronic absorption frequency (s^{-1}) i.e if I is the ionization potential, $I = hv$

ε_o = absolute permittivity (ε_o = 8.854 x 10-12 $C^2\,J^{-1}\,m^{-1}$)

b) Interaction between surfaces

Since adsorption and desorption process comprise of the interaction between the gas adsorbate molecules and a large surface, which is the surface of the activated carbon, the van der Waals interaction free energy between these surfaces is also calculated differently.

The three most important forces for the long range interaction between macroscopic particles and a surface are steric-polymer forces, electrostatic interactions and van de Waals forces. If we assume than the van der Waals interactions between two atoms in a vacuum are non-retarded and additive, then;

For a non retarded van der Waals interaction free energy, *w* between an atom and a flat surface;

$$w = \frac{-\pi C p}{6D^3} \qquad \text{Eqtn. 2.1}$$

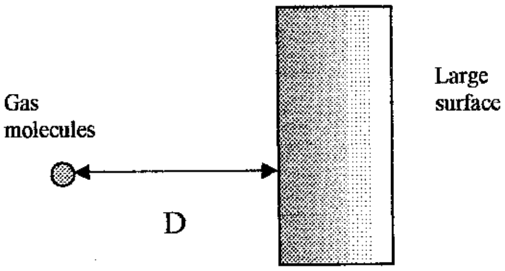

Figure 2.2 : Van der Waals interaction free energy, *w* between an atom and a flat surface

For a non retarded van der Waals interaction free energy, *w* between a molecule and flat surface;

$$w = -\left(\frac{A}{6D}\right)R \qquad \text{Eqtn. 2.2}$$

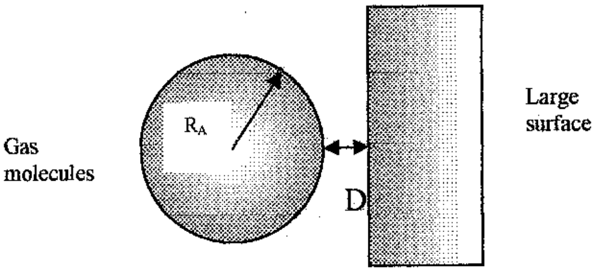

Figure 2.3 : Van der Waals interaction free energy, *w* between an molecule and a flat surface

Where;

C = coefficient in the atom-atom pair potential

D = the distance between the two atoms

ρi = number of atoms per unit volume of each body

A, Hamaker constant = $\pi^2 C \rho_1 \rho_2$

R_A = radius of sphere

2.1.2 Physisorption Potential

Physisorption potential is affected by the van der Waals potential for between molecules and affected by "image charge" potential for between surface and molecules with addition of electric polarizability, α affect.

a) Physisorption potential between molecules, V

$$V = -p_2 \cdot E_1 = -(\alpha_1 E_1) \cdot E_1 = -\alpha_1 (E_1)^2$$

where α = polarizability and E = dipole field

$$V \cong -\alpha \left(\frac{p_1}{r^3}\right)^2 = \frac{\alpha (p_1)^2}{r^6} \qquad \text{Eqtn. 2.3}$$

$$\Rightarrow \quad V \propto -\frac{1}{r^6} \quad \text{van der Waals potential}$$

b) Physisorption potential between molecules and surfaces, V

While for the physisorption potential between molecules and surfaces, V;

$V \propto -\frac{1}{z^3}$ (lowest order term for image-charge attraction)

From both equation in (b), physisorption potential for the CO_2 adsorption in activated carbon can be increased by increasing the image-charge attraction.

2.2 Adsorption and desorption mechanism

In order to have supplementary understanding on the electrical enhanced desorption process, basis knowledge on the adsorption and desorption process has to be firstly understood. Thus, in this segment, we shall look into the factors that may contribute towards better adsorption and desorption, and in the end, relate them with the function of electricity in the adsorption and desorption process. Questions of how electricity contributes towards better desorption will be discussed later in this stage.

2.2.1 Adsorption energy, heat of adsorption and surface area

Activated carbon adsorbs CO_2 gas molecules because there is a reduction in the surface energy of the activated carbon when adsorption takes place. This reduction in energy is adsorption energy and is released as heat when adsorption takes place. As a general rule, the heat of adsorption increases as the size of the molecule increases. For most activated carbons, adsorption is more efficient with non-polar molecules. Molecules with greater adsorption energy displace molecules of lower adsorption energy. The theory is best explained by two adsorption models, which are Langmuir Model and BET (Brunauer-Emmett-Teller) Model.

Langmuir Model, "originally developed for adsorption of gases onto solids, is predicted on the assumptions that adsorption energy (heat of adsorption) is constant and independent of surface coverage; that adsorption occurs on localized sites with no interaction between adsorbate molecules, an that maximum adsorption occurs when the surface is covered by a monolayer of adsorbate." [3]. Further extended by BET Model using multi-layer adsorption phenomena, "assumptions made by BET Model are that any given layer need not be complete before subsequent layers can form, that the first molecules adhere to the surface with an energy comparable to the heat of adsorption for monolayer attachment, and that subsequent layers are essentially condensation reactions." [3] In a constant expressive of the energy of adsorption, B such that

$$B = \left(\frac{d_2 c_1}{d_1 c_2} \right) e^{\left[(E_1 - E_2) / RT \right]} \qquad \text{Eqtn. 2.4}$$

where E_1 is the average heat of adsorption of the first layer, E_2 is the heat of condensation and d_2c_1/d_1c_2 is the ratio of evaporation-condensation coefficients for the adsorbed layers and often is nearly equal to unity.

Understanding the energy of adsorption is essential in explaining the amount of energy required to desorb CO_2 gas from activated carbon using electricity. As explained by Shivaji Shircar, desorption is an endothermic process. As discussed earlier in this chapter, electrical energy is converted to heat energy via Ohmic heating to supply energy to the adsorbate, CO_2 during the desorption process. The amount of heat energy needed is the same as the energy of adsorption of the process.

"The forces responsible for physical adsorption of a gas to a solid are "London dispersion" forces. These are weak attractive forces. Coulombic forces may also be involved if either the solid or gas is polar in nature. Because of the weak nature of these bonds the heat of adsorption of CO_2 on an activated carbon is rather low at 30kJ/mol. Consequently, the energy required to desorb the CO_2 from CFCMS, or any activated carbon, is small. Indeed, in a CO_2 scrubber associated with a 10 kW alkaline fuel cell, the regeneration power requirement for both air and fuel gas streams can be estimated to be of the order of 50W per regeneration cycle." [8].

2.2.2 Polarity of adsorbent and adsorbate

Adsorbate also has a contributing factor towards better adsorption and desorption. "They include concentration, molecular weight, molecular size, molecular structure, **molecular polarity**, steric form or configuration, and the nature of background or competitive adsorbates." [3]. Highlighted in the statement is the polarity of the adsorbate molecules. A molecule is said to be polar if it centers of negative and positive charge do not coincide. One end of a polar molecule has a slight negative charge and the other a slight positive charge. The negative end of one polar molecule and the positive end of another attract each other. Polar molecules are therefore attracted to ions. Whenever two electrical charges of equal magnitude but opposite sign are separated by a distance, a dipole is established. The size of a dipole is measured by its dipole moment, denoted μ.

CO_2 is a non-polar molecule, as the overall dipole moment of the CO_2 molecule, $\mu = 0.00$. Although, both C-O bond is polar, the CO_2 molecule is not polar. Bond dipoles and dipole moments are vector quantities; that is, they both has a magnitude and a direction. The two bond dipoles in CO_2, although equal in magnitude, are exactly opposite in direction. The result of adding them together is zero. Therefore the overall dipole moment of CO_2 is zero. Molecules with mirror symmetry like oxygen, nitrogen, carbon dioxide, and carbon tetrachloride have no permanent dipole moments. Even if there is no permanent dipole moment, it is possible to induce a dipole moment by the application of an external electric field. This is called polarization and the magnitude of the dipole moment induced is a measure of the polarizability of the molecular species. Polarizability is the relative tendency of the electron cloud of an atom to be distorted from its normal shape by the presence of a nearby ion or dipole--that is, by an external electric field. Values are reported in cubic Angstroms (units of 1 E-24 cm^3).

As CO_2 is basically a non-polar molecule, thus the intermolecular attraction that exists for CO_2 is London Dispersion or induced-dipole/induced-dipole interactions. Although there is also an opinion that "CO_2 the leading term is supposed to be the permanent quadrupole-permanent quadrupole interaction, a simple electrostatic force" [9]. The electric properties of a CO_2 molecule are :

Polarizability, $\alpha \times 10^{40}$ ($C^2.m^2 / J^a$) = 3.02
Dipole moment, $\mu \times 10^{30}$ ($C.m^b$) = 0.00
Quadrepole moment, $Q \times 10^{40}$ ($C.m^{2c}$) = -13.71

This properties of α, μ and Q are used to allow accurate qualitative predictions to be made on the strengths of the adsorption of given molecules on an adsorbent. A non-polar adsorbate, the activated carbon has a high-tendency to adsorb more non-polar molecules rather than polar molecules. CO_2 molecules is more adsorbed by activated carbon than any other adsorbents as the molecules have a higher polarizability than other type of molecules. Other than having a non-polar surface area, activated carbon also have more surface area and more surface free energy (surface tension). As described by Gibbs Model but alternately using water as the adsorbent surface area, "most non-polar substances tend to reduce the interfacial tension of water by accumulating at a phase boundary and increasing the area of the interface, as this is energetically preferable to other means of achieving equilibrium" [3].

2.3 Electrical enhanced desorption

"The continuous nature of the monolith's structure imparts electrical conductivity to the material and thus allows for adsorbent regeneration via direct electrical heating. Thus a separation system in which separations are effected by swinging electrical current, rather than pressure or temperature, on an adsorbent bed can be envisioned. Such a process has been named electrical swing adsorption (ESA)" [4].

Activated carbon has a structure which allows electricity to flow through it, thus electrical heating or also known as Ohmic heating can be done to enhance the desorption process in an adsorption and desorption process. Electrical desorption acts similar to the thermal desorption as both supply heat to the adsorbent bed. The theory behind both applications is that the equilibrium extent or the capacity of adsorption is generally found to decrease as the temperature increases due to energy from heating, thus conversely increasing the desorption capability. **"However, electrical desorption is more efficient than thermal desorption (in TSA for**

example) because the heat is generated from within the carbon and not from an external source such as a hot purge gas or external bed heaters" [4].

Further prove was done by Burchell through the electrical enhanced desorption experiment, which included three cycles. " **In the first and second cycles (A and B) desorption is caused by the combined effect of an applied voltage (1V) and He purge gas. In the third cycle (C) desorption is caused only by the He purge gas. A comparison of cycles B and C indicated that the applied voltage reduces the desorption time to less than third of that using only the He purge gas (cycle C). Clearly, the desorption of adsorbed CO2 can be rapidly induced by the application of a DC electrical potential."** [4].

In the desorption process, electricity is used to supply energy towards the adsorbed phase via heat energy. This energy is used to break the London Dispersion bonds between the adsorbate and the adsorbent and known as the desorption energy, which is equal to the adsorption energy. As the heat of adsorption for CO_2 on activated carbon is low, the amount of electricity needed as the source of energy is also comparatively low in order to have an electrical enhanced desorption to occur.

2.3.1 Ohmic heating

Ohmic heating is a newly developed alternative for heating. Currently being used in the food sterilization industry, Ohmic heating is different from other mean of heating techniques as it applies direct heating, in which heat is generated within the material itself. Ohmic heating uses the inherent electrical resistance of a material to generate heat and depend highly on the electrical conductivity of the material. Activated carbon has a very high electrical conductivity, hence allowing Ohmic heating to be applied in the desorption process.

Ohmic heating behavior is different from conventional heating behavior. Whereas with conventional heating methods liquids heat faster than solids, a surprising result with Ohmic heating is that the reverse can occur. Even for a single particle in a liquid, the heating rate is a function of particle shape and particle orientation to the applied electric field.

As a completely independent process, Ohmic heating or Joule heating is simply given by the total power, ***P*** dumped into the desorption system via

$$\mathbf{P} = I^2 R = \frac{V^2}{R} \qquad \text{Eqtn. 2.5}$$

with V = voltage applied, R = total serial resistance of the system and I = electrical current.

When voltage is applied to the adsorbent, and by using a theoretical assumption that all electrical energy is converted to Ohmic energy or thermal energy, and all Ohmic energy is being transferred to the gas adsorbate, we can relate that:

Power in heat form = Power in electrical form

$$\frac{Q_{ad}}{t} = \frac{V^2}{R} \qquad \text{Eqtn. 2.6}$$

with Q_{ad} = heat of adsorption, and t = time taken for desorption

A conclusion can be made that if the voltage, V applied to the adsorbent increased the amount of heat energy being transferred to the adsorbent increases and by having a constant heat of adsorption or desorption, Q_{ad} the time, t will be decreased. In the desorption point of view, the desorption rate will be increased as the voltage applied is increased. Implicit in this calculation is the assumption that all of the electrical energy is converted to thermal energy and transferred to the adsorbed CO_2 for desorption purposes.

"Evidently, the resistance heating effect is acting directly at the desorption sites (fibre microporosity) resulting in a rapid desorption of the adsorbate." [4]

CHAPTER 3
METHODOLOGY AND PROJECT WORK

Methodology and procedure is important to ensure that the project/ experiment is done correctly and good result can be obtained at the end of the project/ experiment. Emphasize was given to the detail study on the electricity effect on the adsorption and desorption mechanism of CO_2 in activated carbon. The methodology and procedure to conduct the research is divided into four main parts:

3.1 Literature Review and Information Gathering

Information regarding the Electrical Swing Adsorption process, and adsorbent and adsorbate polarizability characteristics are gathered referring to respective books, journals and thesis developed by external and internal parties. All the information are skimmed and selected based on importance and relevancy. The relevant information is studied thoroughly and example data for future references.

3.2 Laboratory Work

Laboratory work covers the preparation of activated carbon, preparation of experiment setup for electrical enhanced adsorption process, leak and electrical circuit test, adsorption experiment using different voltage and desorption experiment using different voltage. Detail experimental procedure shall be discussed further below.

3.2.1 Scope of the Experiment

Based on the experiment title and the overall objective of the project, the scope of the experiment is to:

a) Attain the effect of different electrical voltage towards the adsorption and desorption process (uptake and rate of adsorption and desorption).
b) A trend of adsorption and desorption rate vs. voltage shall be obtained by the end of the experiment.
c) A trend of maximum uptake vs. voltage shall be obtained at the end of the experiment.
d) To attain the effect of electrical enhanced adsorption and desorption at different size of activated carbon.

3.2.2 Experimental Apparatus and Chemicals

In order to conduct the experiment, the apparatus and chemicals needed are prepared as listed below, in the next page:

Table 3.1: List of equipments/glass wares/chemicals/others for experiment purposes

NO	EQUIPMENTS/GLASSWARE/OTHERS	SPECIFICATIONS	QUANTITY
Electrical equipments :			
1	Regulated DC Power Supply	Range (0-25V),3.5A	1
2	Mili Ammeter	Range (0-30mA)	1
3	Voltmeter	Range (0-10V)	1
4	Electrical Wire Connector	75 cm	5
5	Copper wire	1 m	2
Other Equipments :			
6	Digital Mini Manometer	Range (0-3000kPa)	1
7	Digital Thermometer	Max 600 deg C	1
8	Digital Balance	Max 3100 deg C	1
9	Vacuum Oven	Max 1000 deg C	1
10	Variable size of tubing (SANG POLYUTHERENE TUBE)	6 x 4 mm	3 m
11	T-Junction	-	5
12	Petri Disc	-	8
13	Spatula	-	1
14	PVC Tape	7 yrds x (1 x 0.13)mm	1
15	Aluminum Foil	-	1 roll
Chemicals:			
16	Purified CO_2	99.99 % purity	1 cylinder
17	Purified N_2	99.99 % purity	1 cylinder
18	Charcoal Activated Carbon	2.5 mm (particle size)	1 kg
19	Charcoal Activated Carbon	1.5 mm (particle size)	1 kg

3.2.3 Type/List of Experiments

Table 3.2: List of experiments with Different Granular Activated Carbon Size and Different Adsorption/ Desorption Voltages

Experiment No.	Granular Activated Carbon Size (mm)	Adsorption Voltages (V)	Desorption Voltages (V)
1	2.5	5	0.3
2	2.5	8	0.5
3	2.5	10	0.6
4	2.5	15	1.0
5	2.5	20	1.5
6	1.5	5	0.3
7	1.5	8	0.5
8	1.5	10	0.6
9	1.5	15	1.0
10	1.5	20	1.5

3.2.4 Experimental Procedure

A. Preparation of activated carbon

1) 8 Petri discs with its cover is weighted using the digital balance.
2) The activated carbon (particles size 2.5 mm) is filled into each disc and (the disc with the activated carbon) is weighted again.
3) All the discs with activated carbon are put into the oven at 100 C for 24 hours.
4) After 24 hours, the discs are taken out from the oven and its weight is recorded.

   (Caution : The disc cover must be properly closed to avoid any contamination)
5) The activated carbon in the petri discs are then kept in the desiccators to be used later.

B. Preparation of experiment setup for electrical enhanced adsorption process

1) The experiment setup as shown in appendix 3 is prepared.
2) The tubing connection is connected from CO_2 and N_2 gas cylinder to the digital mini manometer (P1 and P2), digital pressure differential gauge (PD) and the activated carbon cylinder in order to have continuous flow of CO_2.
3) The tubing at the end of digital manometer (P2) is left open for venting purposes.
4) The electrical connection is connected from positive terminal of the DC power supply with the copper wire going through the tubing in between the inlet of the activated carbon cylinder and the tee junction of PD. The electrical connection ends at the activated carbon cylinder.

   (Caution: The copper wire is ensured to touch a bit of the activated carbon to enable the activated carbon to conduct electricity from one end to the other)

5) The electrical connection is continued from the other end of the activate carbon, and the wire going out from the tube in between the inlet of the activated carbon cylinder and the tee junction of PD (Appendix 3). The electrical connection goes through the ammeter, voltmeter and back to the negative terminal of the DC power supply for a continuous electrical circuit flow through the activated carbon.
6) The digital thermometer is placed at the 150 ml cylinder as shown in appendix 3 and all connections are tightened. **(Caution : The 150 ml cylinder (column) must be wrapped with aluminum before experiment is done to avoid water drops to appear on the column's wall due to condensation)**

C. Electrical and Leak Circuit Test

1) The 150 ml cylinder is filled with the activated carbon and the digital thermometer (T1) is placed as shown in the appendix 3.
2) The voltmeter and ammeter reading is monitored after the DC power supply is switched on. (The electrical circuit connection is checked (positive and negative pole) if there is no reading form both voltmeter and ammeter.)
3) After the electrical check is done, the tubing connection is checked from any leakage by using soap solution.
4) The soap solution is put to all tube connection and the CO_2 gas valve is open until the PI = 25 kPa. (The max required gas flow for the experiment)
5) While the gas is flowing the connection is monitored for any bubble formation.
6) If any leakage found the connection the connection must be tighten up to avoid the gas leakage and error in the experiment.

(Caution : From this point forward, the experiment shall be done in a well ventilated room as to prevent any gas hazards i.e. asphyxiation, the doors shall always be opened)

D. Pre-experiment preparation : Activated Carbon Heating and Purging

1) Continue from step 6 from section C, the digital mini manometer (P1 and P2), digital pressure differential gauge (PD), digital thermometer (T1) and the balance are switched on.
2) The balance is set to zero.
3) The power supply is switched on and is set at 5.0 V. The voltmeter and mili ammeter are ensured to give some readings correspond to the power supply voltage.
4) The N_2 gas cylinder valve is opened (P1 = 20 kPa; keep constant at this value) to let the purge gas flow through the activated carbon.

(Note : Activated carbon purging using N_2 gas and electrical source is important to get a highly generated activated carbon, free from CO_2. The purging process is done in between 15 – 20 minutes prior to every adsorption/desorption experiment)

E. Adsorption experiment using DC current of 10.0 V.

1) Continue from step 4 from section D, the digital mini manometer (P1 and P2), digital pressure differential gauge (PD), digital thermometer (T1) and the balance are still in switched-on mode.
2) The balance is set to zero.
3) The power supply is still in switched-on at 5.0 V. The voltmeter and mili ammeter are again ensured to give some readings correspond to the power supply voltage.
4) The CO_2 gas cylinder valve is opened (P1 = 20 kPa; keep constant at this value) to let the gas flow through the activated carbon.
3) The P1, P2, PD, T1, Voltmeter, Mili Ammeter and balance reading is recorded for 50 minutes.

F. Desorption experiment using DC current of 0.3V and Nitrogen purge (continue from step D).

1) The CO_2 gas cylinder valve is closed and the N_2 cylinder gas valve is opened (P1 = 20 kPa).
2) The DC supply is switched on and is set to 0.3V.
3) The P1, P2, PD, T1, Voltmeter, Mili Ammeter and balance reading is recorded until the balance give almost constant value (about 25 minutes).
4) After 25 minutes, the experiment is stopped and all the equipments are switched off.

(Note: Experiments D, E and F will be repeated with different sets of voltage values, the voltage is determine in the experiment. In every experiment, a new activated carbon shall be used, refer Table 3.2)

G. Electrical enhanced adsorption and desorption using 1.5 mm particle size granular activated carbon

1) Steps A to F is repeated again using granular activated carbon (GAC) with particle size of 1.5 mm.
2) The graphs uptake (mass of CO_2 adsorbed (mg) / mass of activated carbon bed (g)) vs. time is plotted. Also known as adsorption/desorption hysteresis.
3) All the derived graphs below are plotted both for 1.5 mm GAC and 2.5 mm GAC:
    i. Adsorption maximum uptake vs. voltage graph
    ii. Adsorption rate vs. voltage graph
    iii. Desorption rate vs. voltage graph

3.2.5 Data Analysis and Comparison

All the graphical results obtained from experiment is analyzed and discussed by referring to the Ohmic heating theory behind electrical enhanced adsorption and desorption process. The trends of the adsorption and desorption based on the different voltages are taken for trend comparison.

3.2.6 Report Preparation

The report for the research is prepared as part of the requirement for the course. Apart from that, the report also serves as the reference for future study on the respective field.

3.3 Tools Required

3.3.1 Experimental Apparatus and Chemical

Refer to the experimental apparatus in table 1.

3.3.2 Software

Microsoft EXCEL is used to present the experimental results in form of tables and graphs for analysis and discussion purposes.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter presents the results from the experiments and the analysis of the findings. Discussion on the subject matter is also emphasized to get a better view of the findings from the experiments.

4.1 Experimental data

4.1.1 Data collection

The following data were obtained during the experiment and tabulated as follow:

4.1.1.a Mass of Activated Carbon for Each Experiments

For every experiments, the mass of activated carbon in the column is taken for uptake calculation purposes. The mass data is as below:

Table 4.1 : Mass of pre-heated activated carbon in fixed bed column

Experiment No.	Granular Activated Carbon Size (mm)	Adsorption Voltages (V)	Desorption Voltages (V)	**Mass : Activated Carbon (g)**
1	2.5	5	0.3	**76.99**
2	2.5	8	0.5	**77.62**
3	2.5	10	0.6	**83.79**
4	2.5	15	1.0	**75.19**
5	2.5	20	1.5	**90.07**
6	1.5	5	0.3	**85.16**
7	1.5	8	0.5	**83.62**
8	1.5	10	0.6	**84.37**
9	1.5	15	1.0	**84.94**
10	1.5	20	1.5	**87.21**

4.1.1.b Adsorption and Desorption Data

Adsorption and desorption data are data that was obtained during the experiments. The data taken were time, weight, temperature (T1) and pressure (P1 and P2), Tabulated raw data for all experiments can be referred in appendix 1.

4.1.2 Observations

1. The voltmeter and ammeter gave constant readings throughout the experiment for each different values of voltages. Below are the values of current corresponding to its voltages for the experiment.

Table 4.2 : Corresponding Electrical Current against Electrical Voltage

Voltage, V (V)	Current, I (mA)	Voltage, V (V)	Current, I (mA)
5.00	0.50	**0.30**	0.04
8.00	1.00	**0.50**	0.10
10.00	1.80	**0.60**	0.20
15.00	2.70	**1.00**	0.20
20.00	3.70	**1.50**	0.20

2. The pressure difference also gave a constant value throughout the experiment but sometimes fluctuate at ± 3 kPa (Appendix 1: Tabulated raw data)
3. The CO_2 and N_2 gases used in the experiments gave cooling effect to the activated carbon.
4. The experiment measurements data especially mass data fluctuates since the mass balance is very sensitive to any disturbance from surrounding.
5. All adsorption process achieve maximum adsorption capacity or maximum uptake at about the same period of time, which is at 10 to 15 minutes.

