PALM-POLYETHERETHERKETONE POROUS CARBONS AS SORBENTS FOR GAS ADSORPTION APPLICATIONS

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To the almighty, the most beneficient the most merciful.

Also to my parents and all my extended family members.

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ABSTRACT

Carbon dioxide (CO_2) emission is attributed as the major contributing factor for global warming. Absorption with amine solutions is the technology that is currently used for CO_2 capture in industries. Adsorption is seen as a viable alternative technology for CO_2 capture due to the techno-economic reasons against the amine based technology. In this study, palm shell being one of the abundant biomass in Malaysia, was used together with polyetheretherketone (PEEK) as precursors for the preparation of porous carbons via microwave induced potassium carbonate chemical activation. The porous carbons were investigated as potential sorbents for high temperature CO_2 capture and methane storage. Design expert software version 7.1.6. using central composite design coupled with surface response methodology was used in predicting and optimization of the preparation conditions of the porous carbons for CO_2 capture. Effects of microwave power, amount of PEEK and irradiation time on the sorbent performance for CO_2 adsorption were investigated. The characteristics of the porous carbons were studied by Fourier transform infrared spectroscopy, pH, thermogravimetric and derivative thermogravimetric analysis, scanning electron microscopy, nitrogen adsorption, proximate and ultimate analysis. The ideal CO_2 adsorption capacities of porous carbons were determined using volumetric method at temperatures of 30 ^oC, 70 ^oC, 105 ^oC and 170 ^oC and pressures of 1 - 4 bar, while methane (CH_4) adsorption was tested only at 30 ^oC. Microwave power was found to be the most significant factor influencing the porous carbon for CO_2 adsorption. The optimum conditions were microwave power of 500 W, irradiation time of 6.89 min and amount of PEEK 21.91%. Highest CO_2 uptake of 2.97 mmol CO_2 adsorbed/g adsorbent was achieved by M4P2 (400 W of microwave power, 6 min irradiation time and 20% amount of PEEK) among the sorbents at 30 ^oC and 1 bar. Highest CH_4 uptake of 1.144 mmol CH_4 adsorbed/g adsorbent was also recorded by M4P0 (400 W of microwave power, 6 min irradiation time and 0% amount of PEEK) sorbent at 30 ^oC and 1 bar. The CO_2 equilibrium data correlated well with Sips isotherms. In all scenarios studied, increase in temperature led to a decrease in CO_2 adsorption while increase in pressure led to an increase in CO_2 adsorption. The sorbents remained stable after seven CO_2 adsorption/regeneration cycles. As a conclusion, the findings revealed the potential of palm shell-PEEK as CO_2 and CH_4 sorbents which needs improvement for further gas adsorption applications.