4.2 Assumptions and Limitations

1. The experiment was conducted in an ambient conditions where the atmospheric pressure was assumed to be at 1 atm and the ambient temperature was at 27 °C (air condition room) when the experiments were conducted.
2. The experiment was done under a constant CO_2 flow as a constant factor in the experiment. Assumed in the experiment that there was no leakage during the experiments.
3. Volume of the activated carbon used for the experiment was assumed to be 150 ml, which is the same as the volume of the column with the mass reading was at minimum, 76.99 g and maximum at 90.07 g (please refer to Table 4.1)
4. The activated carbon was assume to obey Ohm's Law (current is proportional to voltage) and all the electrical energy is assumed to be converted to thermal energy and transferred to the adsorbed.
5. The straight slope line in determining the rate of adsorption/desorption in the graphs are taken at point where the adsorption/desorption starts until 4 to 5 points where the adsorption/desorption is stable or constant. The value of rate of adsorption/desorption is taken from the slope value taken from the equation developed from the straight line.
6. The concentration of adsorbate (CO_2) for the electrical enhanced adsorption/desorption experiment used is 99.9% CO_2 purity. It is not the same as the industrial application for CO_2 adsorption processes that usually present at small concentration. Pure CO_2 is used for simplicity of the research/experiment.
7. Since there is still no established equipment for the electrical enhanced adsorption/desorption analysis, the adsorption/desorption trend is only monitored using balanced mass balance equipment, which is not accurate. The adsorption has been observed evidence by an increased in the mass and desorption by the decrement of the weight. The steady state is assumed when the weight fluctuates at certain constant range.

4.3 Adsorption of CO_2 at Different Voltage

The CO_2 adsorption into 2.5 mm sized activated carbon process were obtained from the experiments. This subchapter shall discuss on the effect of different voltages towards electrical adsorption.

4.3.1 Adsorption Data

There were 5 adsorption experiments completed by using 2.5 mm activated carbon as the adsorbent. Below are the graphical data obtained from these experiments. The adsorption voltage used range from 5 V to 20 V. Relatively high voltages are used to obtain better difference of effect for different voltages towards the adsorption. The equations for the straight line from the graphs are used to obtain the values of average rate of adsorption for every graphs. The slope value from the equation is the value of rate of adsorption.

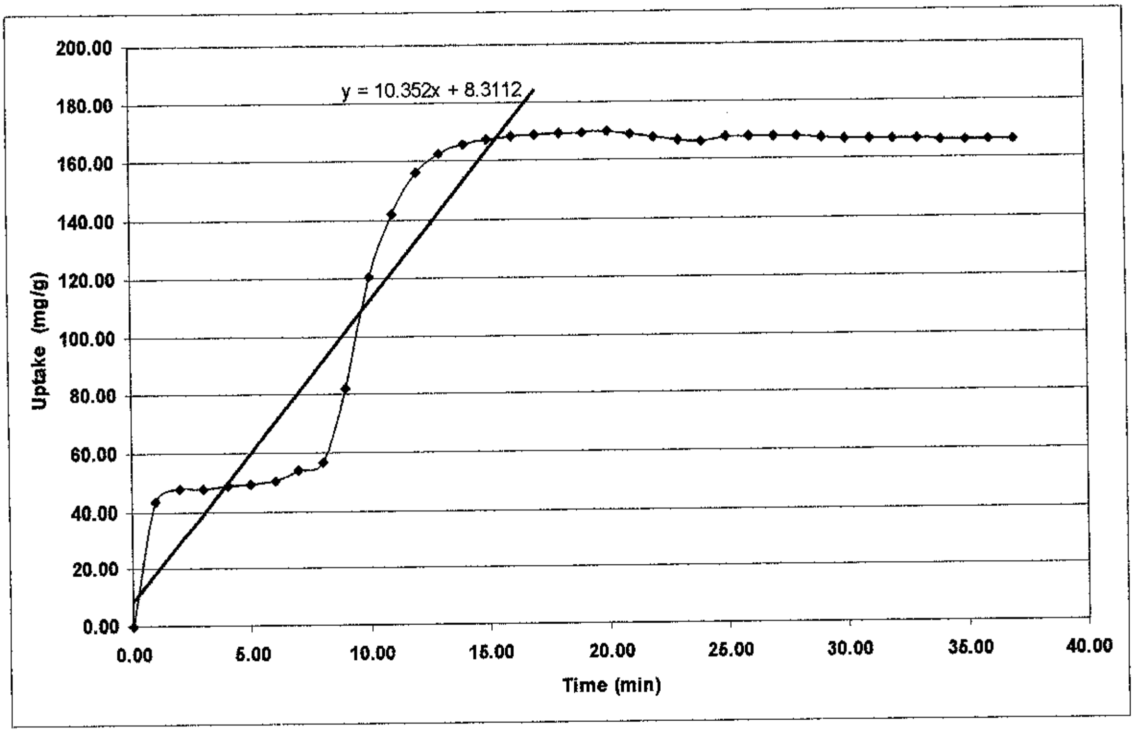

Figure 4.1 : Exp 1 ; 5 V adsorption

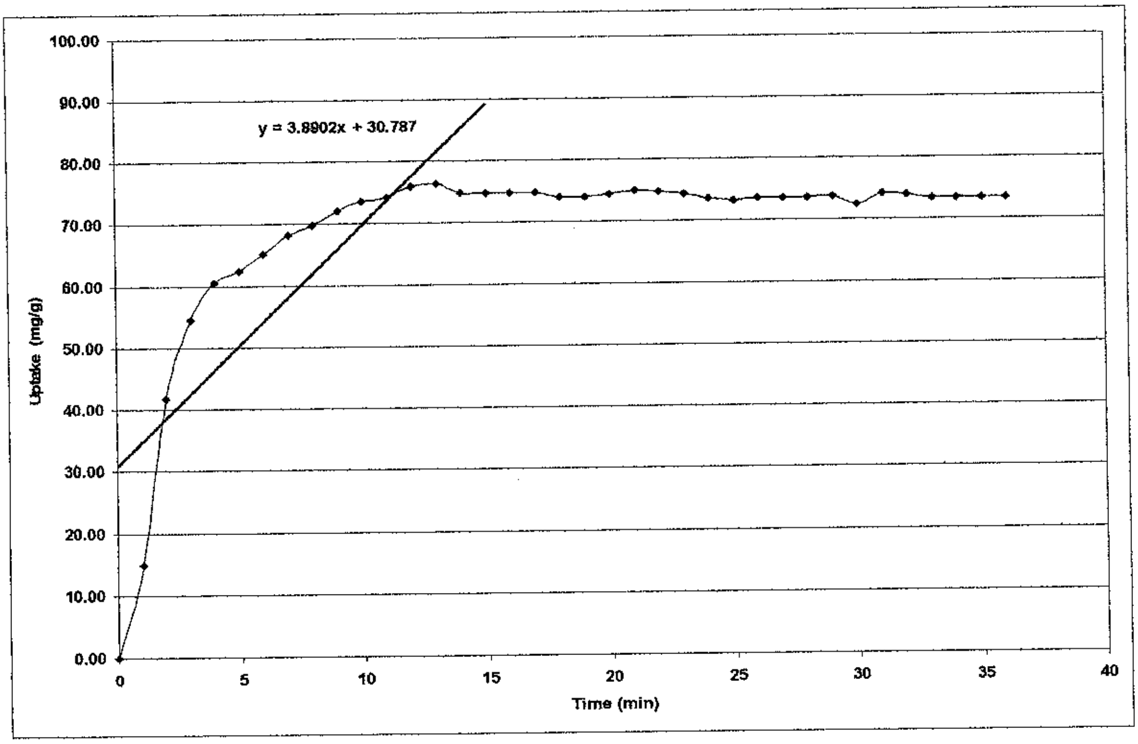

Figure 4.2 : Exp 2 ; 8 V adsorption

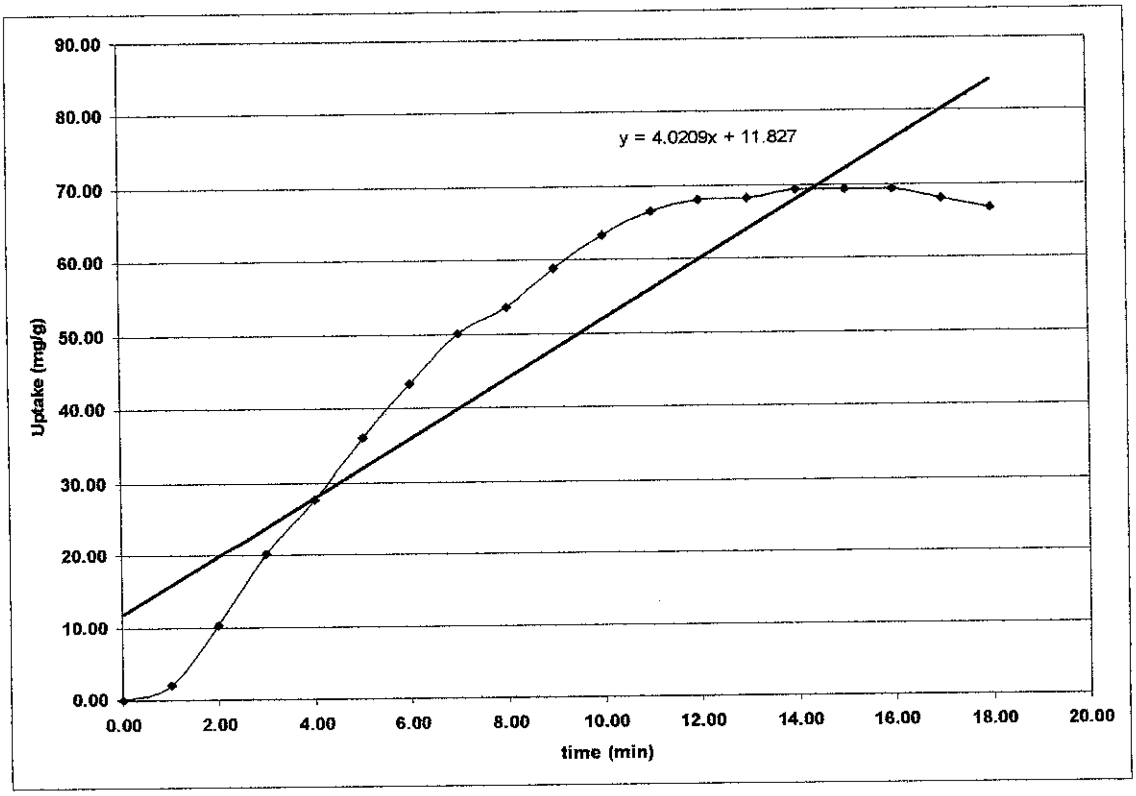

Figure 4.3 : Exp 3 ; 10 V adsorption

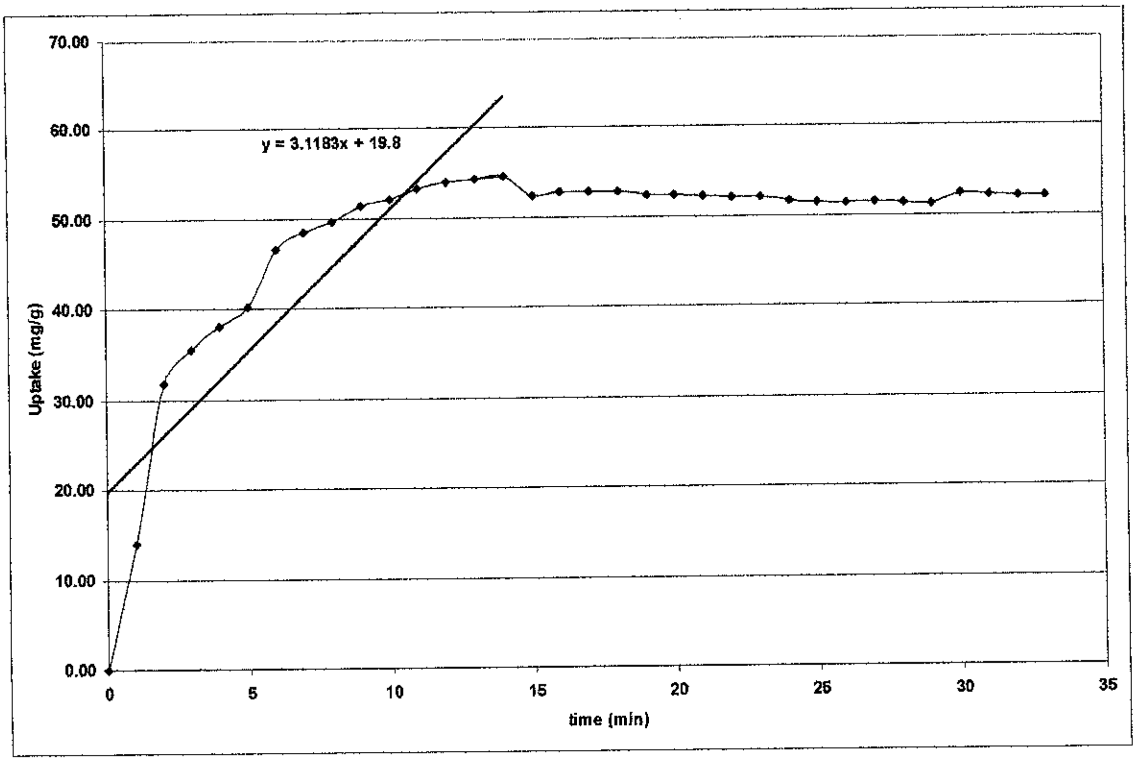

Figure 4.4 : Exp 4 ; 15 V adsorption

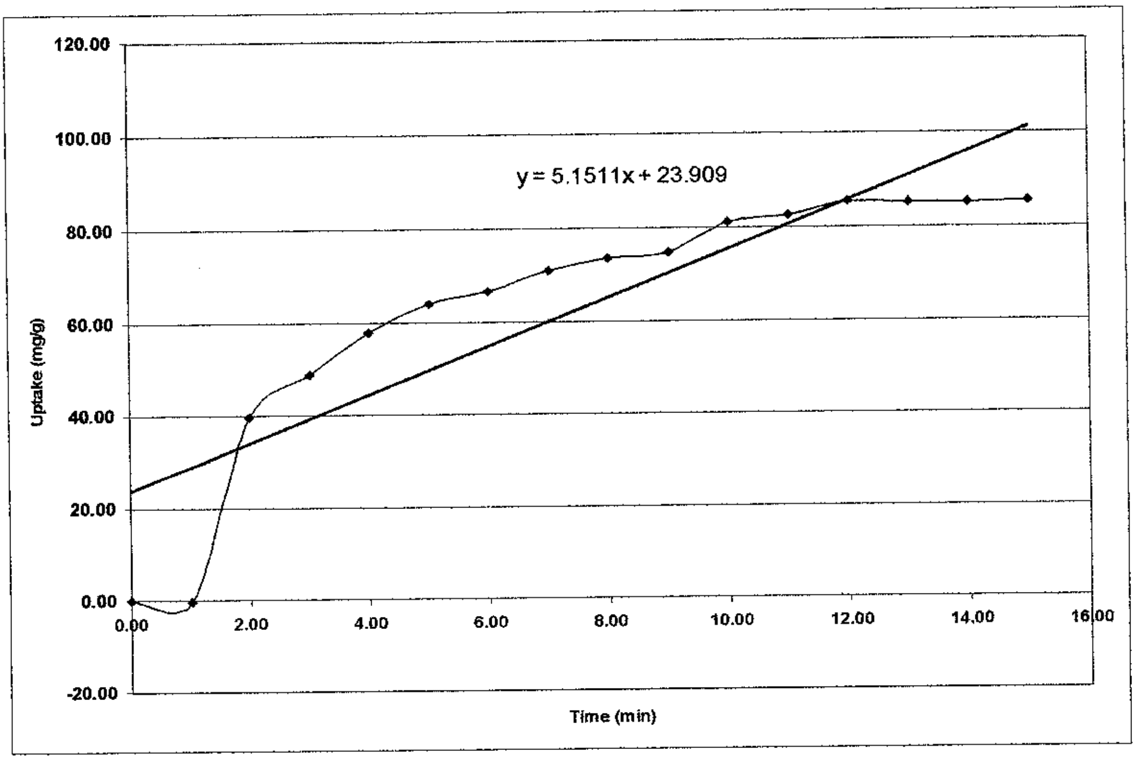

Figure 4.5 : Exp 5 ; 20 V adsorption

Form the graphs obtained in each experiments in figure 4.1, 4.2, 4.3, 4.4 and 4.5, a similar adsorption curve is attained. For each experiment, during the adsorption process, the mass trend is increasing, fluctuating and stabilizes at approximately adsorption time equals to approximately 15 minutes. This trend apply to all of the adsorption curve in each experiment, thus concluding that the approximate time taken for the activated carbon to attain maximum CO_2 capacity or maximum CO_2 uptake is approximately 15 minutes. The figure below shows the average adsorption trend for experiments 1 to 5.

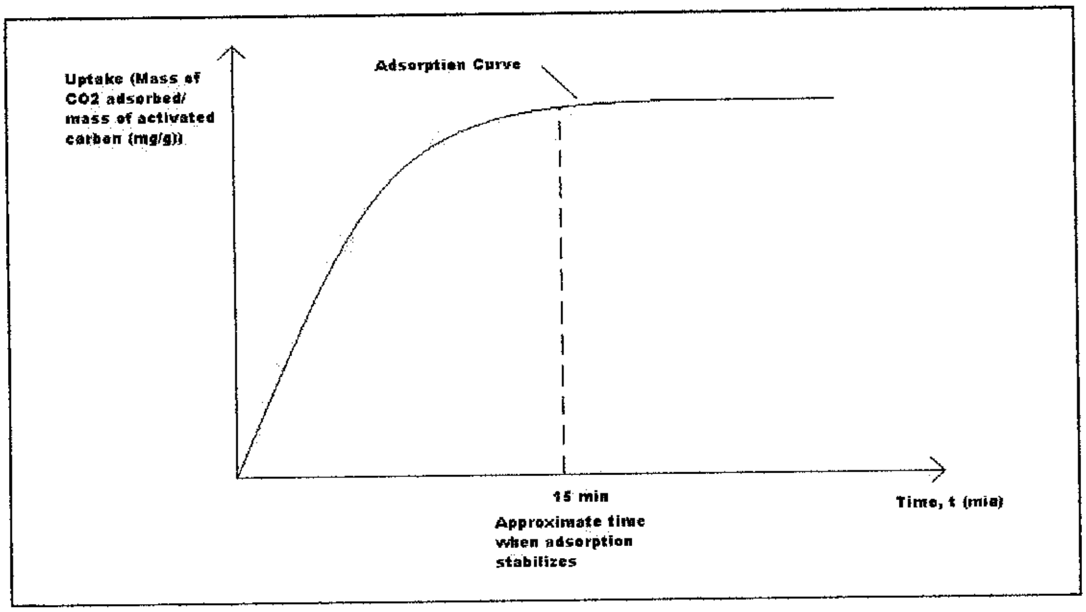

Figure 4.6 : Average adsorption curve trend

The adsorption curve starts at zero and incline rapidly with a high initial slope in the curve line. Average rapid inclination for every adsorption curve starts at time equals to zero and ends approximately at time of adsorption equals to 10 minutes. The slope of the curve then decrease gradually until there is no more increment in the slope and the reading points become constant at approximately adsorption time of 15 minutes.

The data fluctuation is believed to be due to sensitivity of the open balance used for the experiment. The values of maximum CO_2 uptake by the activated carbon also might not be accurate. This is because of the experiments for the adsorption process were only done under a limited amount of time due to time constraint. The process may need a longer period of adsorption time in order for the adsorbed phase to be in equilibrium with the gas phase. Still, the experiments are still valid because a stable horizontal uptake trend could still be obtained for maximum uptake comparison purposes.

Using the graphs obtained, the maximum uptake and the rate of adsorption from each experiments were calculated. Below is the tabulated summary of rate of CO_2 adsorption and maximum uptake of by the activated carbon.

Table 4.3 : Rate of CO_2 Adsorption and Maximum CO_2 Uptake Summary

EXP	Adsorption voltage (V)	Maximum Uptake (mg/g)	Rate of Adsorption ((mg/g)/min)
1	5.00	169.76	10.3520
2	8.00	76.27	3.8902
3	10.00	69.46	4.0209
4	15.00	54.53	3.1183
5	20.00	85.38	5.1511

4.3.2 Maximum CO_2 Uptake in Adsorption at Different Voltage

The uptake is measured by taking the mass of the CO_2 adsorbed in miligram (mg) divided by the mass of the activated carbon bed in gram (g). Thus, the unit for uptake is mg/g. Maximum uptake is the highest amount of uptake achievable during the adsorption process with respect to the adsorption voltage used in that particular experiment. Adsorption voltage is the voltage applied to the granular activated carbon (GAC) during the adsorption process. The summary of the maximum uptake for all 5 experiments using 2.5 mm GAC is as graph below:

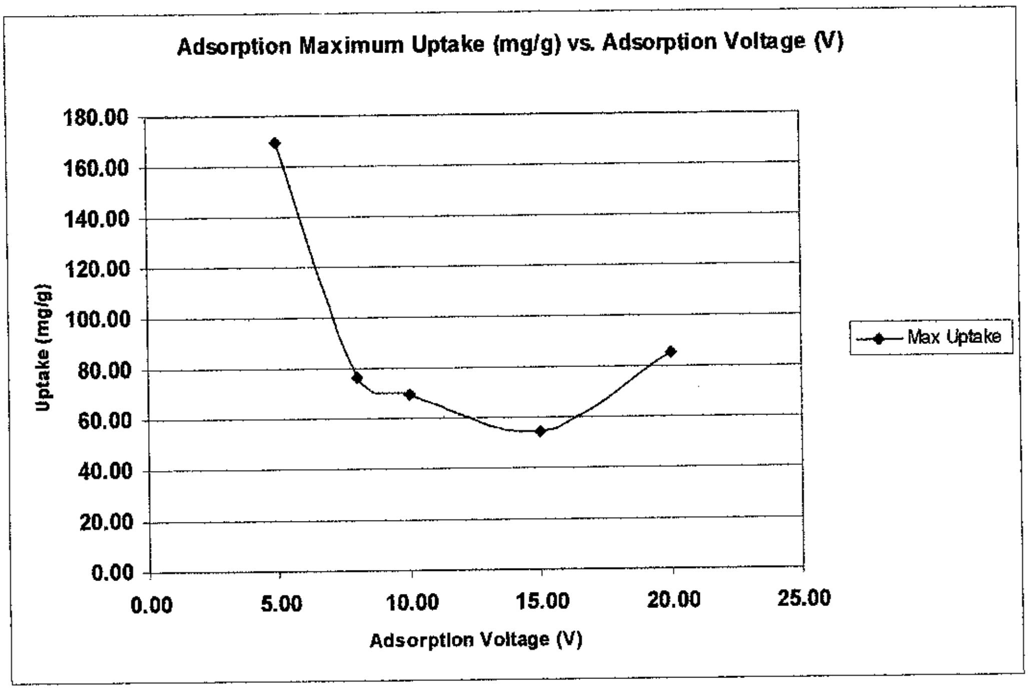

Figure 4.7 : Adsorption Maximum CO_2 Uptake (mg/g) vs. Adsorption Voltage (V)

Figure 4.7 shows that the amount of maximum uptake decreases as the adsorption voltage is increased. The amount of maximum uptake at adsorption voltage equals to 5 V is the highest with the value of 169.76 mg/g. The minimum value of maximum uptake is achieved at 15 V with a value of 54.53 mg/g. Then, the maximum uptake increased to 85.38 mg/g at 20 V. In overall, the maximum uptake is inversely related to adsorption voltage, which, as the voltage is increased the maximum uptake is decreased. This is due to the reason that adsorption is an exothermic process as it releases heat during the process and, when the adsorption voltage is increased, the Ohmic heating effect towards the activated carbon also increased. The application of voltage during the adsorption process also produces heat internally within the activated carbon, and eventually increases the temperature in the column. The increase in temperature will reduce the capability of the adsorbent to adsorb CO_2. The same effect is seen in the temperature swing adsorption mechanism.

"Adsorption isotherms obtained at temperature of 30, 60 and 100 °C and a pressure up to one atmosphere for CO_2 were analyzed and were found adsorbed less CO_2 at 60 and 100 °C than at 30 °C. At 100 °C the amount of CO_2 adsorbed was approximately one third of the amount adsorbed at 30 °C". [4]. This has proven that increment in voltage does not assist in better adsorption uptake instead decreasing the amount of CO_2 adsorbed in the bed.

The graph also shows that this inverse relationship is non-linear and the graph's line is a polynomial line. The polynomial line exists because of the relationship of electrical power and Ohmic heating. Fundamentally, Ohmic heating is linearly related to electrical power source. Since electrical power, P is related with voltage, V under a forward polynomial relation, which is $P = V^2 \bullet R$, then Ohmic heating is also related to V under forward polynomial relation. As known, adsorption rate and uptake is inversely proportional to Ohmic heating. Hence, we can conclude that adsorption rate has an inverse polynomial relation with voltage, V, which produce a polynomial line as depicted in Figure 4.7. The maximum uptake decrease immensely from 169.76 mg/g to 76.27 mg/g from 5 V to 8V voltage application. From 8V to 10 V, the difference in the uptake decreases to only 6.81 mg/g and from 10 V to 15 V the difference is only 14.93 mg/g.

4.3.3 Rate of CO_2 Adsorption at Different Voltage

Rate of adsorption is a measurement of time taken in order for an adsorption process to be completed or to achieve saturation. The rate of adsorption is measured through the amount of uptake per unit time. In this particular experiments, the rate of adsorption is in unit of (mg/g)/min. The rate of adsorption is obtained by taking the slope of a straight line produced from the point the adsorption starts to the point where saturation is achieved (4 to 5 readings of the stabilized adsorption reading) in the adsorption graph. Based on this method, the average rate of adsorption for all 5 experiments were summarized into the graph below.

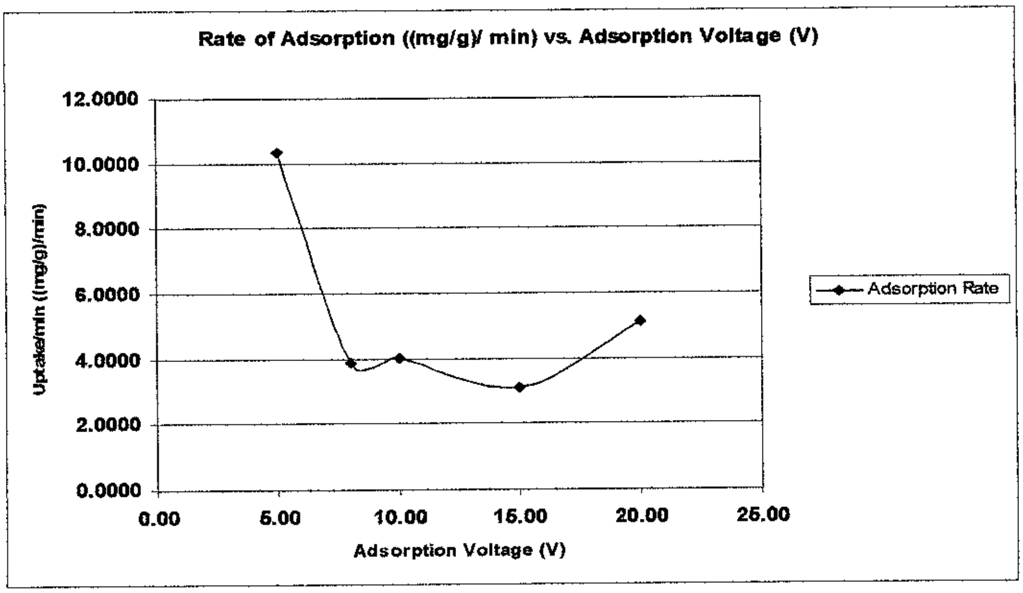

Figure 4.8 : Rate of Adsorption ((mg/g)/ min) vs. Adsorption Voltage (V)

Referring to figure 4.8 for 2.5 mm GAC rate of adsorption the trend of "rate of adsorption vs. adsorption voltage" is similar to the "maximum uptake vs. adsorption voltage" graph. This is because, as stated before the rate of adsorption is directly related with uptake, and under approximately the same adsorption time period, only the uptake affect the rate of adsorption. Form figure 4.8, the rate of adsorption is high at 5 V adsorption voltage with values of 10.3520 (mg/g)/min. Then the graph shows a decrement for rate of adsorption and increases again from 15 V adsorption voltage to 20 V adsorption voltage.

Similar statement by T.D Burchell in **4.3.2** is used to explain the rate of adsorption trend with respect to adsorption voltage. As all adsorption process in the experiments achieve saturation at about the same period of time at approximately 15 minutes, the adsorption rate is directly proportional to the maximum uptake during each experiment. As the voltage increases, Ohmic heat being produced by the activated carbon also increases. As adsorption is an exothermic process, CO_2 tries to release heat to be adsorbed by activated carbon, but since the activated also produces heat energy, less CO_2 can be adsorbed onto the surface of the activated therefore diminishing the maximum uptake, hence decreasing the rate of adsorption. This explains the similarity in the trend of the "rate of adsorption vs. adsorption voltage" graph and "maximum uptake vs. adsorption voltage" graphs from figure 4.8 and figure 4.7 respectively.

4.4 Desorption of CO_2 at Different Voltage

Under the same 5 experiments that was done for 2.5 mm GAC, the trend of desorption process were also obtained. This subchapter shall discuss on the effect of different voltages towards electrical desorption.

4.4.1 Desorption Data

Below are the graphical data for the 5 desorption experiments, with the desorption voltage ranges from 0.30 V to 1.50 V. The desorption voltage is relatively lower than the adsorption voltage because only a small amount of voltage is needed to act as the heat source via Ohmic heating as the heat of adsorption of CO_2 in activated carbon is low that is 30kJ/mol. .The equations for the straight line from the graphs are used to obtain the values of average rate of desorption for every graphs. The slope value from the equation is the value of rate of desorption.

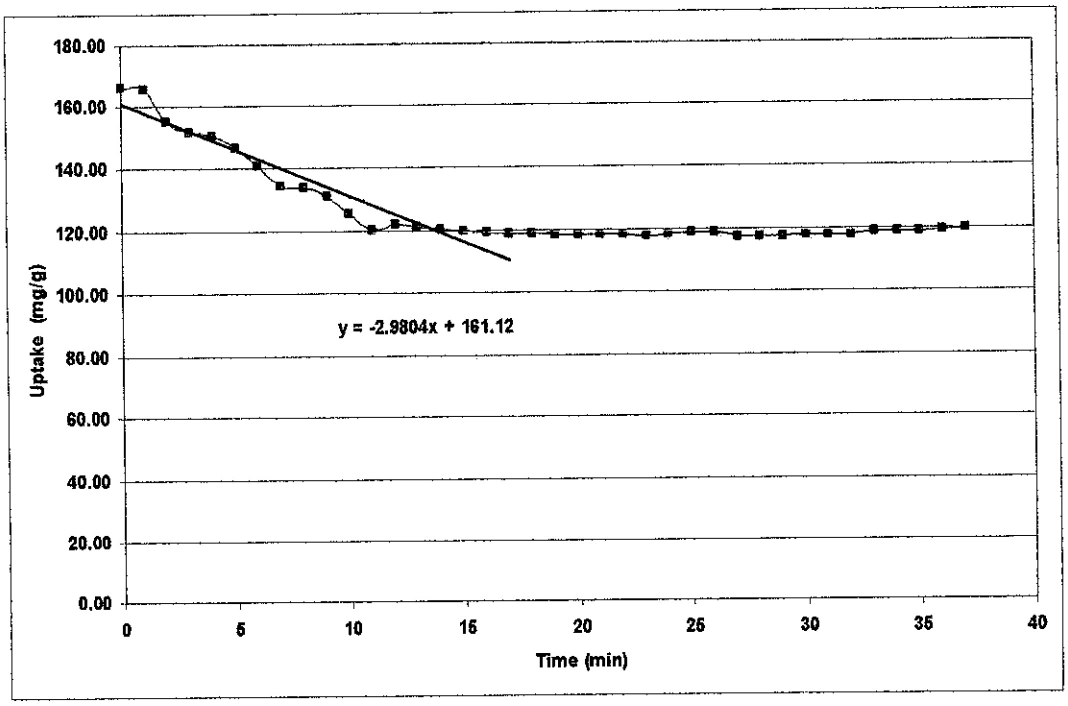

Figure 4.9 : Exp 1 ; 0.3 V desorption

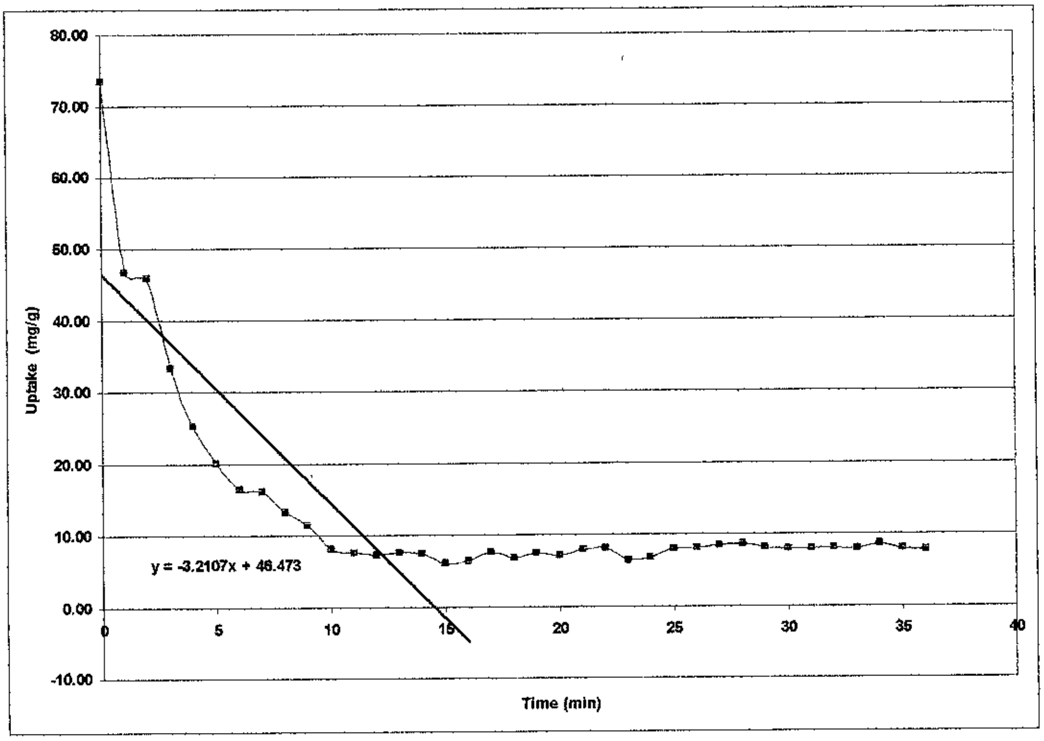

Figure 4.10 : Exp 2 ; 0.5 V desorption

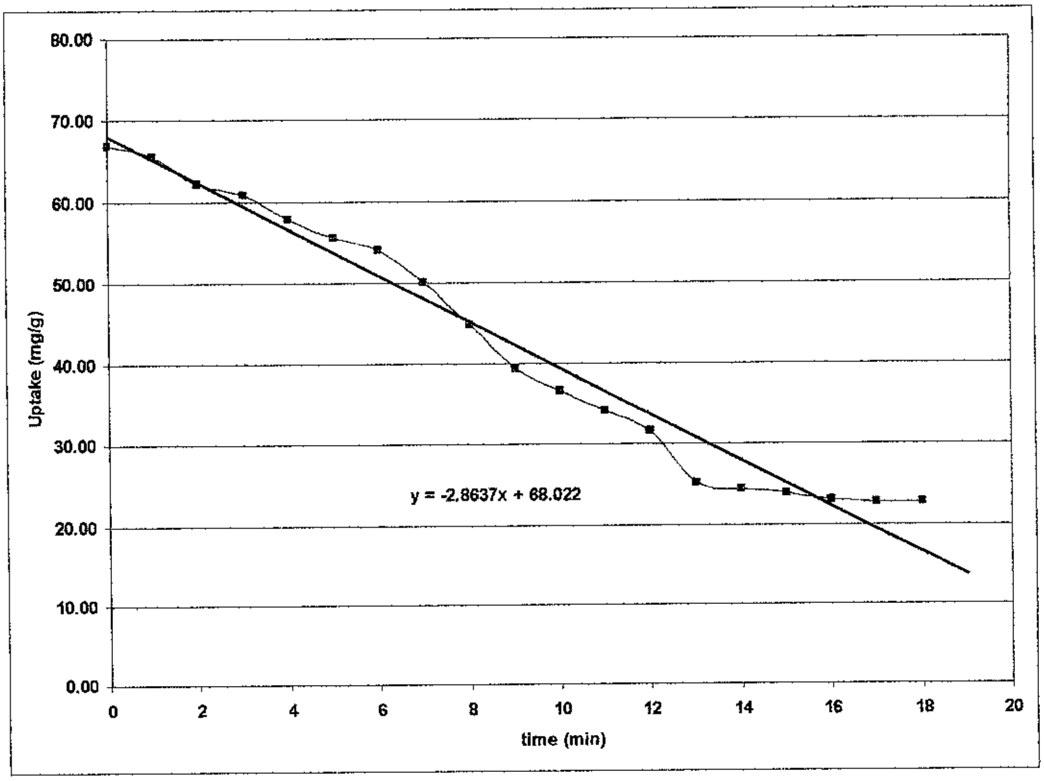

Figure 4.11 : Exp 3 ; 0.8 V desorption

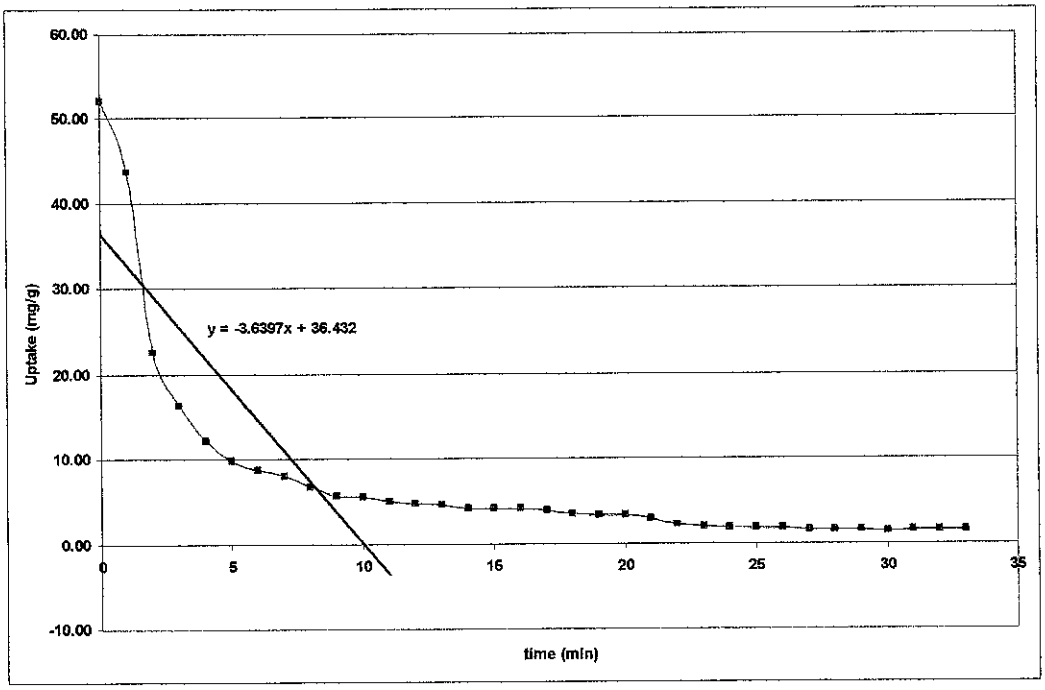

Figure 4.12 : Exp 4 ; 1.0 V desorption

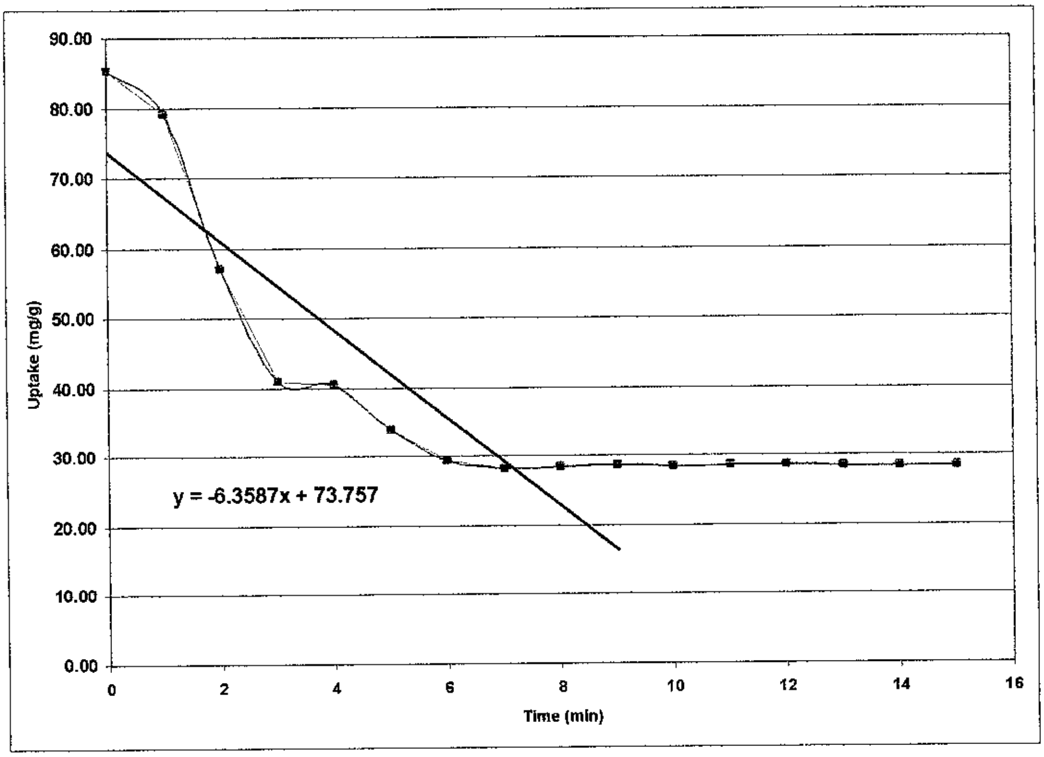

Figure 4.13 : Exp 5 ; 1.5 V desorption

For the desorption process, the mass trend decreases, fluctuates and stabilizes at a certain percentage of the maximum CO_2 uptake by the activated carbon. The horizontal constant line in the graphs shows the amount of CO_2 in terms of uptake that is left in the activated carbon. This amount of CO_2 is not desorbed during the desorption process because the desorption process is not 100 % efficient and thus, a portion of CO_2 gas remains in the activated carbon during the process. An ideal desorption process with 100 % efficiency will give a stable reading at zero uptake. Below is shown the average trend of the desorption process obtained from the Exp 1 to Exp 5 taken from Figure 4.9, 4.10, 4.11, 4.12 and 4.13.

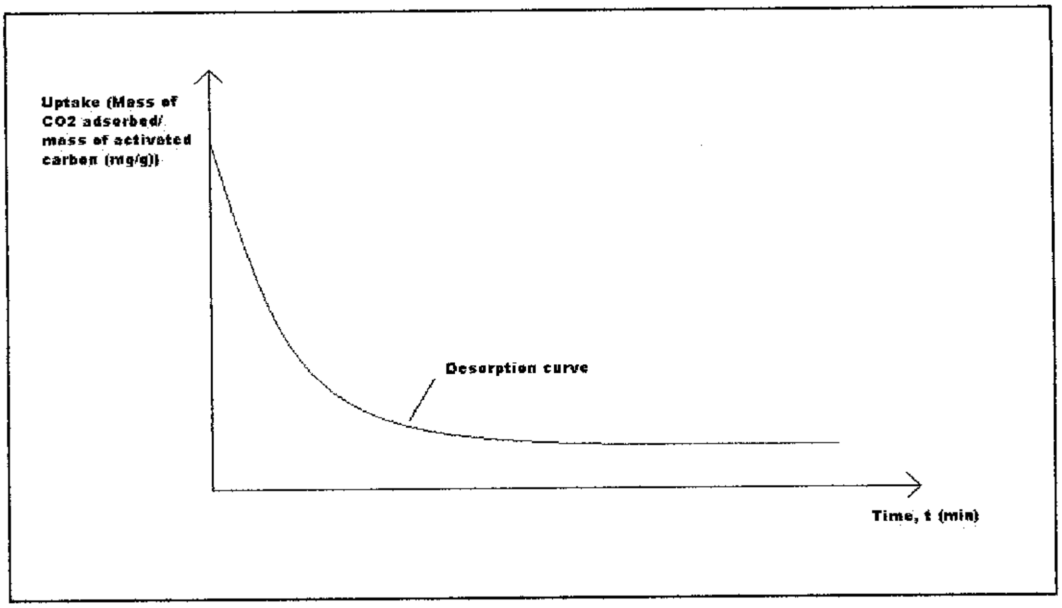

Figure 4.14 : Average desorption curve trend

The constant value of CO_2 mass during the desorption process in which the desorption is considered as has settled is not accurate. This is because the flowing N_2 gas affects the mass reading and in additional, the cooling effect by the flowing gas creates moisture on the activated carbon and on the column surface. The moisture that exists increases the mass reading by the mass balance and eventually disturb the mass reading for the experiments.

Using the graphs obtained, rate of desorption from each experiments were calculated. Below is the tabulated summary of rate of CO_2 desorption by the 2.5 mm activated carbon.

Table 4.4 : Rate of CO_2 Desorption Summary

EXP	Desorption voltage (V)	Rate of Desorption ((mg/g)/min)
1	0.30	2.9804
2	0.50	3.2107
3	0.60	2.8637
4	1.00	3.6015
5	1.50	6.3587

4.4.2 Rate of CO_2 Desorption at different voltage

Rate of desorption is the period of time taken for removal of CO_2 from the activated carbon until it reaches a constant value. Analogous to the rate of adsorption, the rate of desorption is measured by taking the amount of uptake per unit time. In this particular experiments, the rate of adsorption is in (mg/g)/min unit. The rate of desorption is obtained by attaining the straight line slope of the desorption curve in the desorption isotherm. The straight line slope starts at the beginning of the desorption process and ends when the amount of uptake becomes constant and no desorption occur (4 -5 readings of the stabilized desorption process). The summary of all rate of desorption for all experiments is given as below.

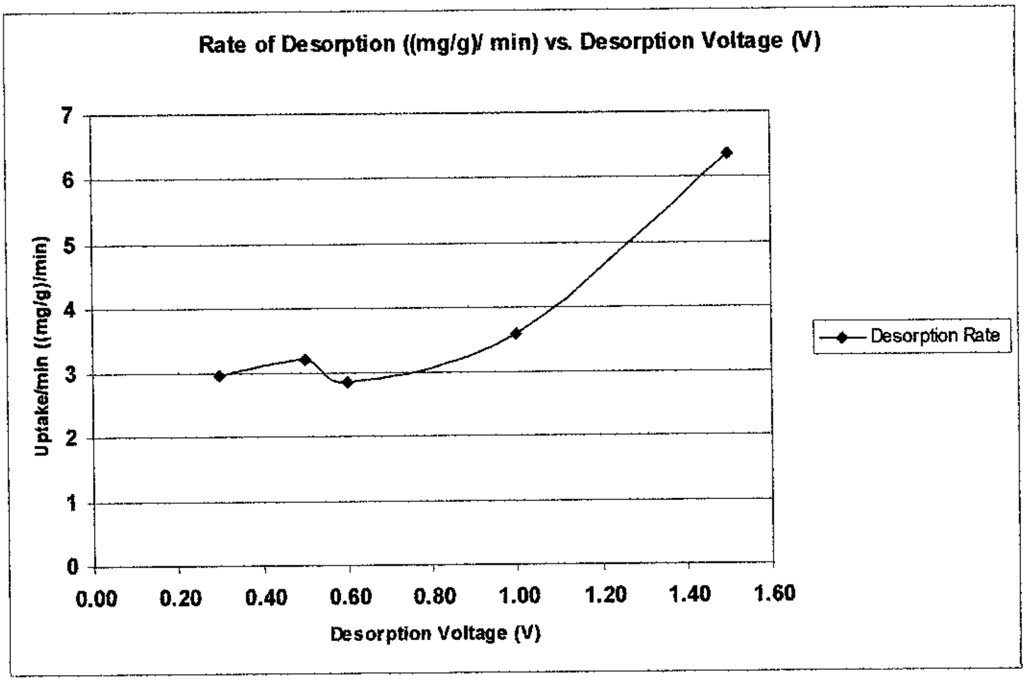

Figure 4.15 : Rate of Desorption ((mg/g)/ min) vs. Desorption Voltage (V)

The heat of adsorption for CO_2 in activated carbon is low, thus a low sets of electrical voltages are used in the experiments. For the lowest applied voltage, 0.3 V, the rate of desorption is low for the 2.5 mm GAC. Referring to Figure 4.15 the obtained rate of desorption is only 2.9804 (mg/g)/min. As the desorption voltage is increased, the rate of desorption also increased. Highest value of rate of desorption for 2.5 mm GAC is 6.3587 (mg/g)/min at voltage equals to 1.5 V.

Both factor of "rate of desorption and desorption voltage" has a non-linear relationship. The graph shows a polynomial graph line, with a low increment of rate of adsorption in the beginning of the graph, but a relatively high increment towards the end. This is because, the relationship between rate of desorption and electricity is as below:

Assuming 100 % energy conversion and constant heat of adsorption, Q and resistance R:

Power in heat form = Power in electrical form

$$\frac{Q_{ad}}{t} = \frac{V^2}{R} \qquad \text{Refer Eqtn. 2.6}$$

Thus, if we have one unit increment of voltage, the time, t will be decreased to a power root of 2. Time, t in this equation correspond to the rate of desorption. A lower amount of time produces a higher rate of desorption. This proves that the relationship between desorption voltage and the desorption rate is polynomial and not linear.

"The heat of adsorption of CO_2 on activated carbon fiber is 30 kJ mol $^{-1}$. A simple calculation for the case shown in FI. 23 where approximately 1 L of CO_2 is adsorbed indicates that at a power level of 5 W, approximately 270 seconds would be required to input the energy (1350 J) required to desorbed the CO_2 on the CFCMS. Implicit in this calculation is the assumption that all of the electrical energy is converted to thermal energy and transferred to the adsorbed CO_2." [4].

Overall, the heating effect due to the electrical application is acting directly at the adsorption sites resulting in rapid desorption of the adsorbate. As the electrical voltage is increased, the rate of desorption also increase.

4.5 Effect of Granular Activated Carbon Particle Size on Electrical Adsorption and Desorption

Experiments 1 to 5 were completed using particle size of 2.5 mm granular activated carbon as the adsorbent. Experiments 6 to 10 were completed using particle size of 1.5 mm granular particle size. The data for experiments 1 to 5 using 2.5 mm were already discussed in the previous subchapter. The adsorption and desorption data for experiments using 1.5 mm GAC will not be discussed, but the graphical data for Exp. 6 to Exp 10 can be obtained in the Appendix 2. In this subchapter, only the data on rate of adsorption, rate of desorption and maximum uptake of CO_2 for all experiments using both particle size of 2.5 mm and 1.5 mm GAC are used for discussion.

Table 4.5 : Maximum Uptake and Adsorption/Desorption Rate Summary

EXP	Adsorption voltage (V)	Uptake (mg/g)	Rate of Adsorption ((mg/g)/min)	Desorption voltage (V)	Rate of Desorption ((mg/g)/min)
1	5.00	169.76	10.3520	0.30	2.9804
2	8.00	76.27	3.8902	0.50	3.2107
3	10.00	69.46	4.0209	0.60	2.8637
4	15.00	54.53	3.1183	1.00	3.6015
5	20.00	85.38	5.1511	1.50	6.3587

Table 4.6 : Maximum Uptake and Adsorption/Desorption Rate Summary

EXP	Adsorption voltage (V)	Uptake (mg/g)	Rate of Adsorption ((mg/g)/min	Desorption voltage (V)	Rate of Desorption ((mg/g)/min)
6	5.00	136.80	5.7063	0.30	1.2556
7	8.00	137.53	5.5234	0.50	1.6925
8	10.00	74.20	2.8144	0.60	5.0759
9	15.00	38.97	1.8169	1.00	1.6570
10	20.00	33.37	1.0657	1.50	2.5736

4.5.1 Effect of GAC Particle Size Towards Maximum Uptake

The data for from Table 4.4 and Table 4.5, the graphical data obtained is as below.

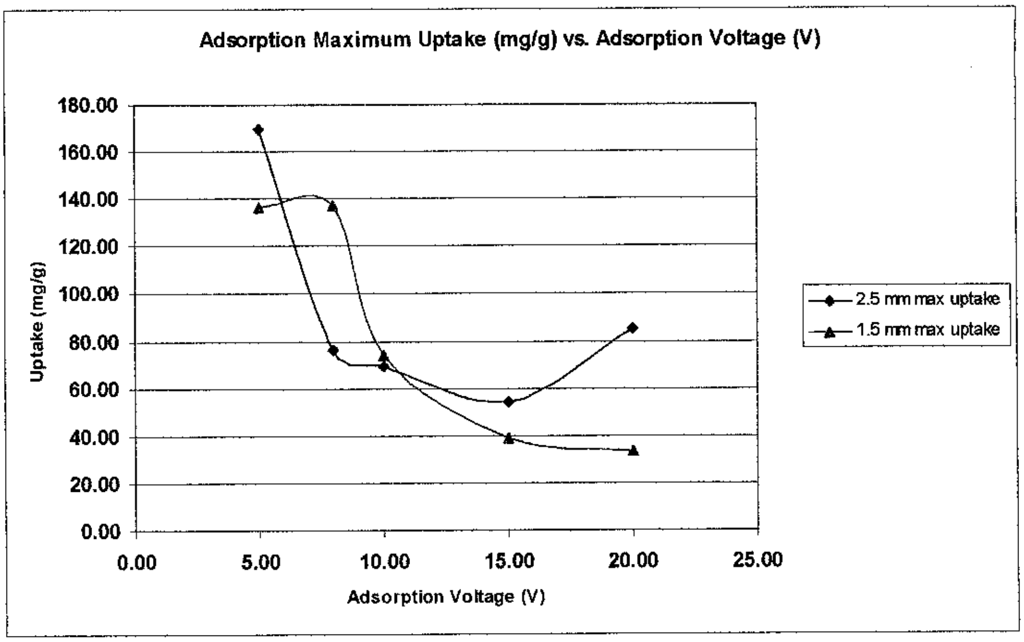

Figure 4.16 : Comparison of 2.5 mm and 1.5 mm GAC for Adsorption Maximum Uptake (mg/g) vs. Adsorption Voltage (V)

Referring to Figure 4.16, the same trend in 2.5 mm GAC maximum uptake also applies to the 1.5 mm GAC with exception on the difference in value of the maximum uptake in each adsorption voltage. Comparing the amount of CO_2 adsorbed by the activated carbon, by generally looking at the trend, 2.5 mm GAC adsorbed better than using 1.5 mm GAC when using electrical enhanced adsorption method. It is believed that this might be caused by the surface area of 1.5 mm GAC that is higher than 2.5 mm GAC. As the surface area is higher, the amount of heat from Ohmic heating source can be dissipated more easily into the environment inside the column. Thus, for the same adsorption voltage, the temperature in the column containing 1.5 mm GAC is higher than in 2.5 mm GAC, in which, as stated above, the CO_2 adsorbed would be less.

4.5.2 Effect of GAC Particle Size Towards Adsorption Rate

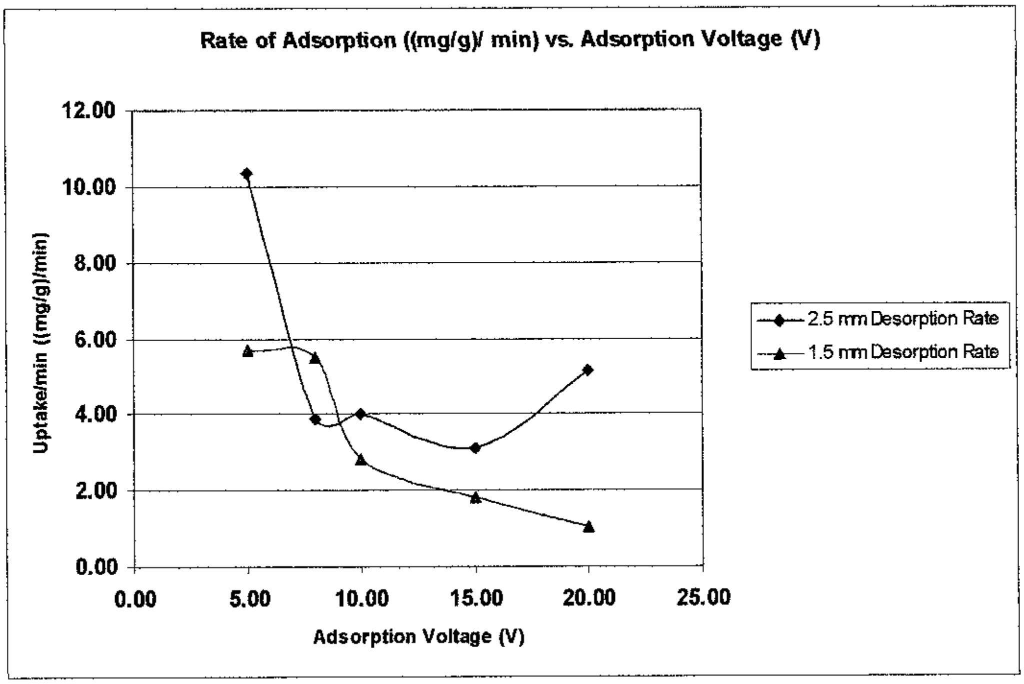

Figure 4.17 : Comparison of 2.5 mm and 1.5 mm GAC for Rate of Adsorption ((mg/g)/ min) vs. Adsorption Voltage (V)

Based on Figure 4.17, 1.5 mm GAC applies the same adsorption rate trend as 2.5 mm, but at one particular adsorption voltage, the rate of adsorption of 2.5 mm GAC is higher than for 1.5 mm GAC. This is true for all adsorption voltage except for 8 V only and this particular value is treated as an error in the experiment. The rate of adsorption is also related to the uptake and temperature of the column environment during the experiment. At the same voltage, 1.5 mm GAC exhibits more heat through larger surface area, increasing the heat in the column. As heat increase in the column, more energy is being given to the CO_2 molecule. The kinetic energy of the molecules increases therefore toughen the process of adsorption onto the surface of the activated carbon as the molecules have to release more heat for adsorption to occur. 1.5 mm GAC which has higher surface area releases more heat thus impeding the amount of CO_2 to be adsorbed by the adsorbent per unit time.

4.5.3 Effect of GAC Particle Size Towards Adsorption Rate

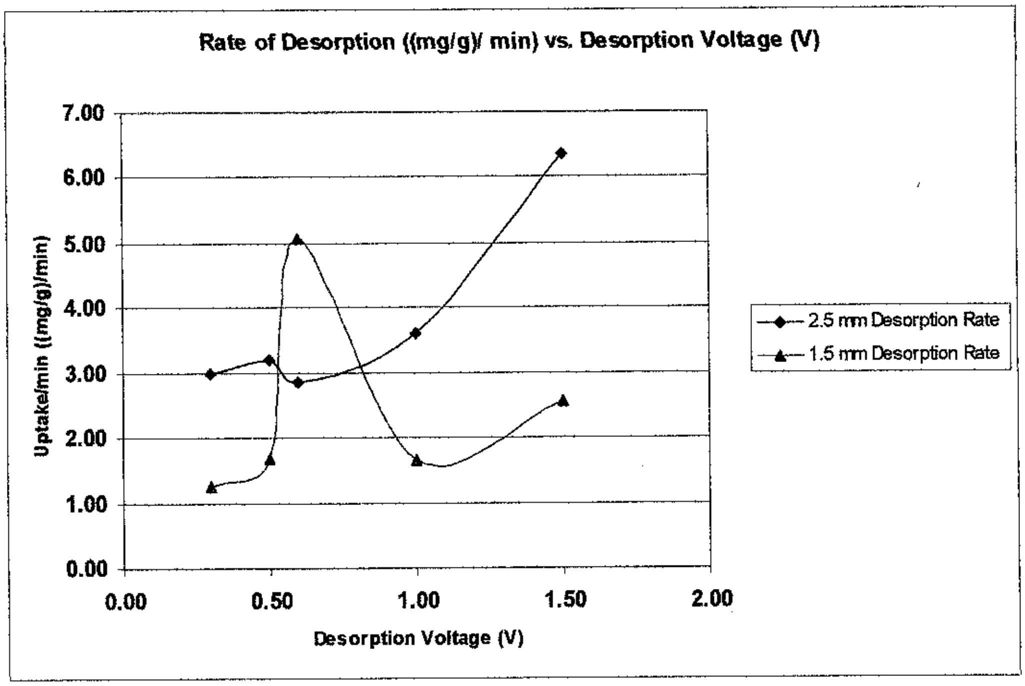

Figure 4.18 : Comparison of 2.5 mm and 1.5 mm GAC for Rate of Desorption ((mg/g)/ min) vs. Desorption Voltage (V)

The desorption rate trend of 1.5 mm GAC is similar to the desorption rate of 2.5 mm GAC when being applied with the same values of voltages. The trend is 'increasing rate of desorption as the desorption voltage increases'. At all desorption voltage, the rate of desorption for 2.5 mm GAC is higher than 1.5 mm GAC, with an exception on 0.6 V rate of desorption. Figure 4.18 shows the comparison between the graph line between both particle sizes effect on the desorption rate. The increment for rate of desorption by 2.5 mm GAC is also higher than 1.5 mm GAC. This can be acquired by comparing the average slope of the graphs. Evidently, 2.5 mm GAC line has a higher slope than 1.5 mm GAC. It is believed that this trend is caused by the electrical resistivity by the activated carbon and the core regions within the activated carbon. 1.5 mm GAC, with higher surface area has higher amount of core regions and "adsorption sites in the core region of the fiber would be desorbed more slowly and overall the desorption would not occur in the time indicated by the simple calculation." [4]. This explains the difference of desorption rate between both size of GAC.

4.6 Temperature and Pressure Difference Profile on Adsorption and Desorption for 2.5 mm GAC and 1.5 mm GAC

During the experiment, two other factors, temperature in the column and pressure difference across the column were obtained to discuss the effect of different voltages towards these factors. Generally, the column temperature and pressure difference shows approximately the same trend for all the experiments. Although the trend is the same, but the value of temperature and pressure difference in which each experiment occur differ with each other. This is due to the different conditions in each experiments i.e. voltage values. Below are the graphical data for the temperature and pressure difference profile of each adsorption and desorption experiments using 2.5 mm GAC and 1.5 mm GAC.

Part 1 : Granular Activated Carbon Size 2.5 mm

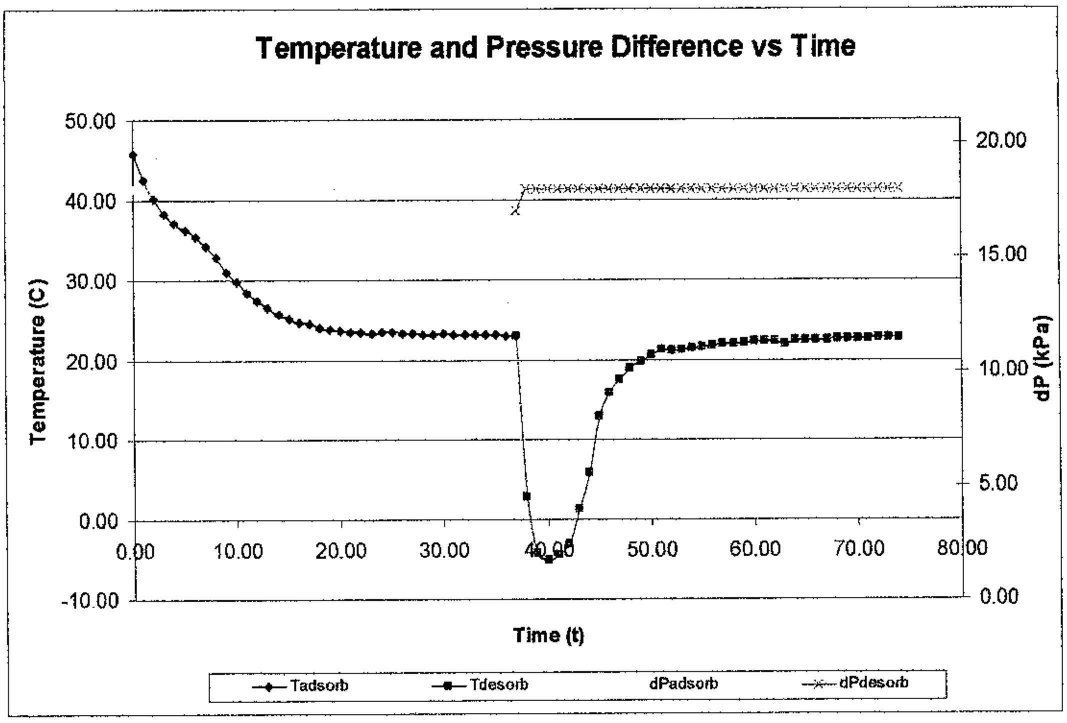

Figure 4.19 : The temperature and pressure difference profile for experiment 1

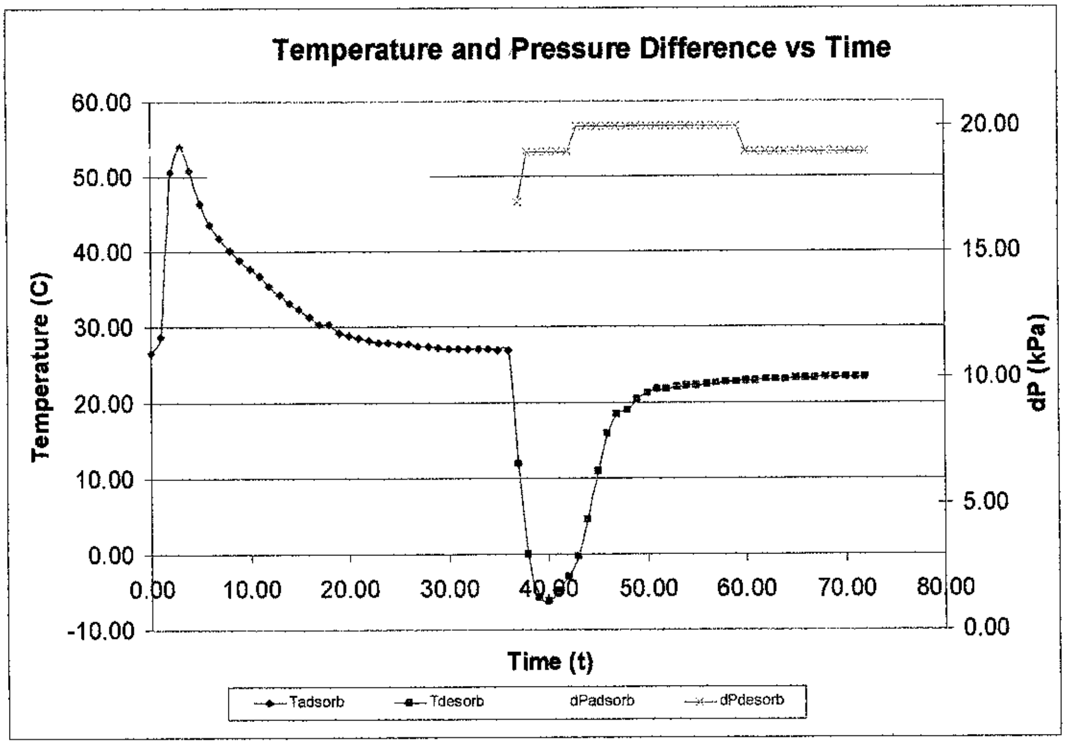

Figure 4.20 : The temperature and pressure difference profile for experiment 2

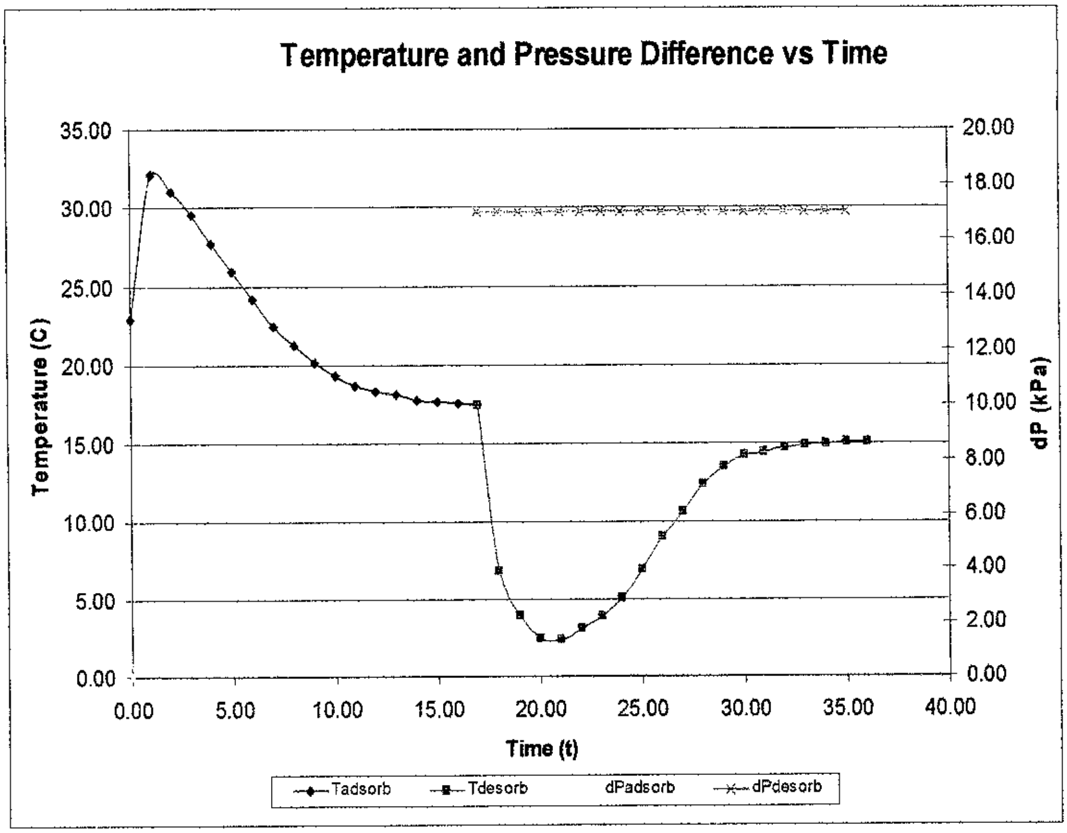

Figure 4.21: The temperature and pressure difference profile for experiment 3

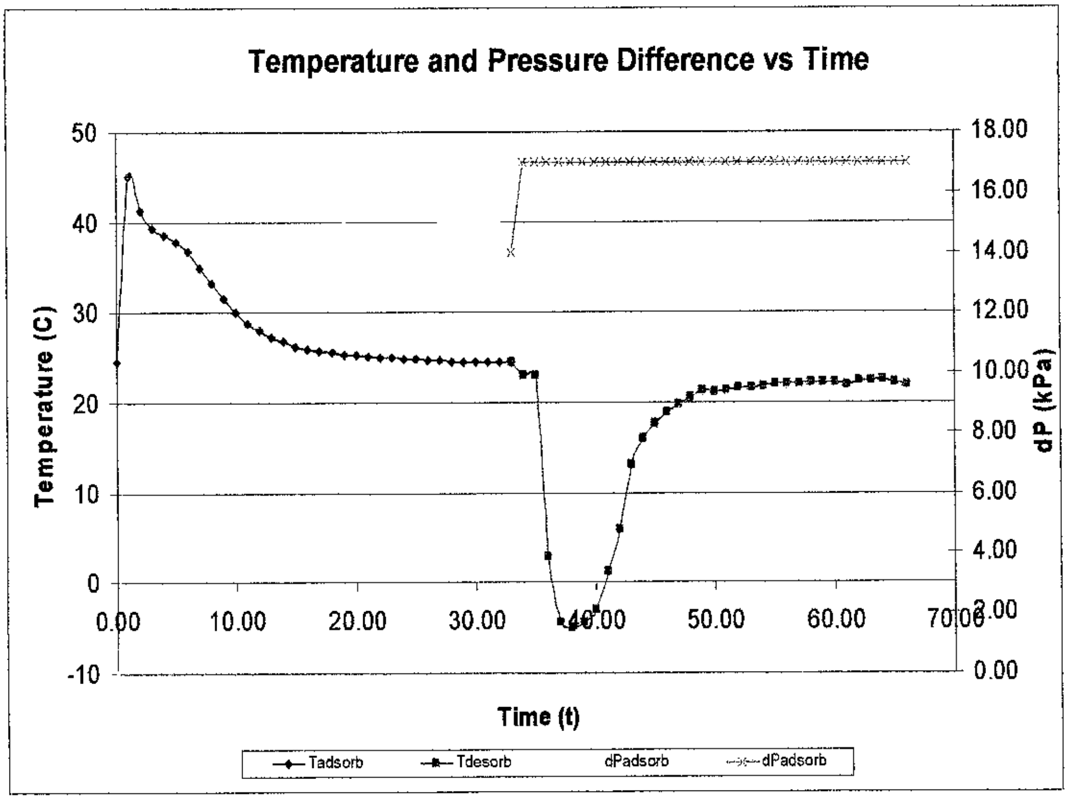

Figure 4.22 : The temperature and pressure difference profile for experiment 4

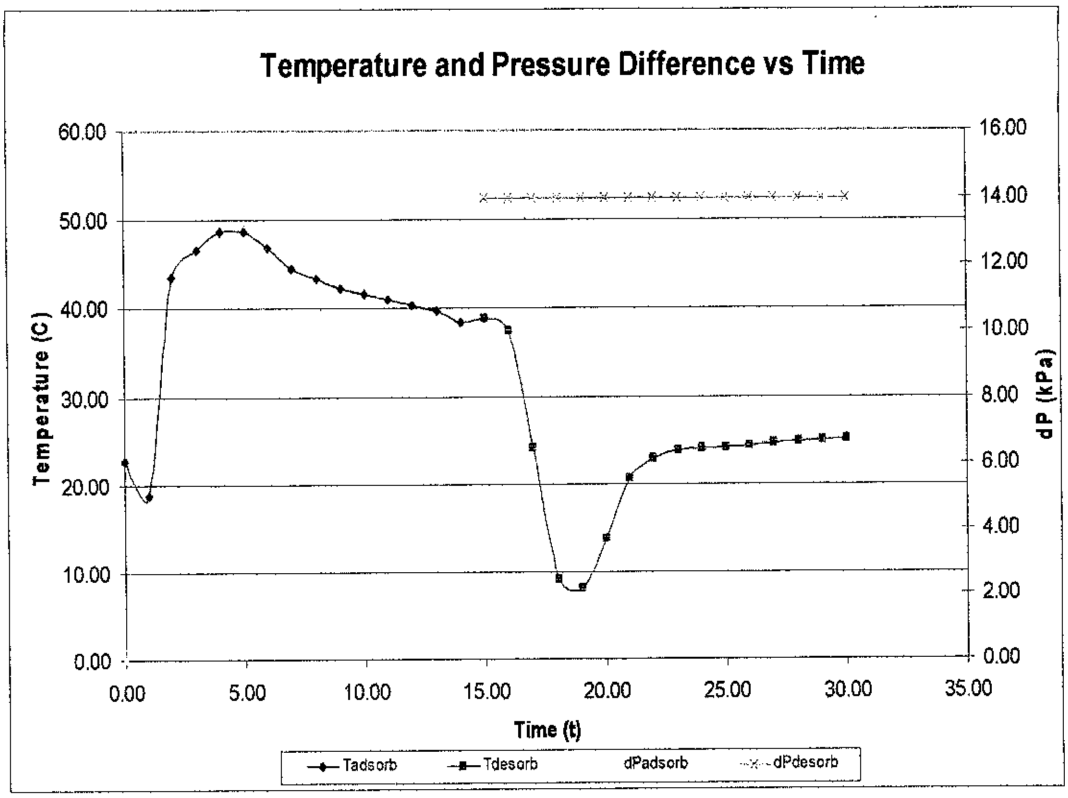

Figure 4.23 : The temperature and pressure difference profile for experiment 5

Part 2 : Granular Activated Carbon Size 1.5 mm

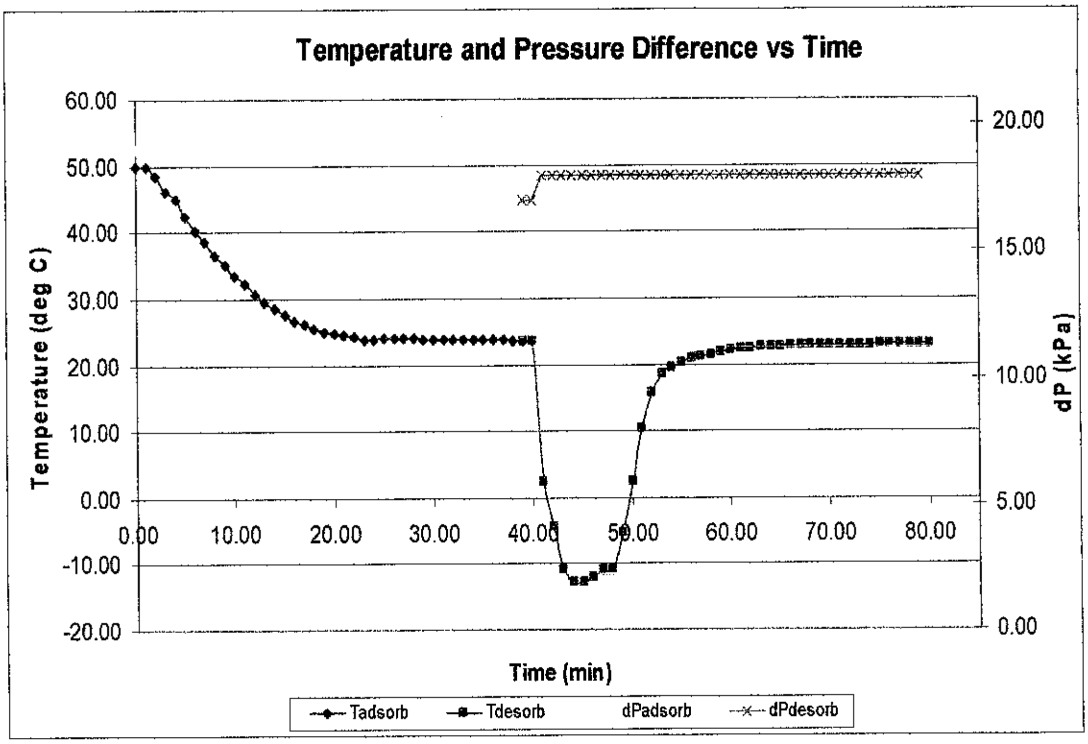

Figure 4.24 : The temperature and pressure difference profile for experiment 6

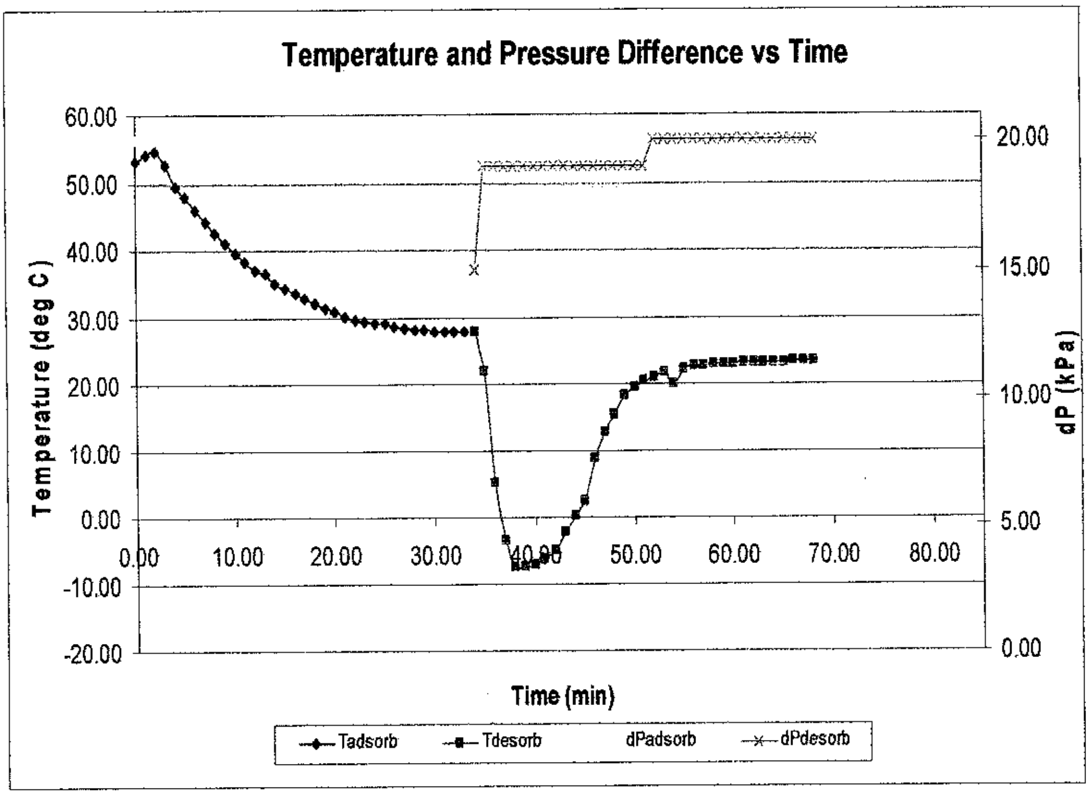

Figure 4.25 : The temperature and pressure difference profile for experiment 7

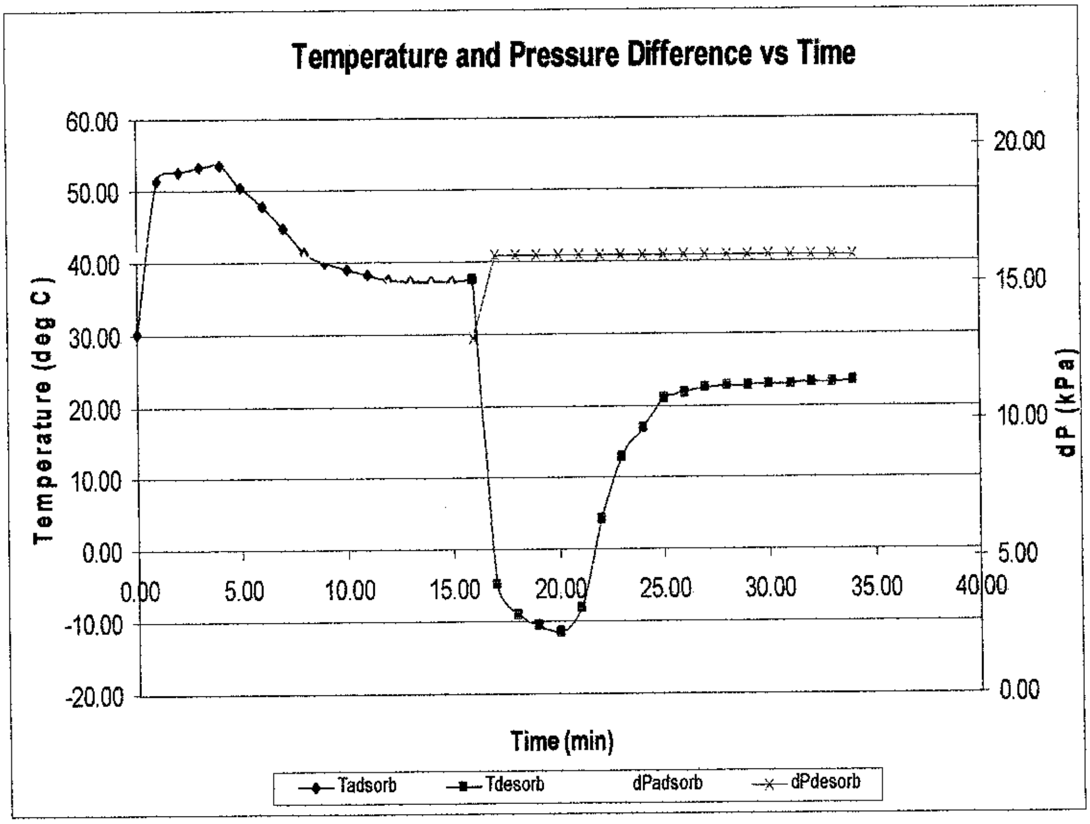

Figure 4.26: The temperature and pressure difference profile for experiment 8

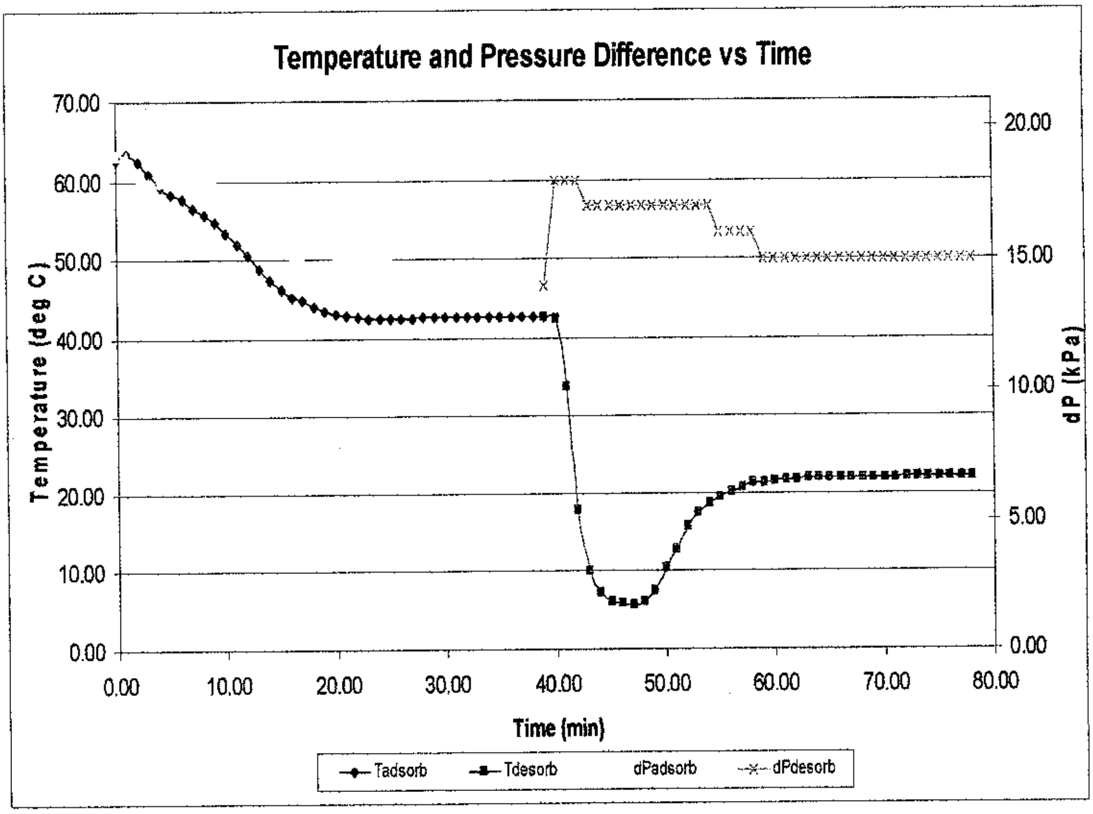

Figure 4.27: The temperature and pressure difference profile for experiment 9

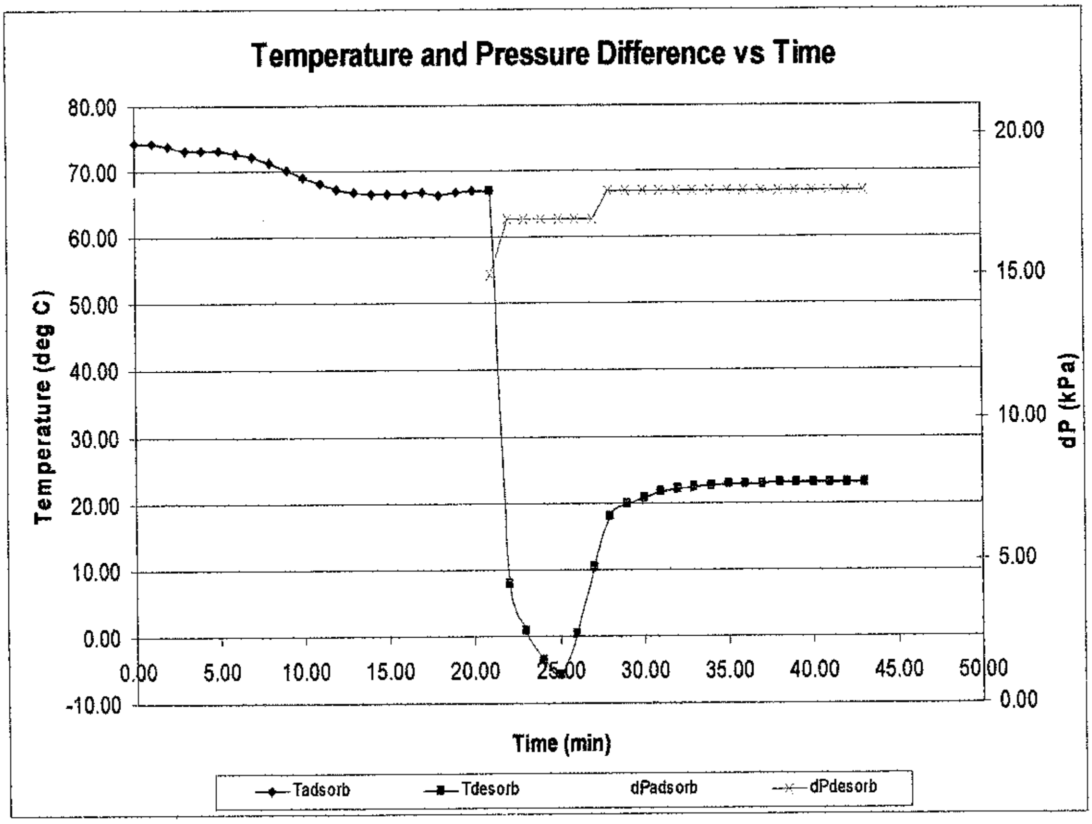

Figure 4.28: The temperature and pressure difference profile for experiment 10

4.6.1 Temperature Profile

From the graphs, mostly the temperature profile starts at ambient temperature, approximately at 23 °C – 26.7 °C. As the adsorption process occurred, the temperature profile had suddenly increased to a value above 30 °C, with a maximum recorded temperature based on Figure 4.28 to be at 74.4 °C .

The sudden rise of temperature is due to the heat of adsorption surface of the activated carbon. Adsorption process is an exothermic process, thus it releases heat to the environment and increases the temperature reading in the column. The temperature during the adsorption period decreased slowly with time and became constant. The temperatures in which each profile become constant differ for every experiment. But, mostly the temperature profile during adsorption period at ambient temperature of 20 °C – 30 °C, with exceptions for experiment 10 in Figure 4.28, which stayed constant at a much higher temperature of 67 °C. There is no exact trend on these constant values for each adsorption experiments.

During desorption for all the experiments, at the beginning of the process the temperature in the column suddenly dropped to a minimum recorded temperature value of –12.8 °C based on Figure 4.24. The temperature was then increased to an approximate value of 24 °C. In overall, there was no increase in the temperature in the early phase of the desorption process because the electrical energy was converted kinetic energy by the CO_2 molecules in order for the molecules to be desorbed from the activated carbon. The temperature dropped due to the cooling effect by the N_2 gas flow across the column. After a certain amount of time, the amount of CO_2 to be desorbed will be less and allow for some of the electrical energy to be converted to heat as excess energy. This excess energy, in form of heat, is dissipated into the atmosphere in the column, in which increased the temperature in the column. The temperature became constant as the steady state condition in the column had been achieved. The time taken from the point where the temperature started to drop until it reached a constant reading was approximately 10 – 15 minutes for all the experiments.

4.6.2 Pressure Difference Profile

In the experiments, there are two types of inlet gas flowing into the activated carbon column, which are CO_2 gas as adsorbate during the adsorption process and N_2 gas as purge gas during the desorption process. In both processes, the inlet gas was kept constant at a pressure of 20 kPa. The pressure difference was generally constant for all the experiments and in both adsorption and desorption processes using whether CO_2 or N_2 gases at an approximate value of 17 kPa. Still, the value is not accurate and may have fluctuations of $\pm$3 kPa.

During the adsorption process, the pressure difference then decreased gradually until the end of the experiment. Based on Figures 4.25, 4.26, 4.27 and 4.28 for experiments 7, 8, 9 and 10 respectively, the pressure difference had decreased to 4 unit of pressure difference. The decreasing pressure difference is due to the increment of CO_2 gas flowing out from the column as the activated carbon had became saturated. The more the pressure difference decrease, more gas is flowing out of the column.

4.7 Errors in the experiment

Whilst doing the experiments, the following errors have been identified.

4.7.1 Random Error

Random errors are errors that are influenced by human deficiencies and may occur spontaneously and uncontrolled. One random error may have occurred during the experiments, which is:

a) Reaction time

The mass, temperature, pressure inlet and outlet data need to be recorded while the experiment is still being performed. The data need to be collected at an interval time of one minute per reading. All stated parameters are supposed to be taken simultaneously at each minute, thus it is impossible to do so when every data is taken manually by one person. Error might occur during the reaction time in between those reading extraction.

4.7.2 Systematic Error

Systematic errors are errors produced by equipment default and can be reproduced repeatedly in any time interval. Among systematic errors that have existed during the experiments are:

a) Mass Balance Sensitivity

The mass balance is the most important equipment among the setup of the experiment as it is being used to record the mass change of the activated carbon column throughout the experiment. The mass balance is very sensitive to any movement, touch and from the surrounding. The reading of the mass balance suddenly changed immensely during the experiment if there was any external disturbance. This problem can be properly avoided by limiting movements and touches during the experiments. Better result may be obtained if the experiments are done in a well insulated area to avoid wind effect o the reading.

b) Inconsistent of inlet pressure, PI

Mini manometer is used to record the gas flow as a replacement of a flow meter. Throughout the experiments, the gas flow should be kept constant Since constant inlet pressure corresponds to a constant gas flow, therefore during the experiment, the inlet pressure must also be constant. From the observation, the inlet pressure fluctuates at ± 3 kPa, hence affecting the outcome of the result by increasing inaccuracy. This error may be controlled by regular adjustment of the gas valve to meet the experiment requirement.

c) Cooling effect from Nitrogen gas flow

During the adsorption process, nitrogen gas is used as purge to enhance the desorption rate. The nitrogen gas flow through the column had decreased the temperature in and around the column. This temperature decrement may even arrive to negative temperature values. This had caused water droplet to exist around the column and causes error in the mass data taken. Prevention step for this problem is to wrap the column with aluminum foil prior to every experiments.

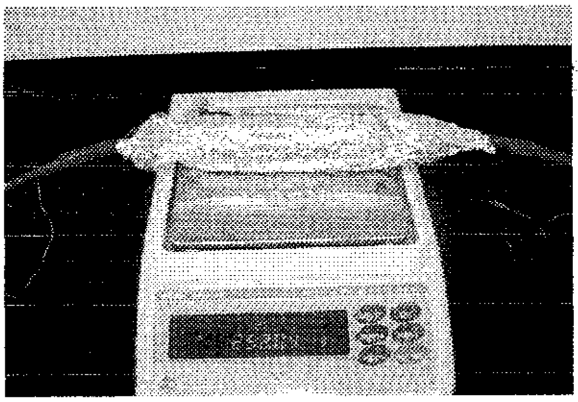

Figure 4.29 : Figure shows activated carbon column wrapped in aluminum foil

d) Leakage

The experimental setup is constructed manually with connection using tubing PVC tape, therefore possibility of leakage to occur is high. Among the location that can contribute to the leakage are:

i) Tubing T-junction connection

ii) Through the digital thermometer probe to the activated carbon column

iii) Through the tubing and copper wire connection.

The leakage are prevented by using PVC tape surrounding the connection.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Previous study on the electrical enhanced adsorption for Electrical Swing Adsorption only limited to constant value of voltage. Therefore, further study and research in the respected field is conducted in this project based on different source of voltages with theoretical and literature support.

Activated carbon packed in the column provide continuous carbon arrangement that electrical conductivity to the material. Ohmic heating principle had been utilized to have an effect of rapid desorption of adsorbed gases in the experiment. From the experiments done for both 2.5 mm and 1.5 mm granular activated carbon (GAC), it can be concluded that increment in voltage causes for the maximum activated carbon capacity or maximum uptake to be decreased. The rate of adsorption also decreases as the effect of increasing adsorption voltage. The outcome for the rate of desorption was as the desorption voltage increases, the rate of desorption also increases in a polynomial proportional trend. Higher rate of desorption assists to quicken the time for desorption process. The trend of maximum uptake versus voltage, rate of adsorption versus voltage and rate of desorption versus voltage for 1.5 mm GAC is lower in calculated value when compared to 2.5 mm GAC particle size.

Problems and deficiencies arose during the experiment such as existence of water droplet and sensitivity of the mass balance was discussed and prevention steps were taken to hinder the problem. The problems were treated as errors and improvements on the bench scale design were discussed in the recommendation stage.

5.2 Recommendations

As the experiment is still in its early stage in which, currently only in second stage, there a lot of room for improvement to be done in order to get a better end result. Below are a few suggestions on how to increase the accuracy and further improve the research/experiment.

5.2.1 Triplicate Results

Each experiment is to be repeated at least three times to attain average sets of results, hence increases the data accuracy. During this particular research project, the experiments were only done once (twice for a few experiments) due to time constraint caused by earlier equipment problem. Average sets of results are important as the experiment are filled with errors.

5.2.2 Temperature Distribution

This particular recommendation was brought on from the previous project study. The recommendation could not be entertained in this project study as there is no such equipment that can support it. This suggestion was to provide a few points of temperature detector along the activated column. This is done in order to obtain the temperature increment movement in the activated column during the adsorption and desorption experiment. The fixed bed theory says that the temperature distribution across the desorbent bed will vary from cylinder inlet to the outlet. Thus, it is important to get a temperature distribution profile during the experiment in order to agree with the previous statement.

5.2.3 Desorbent Adsorption Isotherm

The adsorption isotherm for CO_2 for the particular adsorbent that is used in the electrical enhanced experiment should be obtained, i.e. using Autosorb. By doing this, the efficiency of the electrical enhanced method by comparing with the desorbent adsorption capacity.

process. The experiment should also be prepared in a wind-free location and done at a location with minimal contact with external disturbance. This is to avoid any data disturbance in the experiment. The experiment should also be done using a CO_2 analyzer together with a precision balance to get a more accurate results.

5.2.7 Scale-Up Study on Electrical Enhanced Adsorption/Desorption and Electrical Swing Adsorption (ESA)

In order for the project to be developed into an industrial size application, it is needed to have a larger scale experiment setup for the project. This is to ensure whether the experiments done on the bench scale setup has the same trend if done n a larger scale. The scale-up can be done by using a bigger adsorption column, higher amount of electrical source, higher amount of adsorbate and wider range of electrical voltage. Other than this, it is also recommended that the scale-up experiment setup can also be used to apply an electrical swing adsorption experiment. This is important to have a good swing experiment result to see whether the technology is applicable under a industry-sized condition.

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APPENDICES

APPENDIX 1 : TABULATED RAW DATA

APPENDIX 2 : 1.5 MM GAC ADSORPTION AND DESORPTION GRAPHICAL DATA

APPENDIX 3 : SCHEMATIC DIAGRAM OF EXPERIMENTAL APPARATUS FOR ELECTRICAL ENHANCED SORPTION/DESORPTION EXPERIMENT

APPENDIX 4 : ESA EQUIPMENT IN OAK RIDGE NATIONAL LABORATORY

APPENDIX 5 : GANTT CHART

APPENDIX 1 :

TABULATED RAW DATA

Notes:

Blue : Adsorption process

Red : Desorption process

Part 1: 2.5 mm Size Granular Activated Carbon

Exp 1 : 5 V adsorption , 0.3 V desorption (weight =76.99 g)						
Time (min)	Weight (g)	TI (c)	P1 (kPa)	P2 (kPa)	uptake	dP (P1-P2)
0.00	0.00	45.70	20.00	2.00	0.00	18.00
1.00	3.37	42.60	20.00	2.00	43.77	18.00
2.00	3.70	40.20	20.00	2.00	48.06	18.00
3.00	3.70	38.30	20.00	2.00	48.06	18.00
4.00	3.76	37.20	20.00	2.00	48.84	18.00
5.00	3.83	36.30	20.00	2.00	49.75	18.00
6.00	3.90	35.40	20.00	2.00	50.66	18.00
7.00	4.18	34.30	20.00	2.00	54.29	18.00
8.00	4.37	32.90	20.00	2.00	56.76	18.00
9.00	6.35	31.10	20.00	2.00	82.48	18.00
10.00	9.26	29.80	20.00	2.00	120.28	18.00
11.00	10.91	28.50	20.00	2.00	141.71	18.00
12.00	12.02	27.40	20.00	2.00	156.12	18.00
13.00	12.50	26.60	20.00	2.00	162.36	18.00
14.00	12.76	25.80	20.00	2.00	165.74	18.00
15.00	12.87	25.20	20.00	2.00	167.16	18.00
16.00	12.97	24.80	20.00	2.00	168.46	18.00
17.00	13.01	24.50	20.00	2.00	168.98	18.00
18.00	13.03	24.10	20.00	2.00	169.24	18.00
19.00	13.04	23.90	20.00	2.00	169.37	18.00
20.00	13.07	23.70	20.00	2.00	169.76	18.00
21.00	13.01	23.60	20.00	2.00	168.98	18.00
22.00	12.90	23.50	20.00	2.00	167.55	18.00
23.00	12.82	23.40	20.00	2.00	166.52	18.00
24.00	12.80	23.50	20.00	2.00	166.26	18.00
25.00	12.93	23.50	20.00	2.00	167.94	18.00
26.00	12.94	23.40	19.00	2.00	168.07	17.00
27.00	12.93	23.40	19.00	2.00	167.94	17.00
28.00	12.91	23.30	19.00	2.00	167.68	17.00
29.00	12.87	23.30	19.00	2.00	167.16	17.00
30.00	12.83	23.40	19.00	2.00	166.65	17.00
31.00	12.84	23.30	19.00	2.00	166.77	17.00
32.00	12.84	23.30	19.00	2.00	166.77	17.00
33.00	12.84	23.20	19.00	2.00	166.77	17.00
34.00	12.78	23.20	19.00	2.00	166.00	17.00
35.00	12.81	23.20	19.00	2.00	166.39	17.00
36.00	12.80	23.10	19.00	2.00	166.26	17.00
37.00	12.80	23.00	19.00	2.00	166.26	17.00
38.00	12.75	2.90	20.00	2.00	165.61	18.00
39.00	11.96	-4.30	20.00	2.00	155.34	18.00
40.00	11.70	-5.00	20.00	2.00	151.97	18.00
41.00	11.61	-4.40	20.00	2.00	150.80	18.00
42.00	11.29	-3.00	20.00	2.00	146.64	18.00
43.00	10.86	1.30	20.00	2.00	141.06	18.00
44.00	10.34	6.00	20.00	2.00	134.30	18.00
45.00	10.32	13.10	20.00	2.00	134.04	18.00
46.00	10.11	16.00	20.00	2.00	131.32	18.00

47.00	9.65	17.70	20.00	2.00	125.34	18.00
48.00	9.25	19.00	20.00	2.00	120.15	18.00
49.00	9.41	19.90	20.00	2.00	122.22	18.00
50.00	9.33	20.60	20.00	2.00	121.18	18.00
51.00	9.25	21.40	20.00	2.00	120.15	18.00
52.00	9.22	21.20	20.00	2.00	119.76	18.00
53.00	9.18	21.40	20.00	2.00	119.24	18.00
54.00	9.14	21.60	20.00	2.00	118.72	18.00
55.00	9.14	21.70	20.00	2.00	118.72	18.00
56.00	9.13	21.80	20.00	2.00	118.59	18.00
57.00	9.12	22.10	20.00	2.00	118.46	18.00
58.00	9.12	22.10	20.00	2.00	118.46	18.00
59.00	9.11	22.20	20.00	2.00	118.33	18.00
60.00	9.09	22.30	20.00	2.00	118.07	18.00
61.00	9.13	22.30	20.00	2.00	118.59	18.00
62.00	9.16	22.30	20.00	2.00	118.98	18.00
63.00	9.17	22.00	20.00	2.00	119.11	18.00
64.00	9.05	22.50	20.00	2.00	117.55	18.00
65.00	9.05	22.50	20.00	2.00	117.55	18.00
66.00	9.05	22.60	20.00	2.00	117.55	18.00
67.00	9.07	22.60	20.00	2.00	117.81	18.00
68.00	9.07	22.70	20.00	2.00	117.81	18.00
69.00	9.09	22.70	20.00	2.00	118.07	18.00
70.00	9.16	22.70	20.00	2.00	118.98	18.00
71.00	9.17	22.70	20.00	2.00	119.11	18.00
72.00	9.17	22.80	20.00	2.00	119.11	18.00
73.00	9.2	22.80	20.00	2.00	119.50	18.00
74.00	9.23	22.80	20.00	2.00	119.89	18.00

Exp 2 : 8 V adsorption , 0.5 V desorption (weight =77.62 g)

Time (min)	Weight (g)	TI (c)	P1 (kPa)	P2 (kPa)	uptake	dP (P1-P2)
0.00	0.00	26.70	20.00	1.00	0.00	19.00
1.00	1.17	28.80	20.00	1.00	15.07	19.00
2.00	3.25	50.70	20.00	1.00	41.87	19.00
3.00	4.23	54.00	20.00	1.00	54.50	19.00
4.00	4.70	50.80	20.00	1.00	60.55	19.00
5.00	4.84	46.50	20.00	1.00	62.36	19.00
6.00	5.06	43.70	19.00	1.00	65.19	18.00
7.00	5.30	41.90	19.00	1.00	68.28	18.00
8.00	5.41	40.20	19.00	1.00	69.70	18.00
9.00	5.60	38.90	19.00	1.00	72.15	18.00
10.00	5.72	37.80	19.00	1.00	73.69	18.00
11.00	5.76	36.70	19.00	1.00	74.21	18.00
12.00	5.89	35.40	19.00	1.00	75.88	18.00
13.00	5.92	34.40	19.00	1.00	76.27	18.00
14.00	5.81	33.20	19.00	1.00	74.85	18.00
15.00	5.81	32.30	19.00	1.00	74.85	18.00
16.00	5.80	31.30	19.00	1.00	74.72	18.00
17.00	5.80	30.40	19.00	1.00	74.72	18.00
18.00	5.74	30.40	19.00	1.00	73.95	18.00
19.00	5.74	29.20	19.00	1.00	73.95	18.00
20.00	5.77	28.90	19.00	1.00	74.34	18.00
21.00	5.82	28.60	19.00	1.00	74.98	18.00
22.00	5.80	28.20	19.00	1.00	74.72	18.00
23.00	5.77	28.00	19.00	1.00	74.34	18.00
24.00	5.72	28.00	19.00	1.00	73.69	18.00
25.00	5.69	27.80	19.00	1.00	73.31	18.00
26.00	5.72	27.70	19.00	1.00	73.69	18.00
27.00	5.72	27.50	19.00	1.00	73.69	18.00
28.00	5.72	27.40	19.00	1.00	73.69	18.00
29.00	5.73	27.30	18.00	1.00	73.82	17.00
30.00	5.62	27.20	18.00	1.00	72.40	17.00
31.00	5.76	27.20	18.00	1.00	74.21	17.00
32.00	5.75	27.20	18.00	1.00	74.08	17.00
33.00	5.70	27.10	18.00	1.00	73.43	17.00
34.00	5.70	27.10	18.00	1.00	73.43	17.00
35.00	5.70	27.00	18.00	1.00	73.43	17.00
36.00	5.70	27.00	18.00	1.00	73.43	17.00
37.00	3.63	11.90	18.00	1.00	46.77	17.00
38.00	3.57	0.00	20.00	1.00	45.99	19.00
39.00	2.59	-5.70	20.00	1.00	33.37	19.00
40.00	1.97	-6.20	20.00	1.00	25.38	19.00
41.00	1.56	-5.00	20.00	1.00	20.10	19.00
42.00	1.28	-3.00	20.00	1.00	16.49	19.00
43.00	1.25	-0.40	21.00	1.00	16.10	20.00
44.00	1.04	4.60	21.00	1.00	13.40	20.00
45.00	0.89	10.90	21.00	1.00	11.47	20.00
46.00	0.63	15.90	21.00	1.00	8.12	20.00
47.00	0.59	18.50	21.00	1.00	7.60	20.00
48.00	0.57	18.90	21.00	1.00	7.34	20.00
49.00	0.59	20.40	21.00	1.00	7.60	20.00

50.00	0.58	21.20	21.00	1.00	7.47	20.00
51.00	0.48	21.70	21.00	1.00	6.18	20.00
52.00	0.51	21.80	21.00	1.00	6.57	20.00
53.00	0.59	22.00	21.00	1.00	7.60	20.00
54.00	0.53	22.20	21.00	1.00	6.83	20.00
55.00	0.58	22.30	21.00	1.00	7.47	20.00
56.00	0.55	22.40	21.00	1.00	7.09	20.00
57.00	0.62	22.50	21.00	1.00	7.99	20.00
58.00	0.63	22.70	21.00	1.00	8.12	20.00
59.00	0.51	22.70	21.00	1.00	6.57	20.00
60.00	0.53	22.80	20.00	1.00	6.83	19.00
61.00	0.62	22.90	20.00	1.00	7.99	19.00
62.00	0.63	23.00	20.00	1.00	8.12	19.00
63.00	0.66	23.00	20.00	1.00	8.50	19.00
64.00	0.67	23.10	20.00	1.00	8.63	19.00
65.00	0.64	23.20	20.00	1.00	8.25	19.00
66.00	0.62	23.20	20.00	1.00	7.99	19.00
67.00	0.62	23.20	20.00	1.00	7.99	19.00
68.00	0.64	23.30	20.00	1.00	8.25	19.00
69.00	0.62	23.30	20.00	1.00	7.99	19.00
70.00	0.67	23.30	20.00	1.00	8.63	19.00
71.00	0.62	23.40	20.00	1.00	7.99	19.00
72.00	0.61	23.40	20.00	1.00	7.86	19.00

Exp 3 : 10 V adsorption / 0.6 V desorption (weight = 83.79 g)						
Time (min)	Weight (g)	Ti (c)	P1 (kPa)	P2 (kPa)	uptake	dP (P1-P2)
0.00	0.00	22.90	0.00	0.00	0.00	0.00
1.00	0.18	32.10	21.00	3.00	2.15	18.00
2.00	0.87	31.00	22.00	3.00	10.38	19.00
3.00	1.69	29.60	22.00	3.00	20.17	19.00
4.00	2.32	27.70	21.00	3.00	27.69	18.00
5.00	3.02	26.00	21.00	3.00	36.04	18.00
6.00	3.64	24.20	21.00	3.00	43.44	18.00
7.00	4.20	22.50	22.00	3.00	50.13	19.00
8.00	4.50	21.30	20.00	3.00	53.71	17.00
9.00	4.94	20.20	20.00	3.00	58.96	17.00
10.00	5.32	19.30	21.00	3.00	63.49	18.00
11.00	5.58	18.70	20.00	3.00	66.60	17.00
12.00	5.70	18.30	20.00	3.00	68.03	17.00
13.00	5.73	18.10	20.00	3.00	68.39	17.00
14.00	5.82	17.80	20.00	3.00	69.46	17.00
15.00	5.81	17.70	20.00	3.00	69.34	17.00
16.00	5.81	17.60	20.00	3.00	69.34	17.00
17.00	5.71	17.50	20.00	3.00	68.15	17.00
18.00	5.60	6.80	20.00	3.00	66.83	17.00
19.00	5.50	4.00	20.00	3.00	65.64	17.00
20.00	5.22	2.50	20.00	3.00	62.30	17.00
21.00	5.11	2.40	20.00	3.00	60.99	17.00
22.00	4.85	3.10	20.00	3.00	57.88	17.00
23.00	4.66	3.90	20.00	3.00	55.62	17.00
24.00	4.54	5.10	20.00	3.00	54.18	17.00
25.00	4.20	6.90	20.00	3.00	50.13	17.00
26.00	3.75	9.00	20.00	3.00	44.75	17.00
27.00	3.31	10.70	20.00	3.00	39.50	17.00
28.00	3.08	12.40	20.00	3.00	36.76	17.00
29.00	2.86	13.50	20.00	3.00	34.13	17.00
30.00	2.66	14.30	20.00	3.00	31.75	17.00
31.00	2.12	14.50	20.00	3.00	25.30	17.00
32.00	2.05	14.70	20.00	3.00	24.47	17.00
33.00	2.00	14.90	20.00	3.00	23.87	17.00
34.00	1.93	15.00	20.00	3.00	23.03	17.00
35.00	1.91	15.10	20.00	3.00	22.80	17.00
36.00	1.91	15.10	20.00	3.00	22.80	17.00

Exp 4 : 15 V adsorption , 0.1 V desorption (weight =75.19 g)						
Time (min)	Weight (g)	TI (c)	P1 (kPa)	P2 (kPa)	uptake	dP (P1-P2)
0.00	0	24.6	0	0	0.00	0.00
1.00	1.05	45.20	20.00	3.00	13.96	17.00
2.00	2.39	41.30	20.00	3.00	31.79	17.00
3.00	2.67	39.30	20.00	3.00	35.51	17.00
4.00	2.87	38.60	20.00	3.00	38.17	17.00
5.00	3.03	37.80	20.00	3.00	40.30	17.00
6.00	3.51	36.70	20.00	3.00	46.68	17.00
7.00	3.65	35.00	20.00	3.00	48.54	17.00
8.00	3.74	33.20	20.00	3.00	49.74	17.00
9.00	3.87	31.50	20.00	3.00	51.47	17.00
10.00	3.92	30.00	19.00	3.00	52.13	16.00
11.00	4.01	28.80	19.00	3.00	53.33	16.00
12.00	4.06	28.00	19.00	3.00	54.00	16.00
13.00	4.08	27.30	19.00	3.00	54.26	16.00
14.00	4.10	26.80	19.00	3.00	54.53	16.00
15.00	3.94	26.20	19.00	3.00	52.40	16.00
16.00	3.97	26.00	19.00	3.00	52.80	16.00
17.00	3.97	25.80	19.00	3.00	52.80	16.00
18.00	3.97	25.60	19.00	3.00	52.80	16.00
19.00	3.94	25.40	18.00	3.00	52.40	15.00
20.00	3.94	25.30	18.00	2.00	52.40	16.00
21.00	3.93	25.20	18.00	2.00	52.27	16.00
22.00	3.92	25.10	18.00	2.00	52.13	16.00
23.00	3.92	25.00	18.00	2.00	52.13	16.00
24.00	3.89	24.90	18.00	2.00	51.74	16.00
25.00	3.88	24.80	18.00	2.00	51.60	16.00
26.00	3.87	24.70	18.00	2.00	51.47	16.00
27.00	3.88	24.70	17.00	2.00	51.60	15.00
28.00	3.87	24.60	17.00	2.00	51.47	15.00
29.00	3.86	24.60	17.00	2.00	51.34	15.00
30.00	3.94	24.60	17.00	2.00	52.40	15.00
31.00	3.93	24.50	17.00	2.00	52.27	15.00
32.00	3.92	24.50	17.00	2.00	52.13	15.00
33.00	3.92	24.50	16.00	2.00	52.13	14.00
34.00	3.29	23.00	20.00	3.00	43.76	17.00
35.00	1.70	23.00	20.00	3.00	22.61	17.00
36.00	1.23	2.90	20.00	3.00	16.36	17.00
37.00	0.92	-4.30	20.00	3.00	12.24	17.00
38.00	0.74	-5.00	20.00	3.00	9.84	17.00
39.00	0.66	-4.40	20.00	3.00	8.78	17.00
40.00	0.61	-3.00	20.00	3.00	8.11	17.00
41.00	0.51	1.30	20.00	3.00	6.78	17.00
42.00	0.43	6.00	20.00	3.00	5.72	17.00
43.00	0.42	13.10	20.00	3.00	5.59	17.00
44.00	0.38	16.00	20.00	3.00	5.05	17.00
45.00	0.36	17.70	20.00	3.00	4.79	17.00
46.00	0.35	19.00	20.00	3.00	4.65	17.00
47.00	0.32	19.90	20.00	3.00	4.26	17.00
48.00	0.32	20.60	20.00	3.00	4.26	17.00
49.00	0.32	21.40	20.00	3.00	4.26	17.00

50.00	0.3	21.20	20.00	3.00	3.99	17.00
51.00	0.27	21.40	20.00	3.00	3.59	17.00
52.00	0.25	21.60	20.00	3.00	3.32	17.00
53.00	0.25	21.70	20.00	3.00	3.32	17.00
54.00	0.22	21.80	20.00	3.00	2.93	17.00
55.00	0.17	22.10	20.00	3.00	2.26	17.00
56.00	0.15	22.10	20.00	3.00	1.99	17.00
57.00	0.14	22.20	20.00	3.00	1.86	17.00
58.00	0.14	22.30	20.00	3.00	1.86	17.00
59.00	0.14	22.30	20.00	3.00	1.86	17.00
60.00	0.12	22.30	20.00	3.00	1.60	17.00
61.00	0.12	22.00	20.00	3.00	1.60	17.00
62.00	0.12	22.50	20.00	3.00	1.60	17.00
63.00	0.11	22.50	20.00	3.00	1.46	17.00
64.00	0.12	22.60	20.00	3.00	1.60	17.00
65.00	0.12	22.30	20.00	3.00	1.60	17.00
66.00	0.12	22.00	20.00	3.00	1.60	17.00

Exp 5 : 20 V adsorption / 1.5 V desorption (weight = 90.07 g)						
Time (min)	Weight (g)	TI (c)	P1 (kPa)	P2 (kPa)	uptake	dP (P1-P2)
0.00	0.00	22.90	0.00	0.00	0.00	0.00
1.00	-0.02	18.90	20.00	6.00	-0.22	14.00
2.00	3.60	43.60	20.00	6.00	39.97	14.00
3.00	4.39	46.60	20.00	6.00	48.74	14.00
4.00	5.21	48.80	20.00	6.00	57.84	14.00
5.00	5.76	48.70	20.00	6.00	63.95	14.00
6.00	6.00	46.90	19.00	5.00	66.61	14.00
7.00	6.39	44.60	19.00	5.00	70.94	14.00
8.00	6.61	43.40	20.00	6.00	73.39	14.00
9.00	6.74	42.30	20.00	6.00	74.83	14.00
10.00	7.30	41.60	20.00	6.00	81.05	14.00
11.00	7.43	41.00	21.00	6.00	82.49	15.00
12.00	7.69	40.40	21.00	6.00	85.38	15.00
13.00	7.66	39.80	20.00	6.00	85.04	14.00
14.00	7.68	38.40	20.00	6.00	85.27	14.00
15.00	7.69	39.00	20.00	6.00	85.38	14.00
16.00	7.12	37.40	20.00	6.00	79.05	14.00
17.00	5.13	24.30	20.00	6.00	56.96	14.00
18.00	3.68	9.10	19.00	5.00	40.86	14.00
19.00	3.65	8.20	19.00	5.00	40.52	14.00
20.00	3.05	13.90	20.00	6.00	33.86	14.00
21.00	2.65	20.70	20.00	6.00	29.42	14.00
22.00	2.55	23.00	20.00	6.00	28.31	14.00
23.00	2.56	23.90	20.00	6.00	28.42	14.00
24.00	2.58	24.10	20.00	6.00	28.64	14.00

25.00	2.57	24.30	20.00	6.00	28.53	14.00
26.00	2.59	24.50	20.00	6.00	28.76	14.00
27.00	2.58	24.70	20.00	6.00	28.64	14.00
28.00	2.56	24.90	20.00	6.00	28.42	14.00
29.00	2.57	25.10	20.00	6.00	28.53	14.00
30.00	2.56	25.30	20.00	6.00	28.42	14.00

Part 2 : Granular Activated Carbon Size 1.5 mm

Exp 6 : 5 V adsorption , 0.3 V desorption (weight =85.16 g)						
Time (min)	Weight (g)	TI (c)	P1 (kPa)	P2 (kPa)	uptake	dP (P1-P2)
0.00	0.00	49.80	20.00	1.00	0.00	19.00
1.00	3.73	49.90	20.00	1.00	43.80	19.00
2.00	4.04	48.50	20.00	1.00	47.44	19.00
3.00	4.01	46.20	20.00	1.00	47.09	19.00
4.00	4.28	44.90	20.00	1.00	50.26	19.00
5.00	4.66	42.50	20.00	1.00	54.72	19.00
6.00	5.07	40.40	20.00	1.00	59.53	19.00
7.00	5.77	38.70	20.00	1.00	67.75	19.00
8.00	6.68	36.60	20.00	1.00	78.44	19.00
9.00	7.85	35.10	20.00	1.00	92.18	19.00
10.00	8.60	33.60	20.00	1.00	100.99	19.00
11.00	9.44	32.30	20.00	1.00	110.85	19.00
12.00	10.34	30.70	20.00	1.00	121.42	19.00
13.00	11.04	29.60	20.00	1.00	129.64	19.00
14.00	11.65	28.50	20.00	1.00	136.80	19.00
15.00	11.22	27.60	20.00	1.00	131.75	19.00
16.00	11.20	26.60	20.00	1.00	131.52	19.00
17.00	10.83	26.20	20.00	1.00	127.17	19.00
18.00	10.80	25.50	20.00	1.00	126.82	19.00
19.00	10.79	25.00	20.00	1.00	126.70	19.00
20.00	10.79	24.70	20.00	1.00	126.70	19.00
21.00	10.77	24.50	20.00	1.00	126.47	19.00
22.00	10.80	24.30	20.00	1.00	126.82	19.00
23.00	10.83	23.90	20.00	1.00	127.20	19.00
24.00	10.79	23.90	20.00	1.00	126.70	19.00
25.00	10.77	24.10	20.00	1.00	126.47	19.00
26.00	10.78	24.10	19.00	1.00	126.59	18.00
27.00	10.77	24.10	19.00	1.00	126.47	18.00
28.00	10.75	24.00	19.00	1.00	126.23	18.00
29.00	10.75	23.90	19.00	1.00	126.23	18.00
30.00	10.74	23.90	19.00	1.00	126.12	18.00
31.00	10.83	23.90	19.00	1.00	127.17	18.00
32.00	10.81	23.80	19.00	1.00	126.94	18.00
33.00	10.90	23.90	19.00	1.00	127.99	18.00
34.00	10.85	23.90	19.00	1.00	127.41	18.00
35.00	10.81	23.80	19.00	1.00	126.94	18.00

36.00	10.79	23.80	19.00	1.00	126.70	18.00
37.00	10.77	23.80	19.00	1.00	126.47	18.00
38.00	10.79	23.70	18.00	1.00	126.70	17.00
39.00	10.76	23.70	18.00	1.00	126.35	17.00
40.00	10.75	23.60	18.00	1.00	126.23	17.00
41.00	10.73	2.50	20.00	2.00	126.00	18.00
42.00	9.88	-4.30	20.00	2.00	116.02	18.00
43.00	9.41	-10.80	20.00	2.00	110.50	18.00
44.00	8.88	-12.80	20.00	2.00	104.27	18.00
45.00	8.88	-12.70	20.00	2.00	104.27	18.00
46.00	8.45	-12.00	20.00	2.00	99.22	18.00
47.00	8.65	-10.90	20.00	2.00	101.57	18.00
48.00	8.31	-10.90	20.00	2.00	97.58	18.00
49.00	8.29	-5.30	20.00	2.00	97.35	18.00
50.00	8.09	2.50	20.00	2.00	95.00	18.00
51.00	8.06	10.50	20.00	2.00	94.65	18.00
52.00	8.14	15.90	20.00	2.00	95.58	18.00
53.00	8.13	18.60	20.00	2.00	95.47	18.00
54.00	8.17	19.60	20.00	2.00	95.94	18.00
55.00	8.13	20.30	20.00	2.00	95.47	18.00
56.00	7.94	21.00	20.00	2.00	93.24	18.00
57.00	7.50	21.30	20.00	2.00	88.07	18.00
58.00	7.29	21.60	20.00	2.00	85.60	18.00
59.00	7.35	22.10	20.00	2.00	86.31	18.00
60.00	7.46	22.30	20.00	2.00	87.60	18.00
61.00	7.50	22.50	20.00	2.00	88.07	18.00
62.00	7.55	22.50	20.00	2.00	88.66	18.00
63.00	7.66	22.60	20.00	2.00	89.95	18.00
64.00	7.64	22.70	20.00	2.00	89.71	18.00
65.00	7.69	22.80	20.00	2.00	90.30	18.00
66.00	7.67	22.90	20.00	2.00	90.07	18.00
67.00	7.67	22.90	20.00	2.00	90.07	18.00
68.00	7.71	22.90	20.00	2.00	90.54	18.00
69.00	7.74	22.90	20.00	2.00	90.89	18.00
70.00	7.72	22.90	20.00	2.00	90.65	18.00
71.00	7.68	23.00	20.00	2.00	90.18	18.00
72.00	7.72	23.00	20.00	2.00	90.65	18.00
73.00	7.66	23.00	20.00	2.00	89.95	18.00
74.00	7.83	23.00	20.00	2.00	91.94	18.00
75.00	7.80	23.10	20.00	2.00	91.59	18.00
76.00	7.78	23.10	20.00	2.00	91.36	18.00
77.00	7.79	23.10	20.00	2.00	91.47	18.00
78.00	7.78	23.10	20.00	2.00	91.36	18.00
79.00	7.78	23.10	20.00	2.00	91.36	18.00
80.00	7.78	23.10	20.00	2.00	91.36	18.00

Exp 7 : 8 V adsorption , 0.5 V desorption (weight = 83.62 g)

Time (min)	Weight (g)	TI (c)	P1 (kPa)	P2 (kPa)	uptake	dP (P1-P2)
0.00	0.00	53.00	21.00	1.00	0.00	20.00
1.00	3.56	54.00	21.00	1.00	42.57	20.00
2.00	8.47	54.50	21.00	1.00	101.29	20.00
3.00	9.03	52.70	21.00	1.00	107.99	20.00
4.00	9.74	49.50	21.00	1.00	116.48	20.00
5.00	10.20	48.00	21.00	1.00	121.98	20.00
6.00	10.78	46.00	20.00	1.00	128.92	19.00
7.00	11.07	44.20	20.00	1.00	132.38	19.00
8.00	11.40	42.40	20.00	1.00	136.33	19.00
9.00	11.45	40.90	20.00	1.00	136.93	19.00
10.00	11.49	39.60	19.00	1.00	137.41	18.00
11.00	11.43	38.30	19.00	1.00	136.69	18.00
12.00	11.50	37.10	19.00	1.00	137.53	18.00
13.00	11.42	36.60	18.00	1.00	136.57	17.00
14.00	11.41	35.10	18.00	1.00	136.45	17.00
15.00	11.40	34.30	18.00	1.00	136.33	17.00
16.00	11.43	33.60	18.00	1.00	136.69	17.00
17.00	11.32	32.80	18.00	1.00	135.37	17.00
18.00	11.25	32.20	17.00	1.00	134.54	16.00
19.00	11.31	31.30	17.00	1.00	135.25	16.00
20.00	11.11	30.80	17.00	1.00	132.86	16.00
21.00	11.04	30.10	17.00	1.00	132.03	16.00
22.00	10.99	29.60	17.00	1.00	131.43	16.00
23.00	10.94	29.50	17.00	1.00	130.83	16.00
24.00	10.93	29.20	17.00	1.00	130.71	16.00
25.00	10.77	29.10	16.00	1.00	128.80	15.00
26.00	10.72	28.60	16.00	1.00	128.20	15.00
27.00	10.62	28.40	16.00	1.00	127.00	15.00
28.00	10.64	28.10	16.00	1.00	127.24	15.00
29.00	10.64	28.10	16.00	1.00	127.24	15.00
30.00	10.62	28.00	16.00	1.00	127.00	15.00
31.00	10.62	27.90	16.00	1.00	127.00	15.00
32.00	10.62	27.90	16.00	1.00	127.00	15.00
33.00	10.61	27.90	16.00	1.00	126.88	15.00
34.00	10.62	27.80	16.00	1.00	127.00	15.00
35.00	9.42	22.00	20.00	1.00	112.65	19.00
36.00	6.16	5.30	20.00	1.00	73.67	19.00
37.00	4.70	-3.50	20.00	1.00	56.21	19.00
38.00	3.43	-7.30	20.00	1.00	41.02	19.00
39.00	2.96	-7.50	20.00	1.00	35.40	19.00
40.00	2.51	-7.10	20.00	1.00	30.02	19.00
41.00	2.21	-6.10	20.00	1.00	26.43	19.00
42.00	2.01	-4.90	20.00	1.00	24.04	19.00
43.00	2.03	-2.20	20.00	1.00	24.28	19.00
44.00	2.05	0.20	20.00	1.00	24.52	19.00
45.00	2.06	2.50	20.00	1.00	24.64	19.00
46.00	2.10	8.90	20.00	1.00	25.11	19.00
47.00	2.15	12.80	20.00	1.00	25.71	19.00
48.00	2.32	15.50	20.00	1.00	27.74	19.00
49.00	2.51	18.30	20.00	1.00	30.02	19.00

50.00	2.55	19.40	20.00	1.00	30.50	19.00
51.00	2.80	20.60	20.00	1.00	33.48	19.00
52.00	2.97	21.10	21.00	1.00	35.52	20.00
53.00	3.04	21.70	21.00	1.00	36.35	20.00
54.00	3.11	20.00	21.00	1.00	37.19	20.00
55.00	3.15	22.30	21.00	1.00	37.67	20.00
56.00	3.39	22.60	21.00	1.00	40.54	20.00
57.00	3.45	22.70	21.00	1.00	41.26	20.00
58.00	3.57	22.90	21.00	1.00	42.69	20.00
59.00	3.18	22.90	21.00	1.00	38.03	20.00
60.00	3.58	23.00	21.00	1.00	42.81	20.00
61.00	3.59	23.10	21.00	1.00	42.93	20.00
62.00	3.59	23.10	21.00	1.00	42.93	20.00
63.00	3.59	23.20	21.00	1.00	42.93	20.00
64.00	3.58	23.30	21.00	1.00	42.81	20.00
65.00	3.57	23.30	21.00	1.00	42.69	20.00
66.00	3.58	23.40	21.00	1.00	42.81	20.00
67.00	3.58	23.40	21.00	1.00	42.81	20.00
68.00	3.57	23.50	21.00	1.00	42.69	20.00

Exp 8 : 10 V adsorption , 0.6 V desorption (weight = 84.37 g)

Time (min)	Weight (g)	TI (c)	P1 (kPa)	P2 (kPa)	uptake	dP (P1-P2)
0.00	0.00	30.10	20.00	4.00	0.00	16.00
1.00	3.14	51.40	20.00	3.00	37.22	17.00
2.00	3.85	52.50	20.00	3.00	45.63	17.00
3.00	5.24	53.30	20.00	3.00	62.11	17.00
4.00	5.25	53.50	20.00	4.00	62.23	16.00
5.00	5.27	50.50	20.00	4.00	62.46	16.00
6.00	5.43	47.80	20.00	4.00	64.36	16.00
7.00	5.74	44.60	20.00	4.00	68.03	16.00
8.00	5.96	41.40	20.00	4.00	70.64	16.00
9.00	6.07	39.90	20.00	4.00	71.95	16.00
10.00	6.12	38.90	20.00	3.00	72.54	17.00
11.00	6.14	38.20	19.00	3.00	72.77	16.00
12.00	6.18	37.60	18.00	3.00	73.25	15.00
13.00	6.22	37.40	18.00	3.00	73.72	15.00
14.00	6.26	37.30	18.00	3.00	74.20	15.00
15.00	6.06	37.40	18.00	3.00	71.83	15.00
16.00	6.13	37.50	16.00	3.00	72.66	13.00
17.00	6.13	-4.60	20.00	4.00	72.66	16.00
18.00	5.04	-9.00	20.00	4.00	59.74	16.00
19.00	4.81	-10.40	20.00	4.00	57.01	16.00
20.00	4.04	-11.30	20.00	4.00	47.88	16.00
21.00	3.43	-8.00	20.00	4.00	40.65	16.00
22.00	2.54	4.40	20.00	4.00	30.11	16.00
23.00	0.95	13.00	20.00	4.00	11.26	16.00
24.00	0.66	17.00	20.00	4.00	7.82	16.00
25.00	0.46	21.00	20.00	4.00	5.45	16.00
26.00	0.31	21.90	20.00	4.00	3.67	16.00
27.00	0.27	22.40	20.00	4.00	3.20	16.00

28.00	0.28	22.70	20.00	4.00	3.32	16.00
29.00	0.45	22.80	20.00	4.00	5.33	16.00
30.00	0.39	23.00	20.00	4.00	4.62	16.00
31.00	0.31	23.10	20.00	4.00	3.67	16.00
32.00	0.30	23.20	20.00	4.00	3.56	16.00
33.00	0.34	23.30	20.00	4.00	4.03	16.00
34.00	0.22	23.40	20.00	4.00	2.61	16.00

Exp 9 : 15 V adsorption , 1.0 V desorption (weight = 84.94 g)

Time (min)	Weight (g)	TI (c)	P1 (kPa)	P2 (kPa)	uptake	dP (P1-P2)
0.00	0.00	62.60	21.00	2.00	0.00	19.00
1.00	0.30	63.50	21.00	2.00	3.53	19.00
2.00	0.46	62.40	20.00	2.00	5.42	18.00
3.00	0.78	61.00	20.00	2.00	9.18	18.00
4.00	1.07	59.40	20.00	2.00	12.60	18.00
5.00	1.25	58.30	20.00	2.00	14.72	18.00
6.00	1.45	57.70	20.00	2.00	17.07	18.00
7.00	1.75	56.60	20.00	2.00	20.60	18.00
8.00	1.96	55.80	20.00	2.00	23.08	18.00
9.00	2.24	54.70	20.00	2.00	26.37	18.00
10.00	2.48	53.40	19.00	2.00	29.20	17.00
11.00	2.60	52.00	19.00	2.00	30.61	17.00
12.00	2.81	50.60	19.00	2.00	33.08	17.00
13.00	3.05	48.80	19.00	2.00	35.91	17.00
14.00	3.02	47.50	19.00	2.00	35.55	17.00
15.00	3.15	46.30	19.00	2.00	37.09	17.00
16.00	3.16	45.30	17.00	2.00	37.20	15.00
17.00	3.18	44.80	17.00	2.00	37.44	15.00
18.00	3.26	44.00	16.00	2.00	38.38	14.00
19.00	3.31	43.50	16.00	2.00	38.97	14.00
20.00	3.23	43.20	16.00	1.00	38.03	15.00
21.00	3.24	42.90	16.00	1.00	38.14	15.00
22.00	3.22	42.70	16.00	1.00	37.91	15.00
23.00	3.19	42.60	16.00	1.00	37.56	15.00
24.00	3.21	42.50	16.00	1.00	37.79	15.00
25.00	3.22	42.50	16.00	1.00	37.91	15.00
26.00	3.22	42.50	15.00	1.00	37.91	14.00
27.00	3.23	42.60	15.00	1.00	38.03	14.00
28.00	3.16	42.70	15.00	1.00	37.20	14.00
29.00	3.20	42.70	15.00	1.00	37.67	14.00
30.00	3.13	42.70	15.00	1.00	36.85	14.00
31.00	3.20	42.70	15.00	1.00	37.67	14.00
32.00	3.21	42.70	15.00	1.00	37.79	14.00
33.00	3.23	42.70	15.00	1.00	38.03	14.00
34.00	3.17	42.80	15.00	1.00	37.32	14.00
35.00	3.17	42.70	15.00	1.00	37.32	14.00
36.00	3.18	42.80	15.00	1.00	37.44	14.00
37.00	3.18	42.80	15.00	1.00	37.44	14.00
38.00	3.18	42.80	15.00	1.00	37.44	14.00

39.00	3.18	42.80	15.00	1.00	37.44	14.00
40.00	3.18	42.60	20.00	2.00	37.44	18.00
41.00	2.97	33.90	20.00	2.00	34.97	18.00
42.00	2.95	17.90	20.00	2.00	34.73	18.00
43.00	2.88	10.00	19.00	2.00	33.91	17.00
44.00	2.78	7.30	19.00	2.00	32.73	17.00
45.00	2.65	6.20	19.00	2.00	31.20	17.00
46.00	2.47	6.00	19.00	2.00	29.08	17.00
47.00	2.23	5.80	19.00	2.00	26.25	17.00
48.00	2.06	6.10	19.00	2.00	24.25	17.00
49.00	1.90	7.50	19.00	2.00	22.37	17.00
50.00	1.73	10.40	18.00	1.00	20.37	17.00
51.00	1.68	12.90	18.00	1.00	19.78	17.00
52.00	1.57	15.80	18.00	1.00	18.48	17.00
53.00	1.43	17.60	18.00	1.00	16.84	17.00
54.00	1.39	18.70	18.00	1.00	16.36	17.00
55.00	1.37	19.60	17.00	1.00	16.13	16.00
56.00	1.36	20.20	17.00	1.00	16.01	16.00
57.00	1.37	20.80	17.00	1.00	16.13	16.00
58.00	1.37	21.30	17.00	1.00	16.13	16.00
59.00	1.38	21.40	16.00	1.00	16.25	15.00
60.00	1.46	21.60	16.00	1.00	17.19	15.00
61.00	1.38	21.80	16.00	1.00	16.25	15.00
62.00	1.36	21.80	16.00	1.00	16.01	15.00
63.00	1.35	21.90	16.00	1.00	15.89	15.00
64.00	1.29	21.90	16.00	1.00	15.19	15.00
65.00	1.32	21.90	16.00	1.00	15.54	15.00
66.00	1.34	21.90	16.00	1.00	15.78	15.00
67.00	1.37	21.90	16.00	1.00	16.13	15.00
68.00	1.39	22.00	16.00	1.00	16.36	15.00
69.00	1.45	22.00	16.00	1.00	17.07	15.00
70.00	1.30	22.00	16.00	1.00	15.30	15.00
71.00	1.34	22.00	16.00	1.00	15.78	15.00
72.00	1.34	22.10	16.00	1.00	15.78	15.00
73.00	1.39	22.10	16.00	1.00	16.36	15.00
74.00	1.38	22.10	16.00	1.00	16.25	15.00
75.00	1.29	22.10	16.00	1.00	15.19	15.00
76.00	1.37	22.10	16.00	1.00	16.13	15.00
77.00	1.37	22.10	16.00	1.00	16.13	15.00
78.00	1.39	22.10	16.00	1.00	16.36	15.00

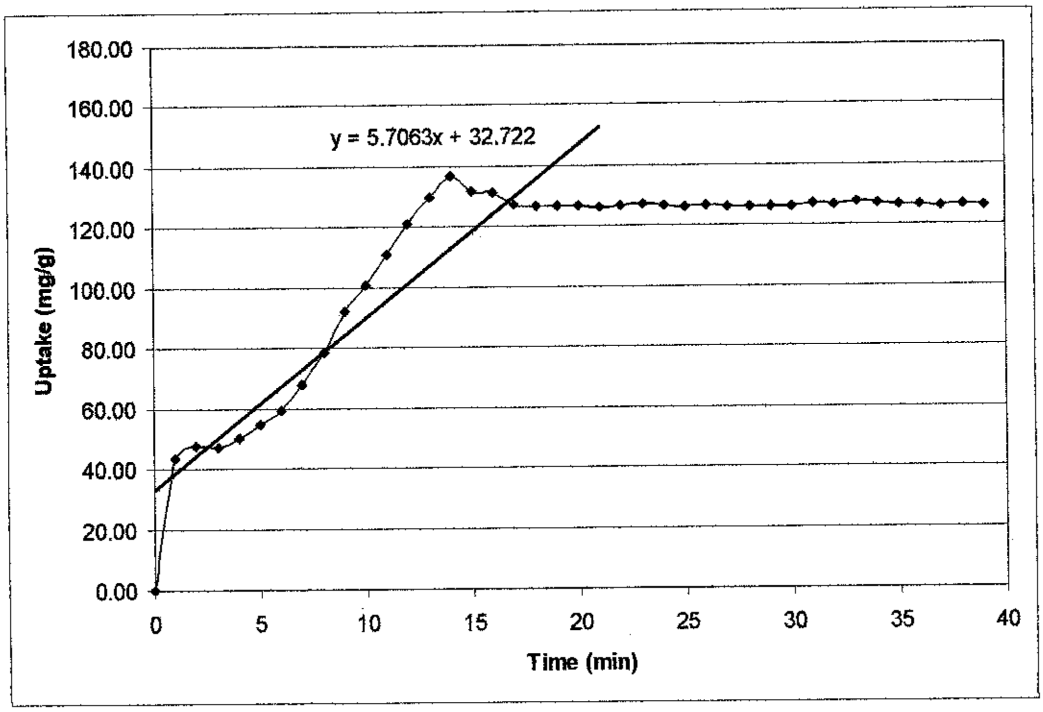
Exp 10 : 20 V adsorption , 1.5 V desorption (weight =87.21 g)

Time (min)	Weight (g)	TI (c)	P1 (kPa)	P2 (kPa)	uptake	dP (P1-P2)
0.00	0.00	74.40	20.00	2.00	0.00	18.00
1.00	0.88	74.40	20.00	2.00	10.09	18.00
2.00	1.16	73.80	20.00	2.00	13.30	18.00
3.00	1.28	73.10	20.00	2.00	14.68	18.00
4.00	1.63	73.20	20.00	2.00	18.69	18.00
5.00	1.84	73.10	20.00	2.00	21.10	18.00
6.00	2.17	72.70	20.00	2.00	24.88	18.00
7.00	2.37	72.20	19.00	2.00	27.18	17.00
8.00	2.59	71.30	19.00	2.00	29.70	17.00
9.00	2.60	70.20	19.00	2.00	29.81	17.00
10.00	2.68	69.20	19.00	2.00	30.73	17.00
11.00	2.83	68.10	18.00	2.00	32.45	16.00
12.00	2.84	67.40	18.00	2.00	32.57	16.00
13.00	2.86	66.90	18.00	2.00	32.79	16.00
14.00	2.91	66.70	18.00	2.00	33.37	16.00
15.00	2.69	66.60	18.00	2.00	30.85	16.00
16.00	2.70	66.60	18.00	2.00	30.96	16.00
17.00	2.74	66.80	18.00	2.00	31.42	16.00
18.00	2.59	66.40	17.00	2.00	29.70	15.00
19.00	2.59	66.90	17.00	2.00	29.70	15.00
20.00	2.58	67.00	17.00	2.00	29.58	15.00
21.00	2.56	67.00	17.00	2.00	29.35	15.00
22.00	2.56	7.80	20.00	3.00	29.35	17.00
23.00	2.46	0.90	20.00	3.00	28.21	17.00
24.00	2.13	-3.50	20.00	3.00	24.42	17.00
25.00	1.91	-5.60	20.00	3.00	21.90	17.00
26.00	1.74	0.50	20.00	3.00	19.95	17.00
27.00	1.57	10.50	20.00	3.00	18.00	17.00
28.00	1.21	18.10	21.00	3.00	13.87	18.00
29.00	0.75	19.90	21.00	3.00	8.60	18.00
30.00	0.50	20.90	21.00	3.00	5.73	18.00
31.00	0.52	21.80	21.00	3.00	5.96	18.00
32.00	0.41	22.30	21.00	3.00	4.70	18.00
33.00	0.37	22.50	21.00	3.00	4.24	18.00
34.00	0.37	22.70	21.00	3.00	4.24	18.00
35.00	0.39	22.80	21.00	3.00	4.47	18.00
36.00	0.37	22.90	21.00	3.00	4.24	18.00
37.00	0.40	22.90	21.00	3.00	4.59	18.00
38.00	0.54	23.00	21.00	3.00	6.19	18.00
39.00	0.48	23.00	21.00	3.00	5.50	18.00
40.00	0.50	23.00	21.00	3.00	5.73	18.00
41.00	0.48	23.00	21.00	3.00	5.50	18.00
42.00	0.48	23.00	21.00	3.00	5.50	18.00
43.00	0.52	23.00	21.00	3.00	5.96	18.00

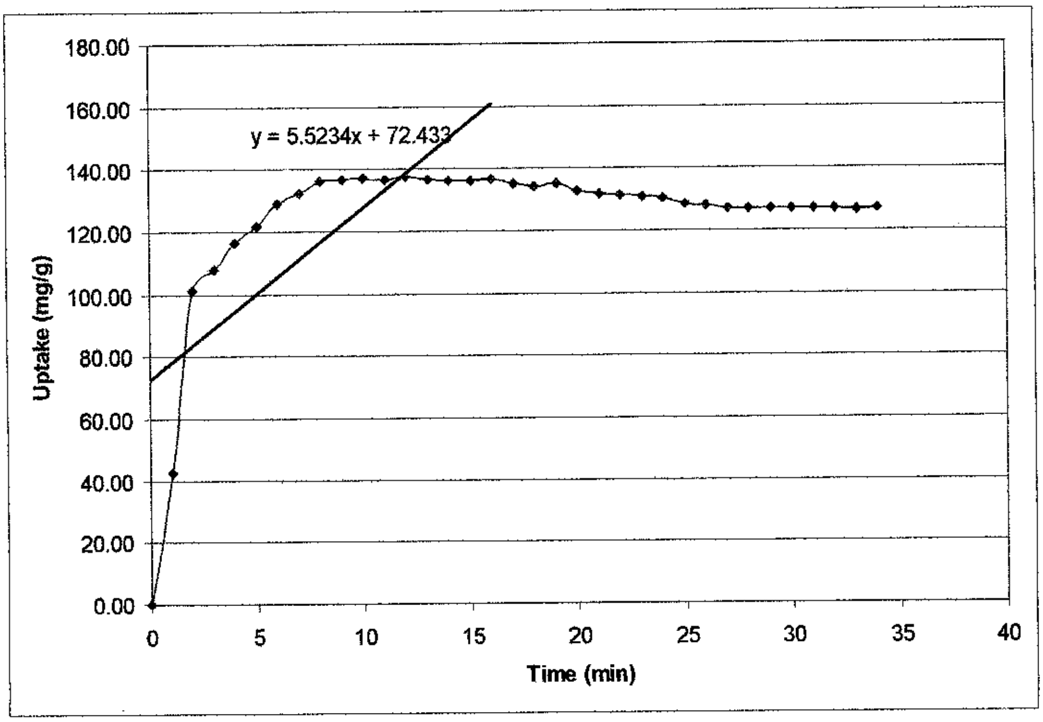
APPENDIX 2 :

1.5 MM GAC ADSORPTION AND DESORPTION GRAPHICAL DATA

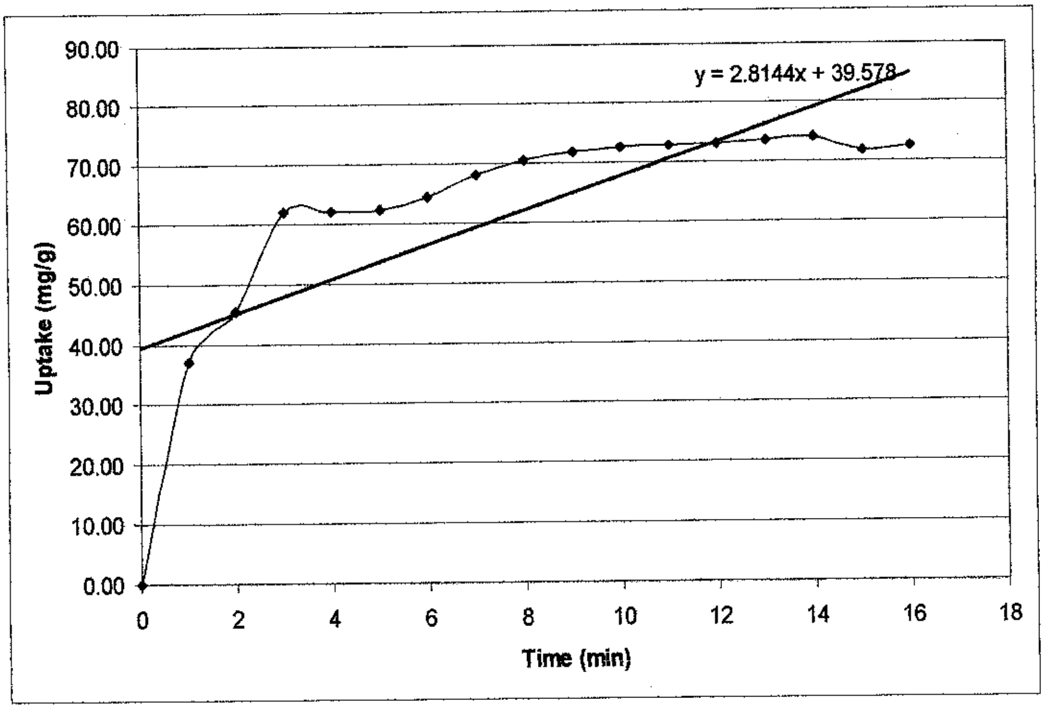
Part 1 : Graphical Adsorption Data for 1.5 mm Granular Activated Carbon



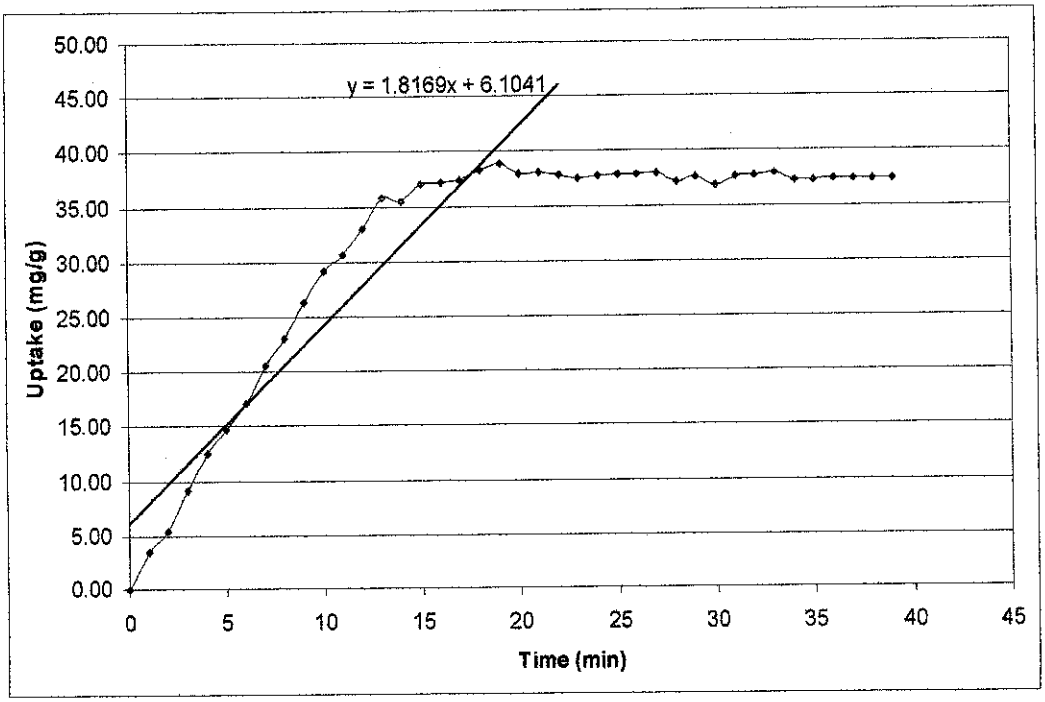
Exp 6 : 5 V adsorption



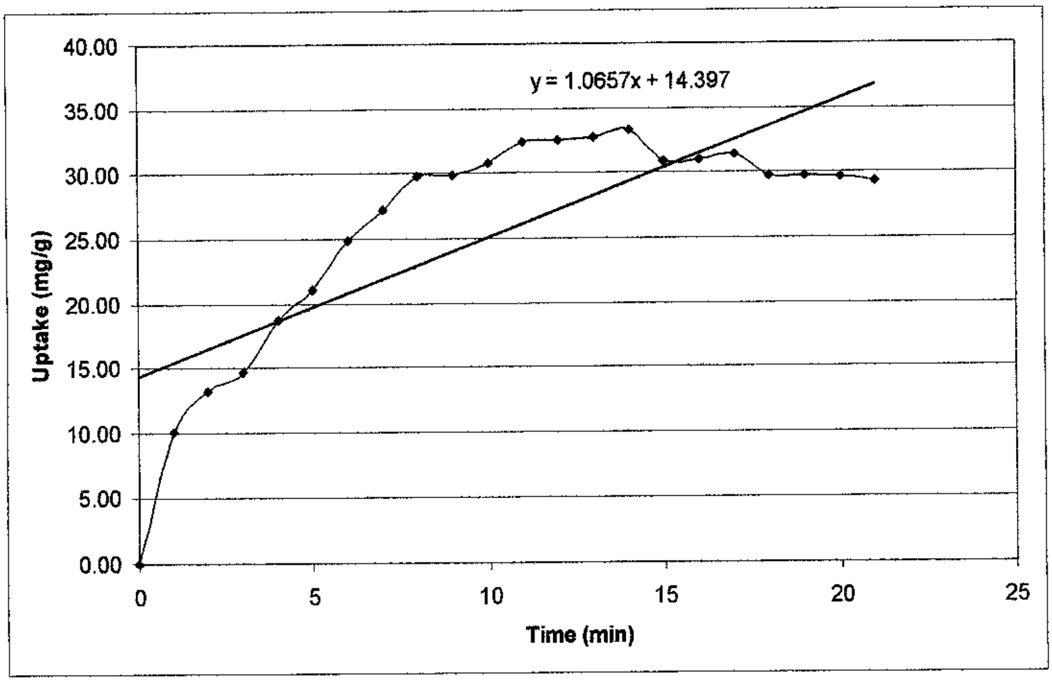
Exp 7 : 8 V adsorption



Exp 8 : 10 V adsorption

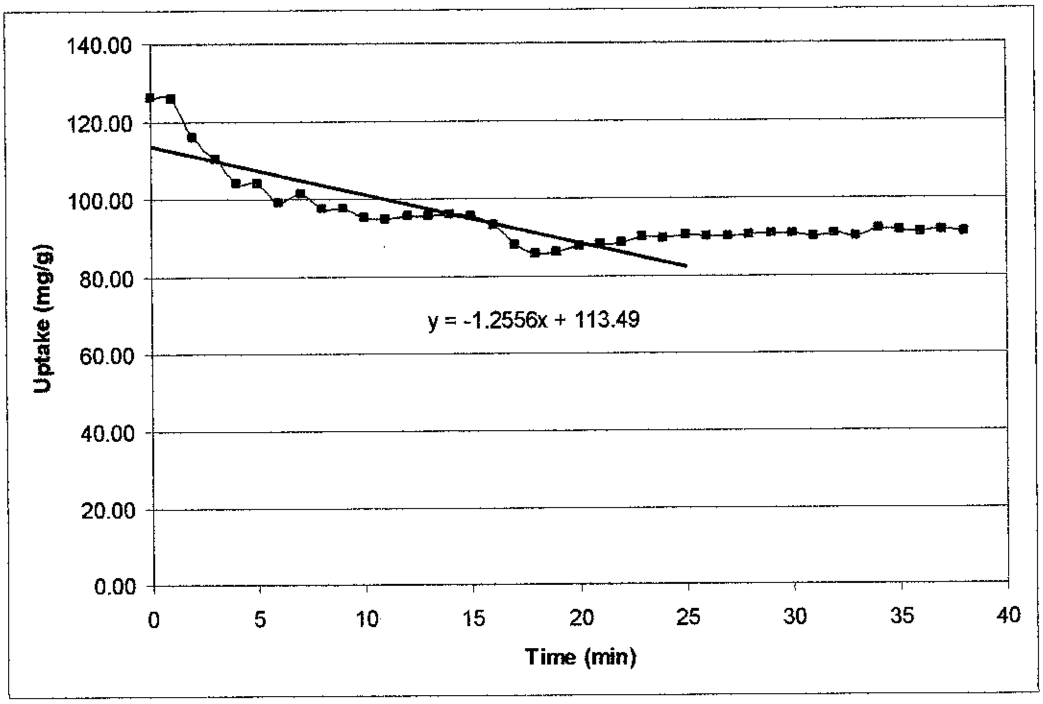


Exp 9 : 15 V adsorption

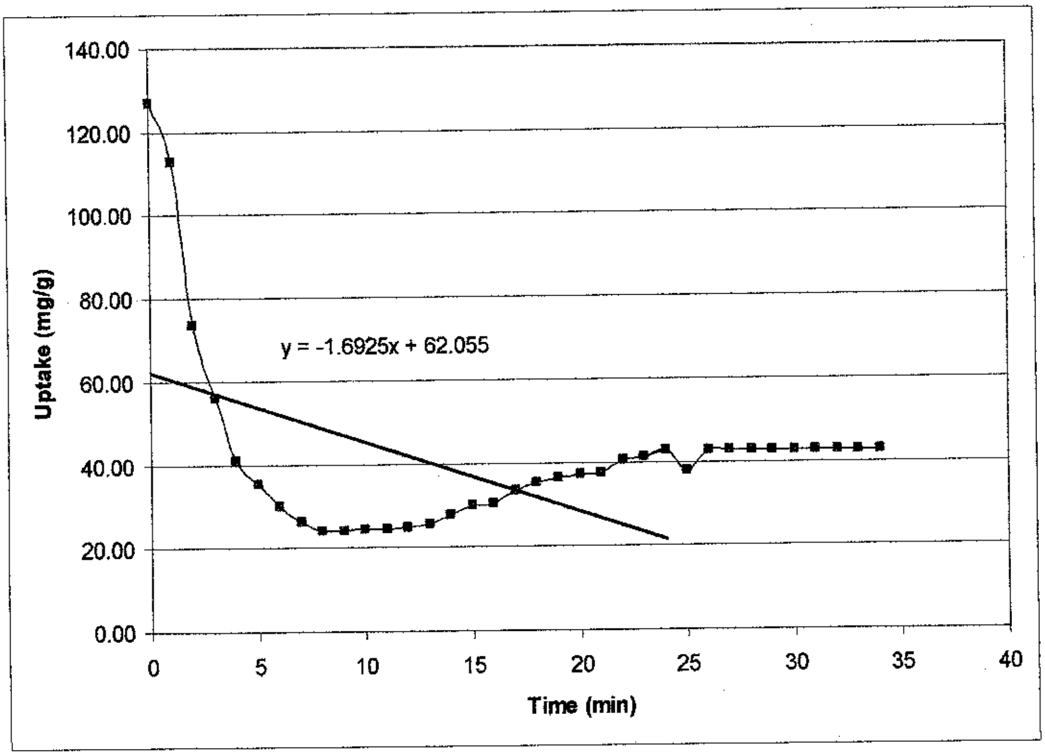


Exp 10 : 20 V adsorption

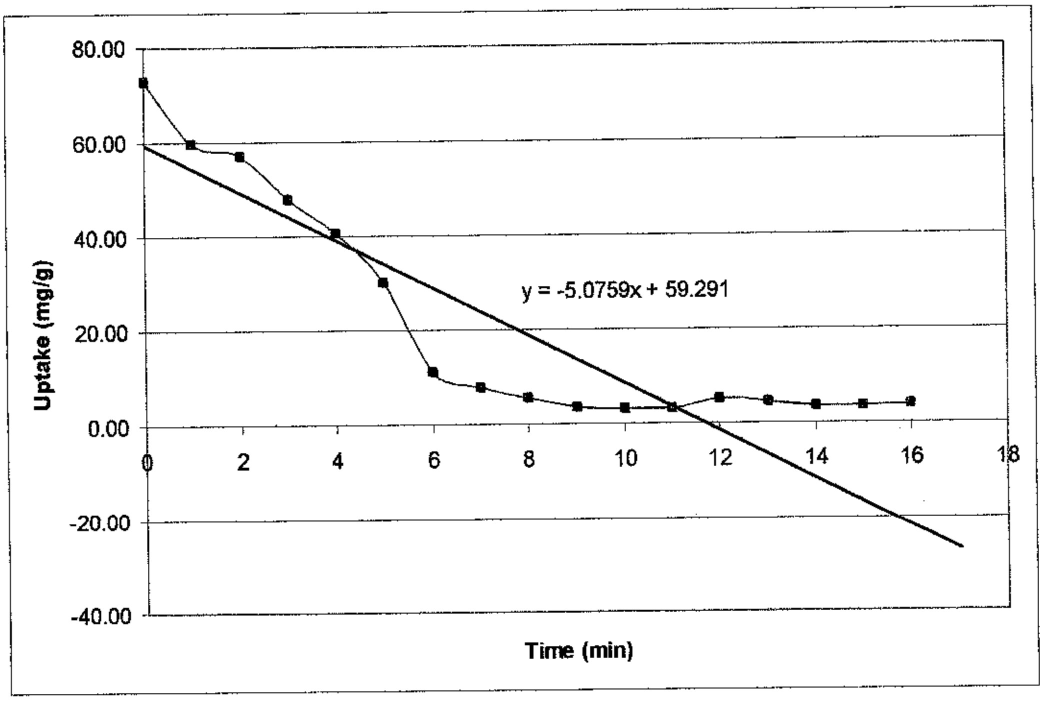
Part 2 : Graphical Desorption Data for 1.5 mm Granular Activated Carbon



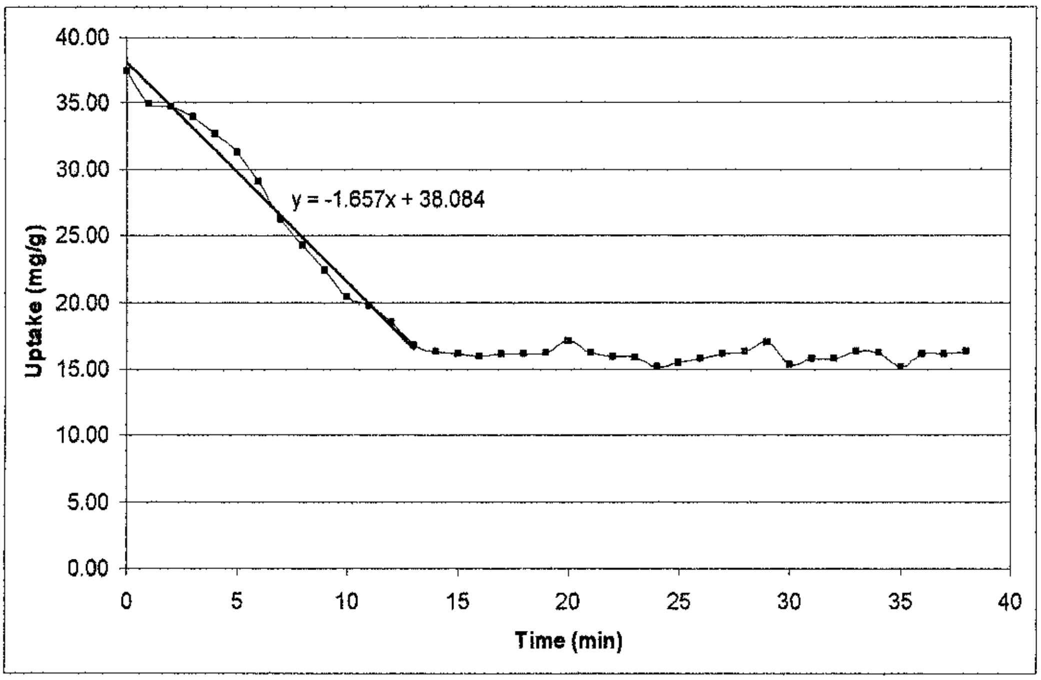
Exp 6 : 0.3 V desorption



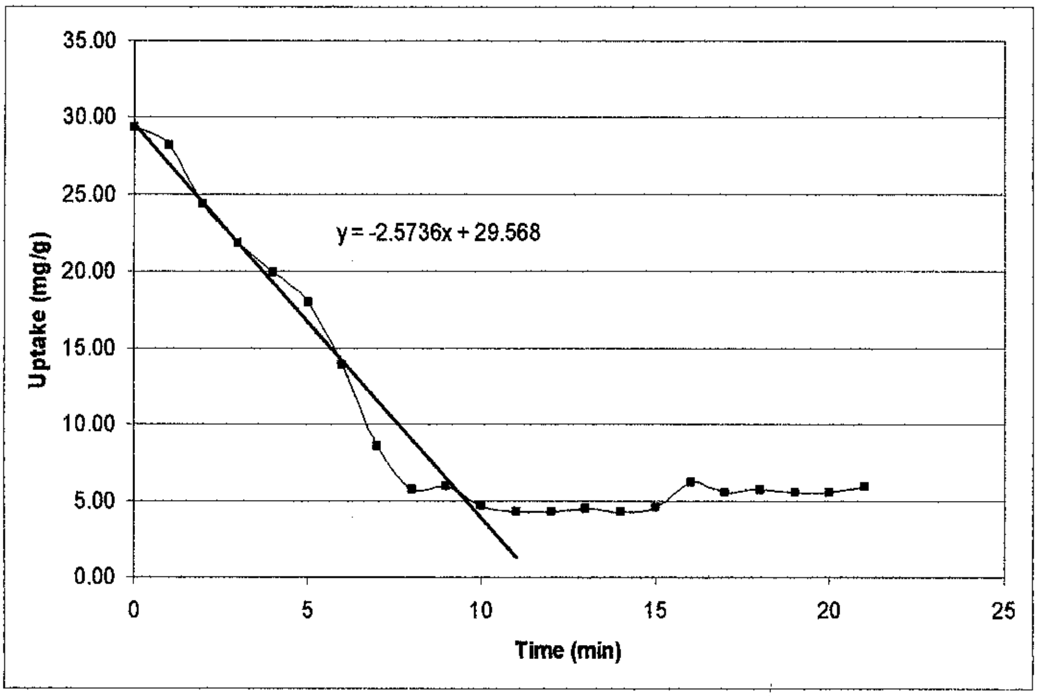
Exp 7 : 0.5 V desorption



Exp 8 : 0.6 V desorption



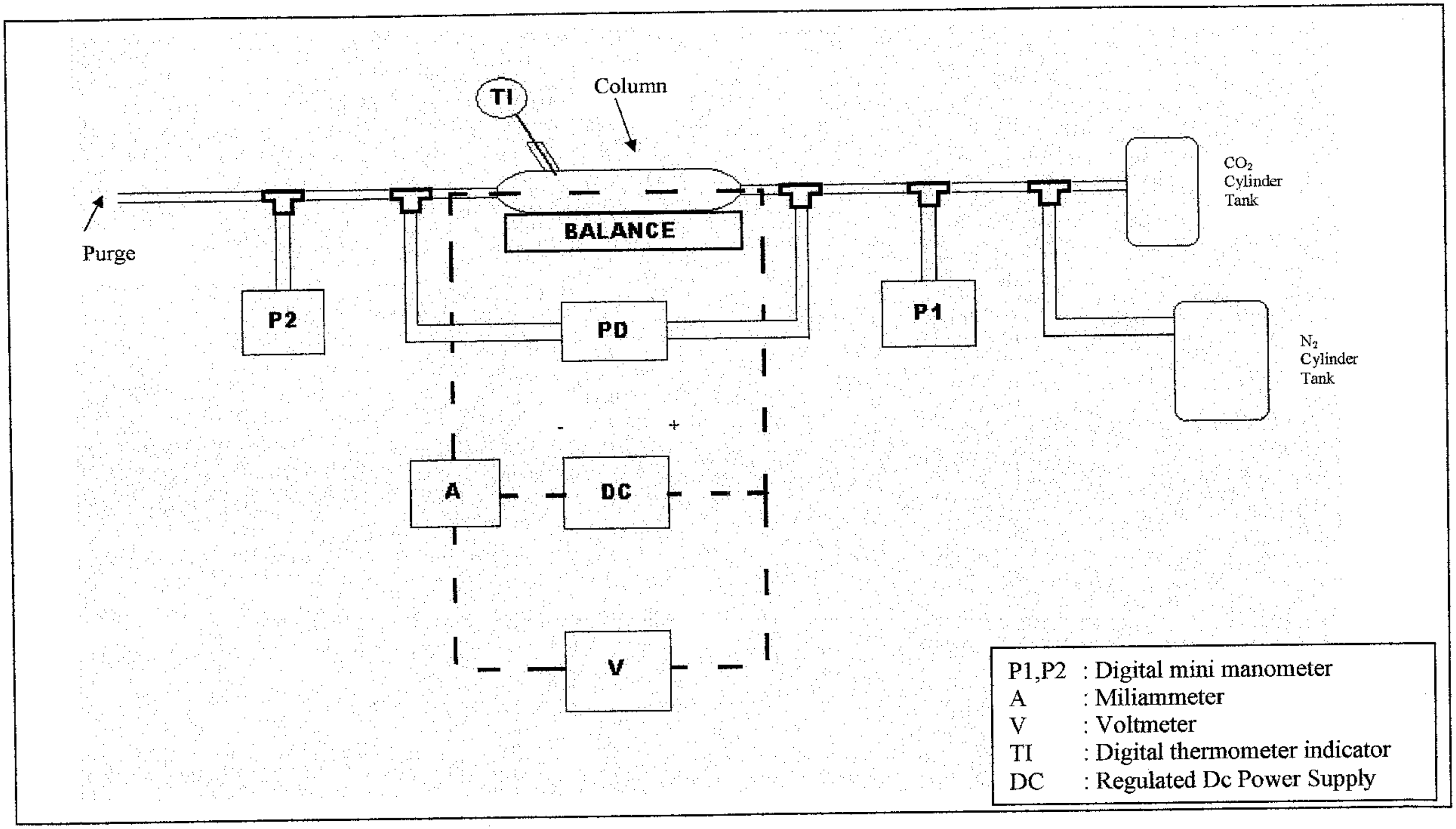
Exp 9 : 1.0 V desorption



Exp 10 : 1.5 V desorption

APPENDIX 3 :

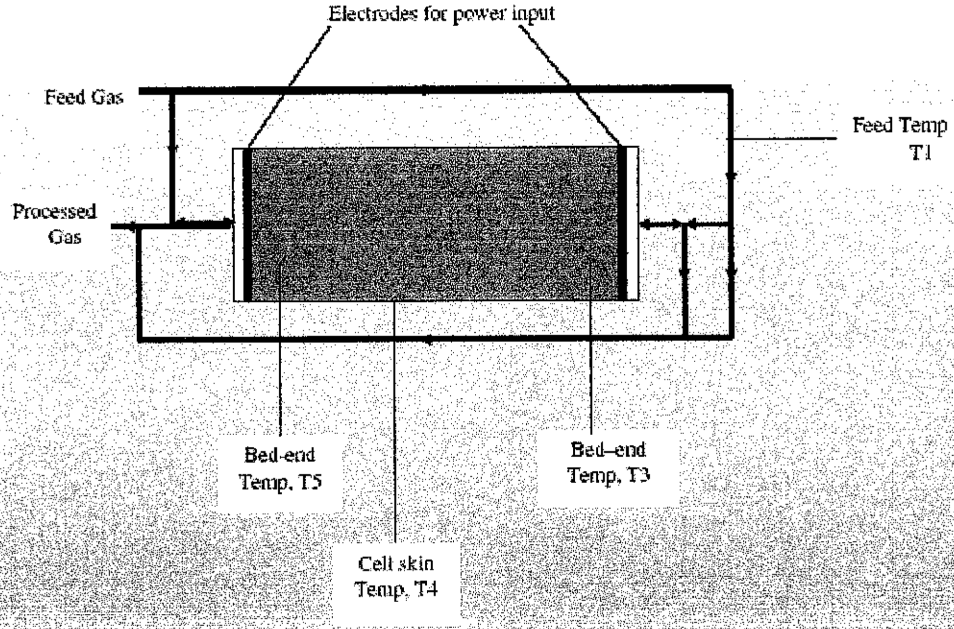
SCHEMATIC DIAGRAM OF EXPERIMENTAL APPARATUS FOR ELECTRICAL ENHANCED DSORPTION/DESORPTION EXPERIMENT


TI
Column
CO_2 Cylinder Tank
BALANCE
Purge
P2
PD
P1
N_2 Cylinder Tank
-
+
A
DC
V
P1,P2 : Digital mini manometer
A : Miliammeter
V : Voltmeter
TI : Digital thermometer indicator
DC : Regulated Dc Power Supply

APPENDIX 4 :

ESA EQUIPMENT IN OAK RIDGE NATIONAL LABORATORY

Schematic of the CFCMS Cell Set-up



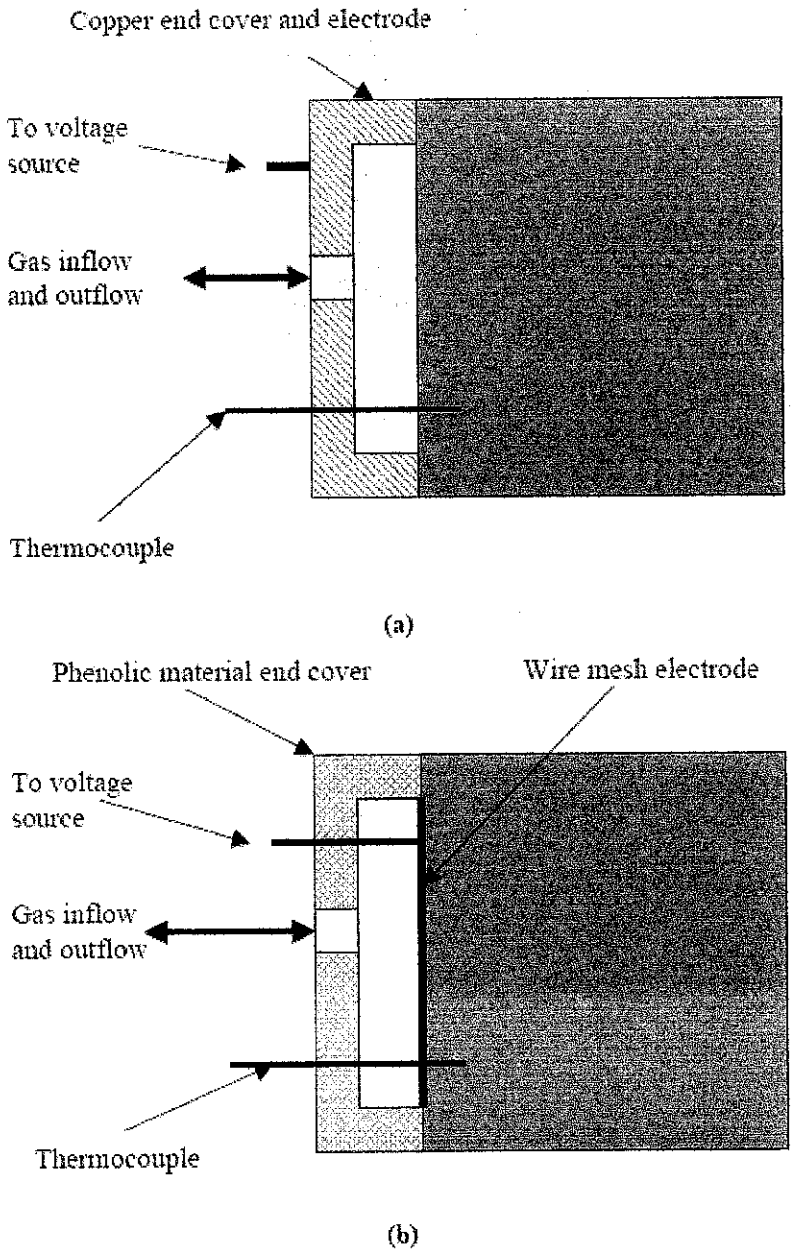


Fig. 3, (a) Schematic of a cell end showing copper end cover as an electrode. (b) Schematic of a cell end showing phenolic end cover and wire mesh electrode.

APPENDIX 4 :
GANTT CHART

NO	DETAILS	WEEK NO														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	***Selection of Project Topic***															
	◆ Topic assigned to student	■														
		▨														
2	***Preliminary Research/ Design Work***															
	◆ Introduction		■	■												
			▨													
	◆ Objective and scope of study		■	■												
			▨													
	◆ List of references/literature		■	■												
			▨													
	◆ Project planning		■	■												
3	***Submission of Preliminary Report***			●												
4	***Project Work***															
	◆ ESA Concept (Literature)			■	■											
	◆ Polarizability of CO2 (adsorbate) and activated carbon (adsorbent) study			■	■											
	◆ Practical/Laboratory Work			■	■	■	■									
	◆ Result analysis -					■	■									
5	***Submission of Progress Report***								●							
	Project Work continue															
	◆ Results and Discussion								■	■	■	■				

6	◆ Recommendations									■	■	■				
	◆ Conclusion										■	■				
	◆ Literature											■				
7	***EDX***													●		
8	***Submission of Dissertation Draft to Supervisor***															
9	***Submission of Dissertation Final Draft to Supervisor and Coordinator (16th April 2004)***															
10	***Oral Presentation (3 - 7 May 2003)***															
11	***Submission of Hardbound Copy of Project Dissertation to Coordinator (10 - 28 May)***															