ABSTRAK

Pembebasan karbon dioksida (CO_2) telah dikenalpasti sebagai faktor penyumbang utama terhadap pemanasan global. Penjerapan dengan larutan amina adalah teknologi yang kini digunakan untuk penangkapan CO_2 dalam industri. Penjerapan dilihat sebagai teknologi alternatif yang berdaya maju untuk menangkap CO_2 kerana faktor tekno-ekonomi terhadap teknologi berasaskan amina. Dalam kajian ini, tempurung kelapa sawit, salah satu daripada biojisim yang terdapat di Malaysia, telah digunakan bersama dengan polietereterketon (PEEK) sebagai prekursor untuk penyediaan karbon berliang melalui ketuhar gelombang mikro yang menghasilkan pengaktifan kimia kalium karbonat. Karbon berliang telah dijadikan sebagai agen penjerap yang berpotensi untuk suhu penangkapan CO_2 suhu tinggi dan penyimpanan metana. Perisian Design Expert versi 7.1.6. menggunakan reka bentuk komposit berpusat dengan kaedah respon permukaan telah digunakan dalam meramalkan dan pengoptimuman syarat penyusunan karbon berliang untuk pengumpulan CO_2. Kesan kuasa gelombang mikro, jumlah PEEK dan masa sinaran ke atas prestasi bahan penjerap untuk penjerapan CO_2 telah disiasat. Ciri-ciri karbon berliang telah dikenalpasti melalui spektroskopi inframerah transformasi Fourier, pH, analisis termogravimetri dan derivatif termogravimetri, mikroskop imbasan elektron, nitrogen penjerapan, analisis proksimat dan muktamad. Kapasiti ideal penjerapan CO_2 oleh karbon berliang ditentukan dengan menggunakan kaedah isipadu pada suhu 30 ^oC, 70 ^oC, 105 ^oC dan 170 ^oC dan tekanan 1 - 4 bar manakala penjerapan metana (CH_4) telah diuji hanya pada 30 ^oC. Kuasa ketuhar gelombang mikro didapati faktor yang paling penting mempengaruhi karbon berliang untuk menjerap CO_2. Keadaan optimum telah ditemui pada kuasa gelombang mikro 500 W, masa penyinaran 6.89 min dan jumlah PEEK 21.91%. Penjerapan CO_2 yang paling tinggi adalah 2.97 mmol CO_2 terserap/g penjerap dicapai dengan M4P2 (400 W kuasa mikro gelombang, 6 min masa penyinaran dan 20% jumlah PEEK) di kalangan penjerap yang berlaku pada 30 ^oC dan 1 bar. Penjerapan CH_4 yang paling tinggi pada 1.144 mmol CH_4 terserap/g penjerap juga dicatat oleh M4P0 (400 W kuasa mikro gelombang, 6 min masa penyinaran dan 0% jumlah PEEK) penjerap pada 30 ^oC dan 1 bar. Data keseimbangan CO_2 telah mematuhi isoterma Sips. Dalam semua senario yang dikaji, peningkatan suhu menyebabkan penurunan dalam penjerapan CO_2 manakala peningkatan tekanan menyebabkan peningkatan penjerapan CO_2. Penjerap-penjerap kekal stabil selepas tujuh kitaran penjerapan/pertumbuhan semula CO_2. Kesimpulannya, hasil kajian menunjukkan potensi tempurung kelapa sawit-PEEK yang baik sebagai penjerap gas CO_2 dan CH_4 yang mana memerlukan penambahbaikan untuk aplikasi penjerapan gas yang seterusnya.

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LIST OF SYMBOLS

A^0 - Angstrom
atm - Atmospheres
$CaCO_3$ - Calcium carbonate
CaO - Calcium oxide
CH_4 - Methane
CO_2 - Carbon dioxide
CO - Carbon monoxide
^0C - Degree Celsius
et al. - and others
etc - Et cetera
g - gram
Gt - Giga tone
h - hour
H_2 - Hydrogen
Hg - Mercury
HCL - Hydrochloric acid
HF - Hydrofluoric acid
HNO_3 - Nitric acid
H_2O - Water
H_2SO_4 - Sulphuric acid
ΔH - Heat of adsorption
Ib - Pounds
in - Inch
J - Joule
K - Kelvin
k - Kilo

K_2CO_3 - Potassium carbonate
KOH - Potassium hydroxide
kPa - Kilo Pascal
KHz - kilo Hertz
mL - millilitre
mm - millimetre
mmol - millimole
nm - nanometre
N_2 - Nitrogen
NO_x - Nitrogen oxides
min - Minute
Psia - Pound per square inch
R - Gas constant
SO_2 - Sulphur dioxide
V_v - Void volume
x_1 - Microwave power
x_2 - Time
x_3 - Amount of PEEK
x_i - Coded values of the independent variables
Y - Predicted response
z - Compressibility factor
% - Percent
Θ - Surface coverage
α_T - Toths constant

LIST OF ABBREVIATIONS

a	-	Adsorption cell
AC	-	Activated carbon
ASU	-	Air separation units
ANG	-	Adsorbed natural gas
ANOVA	-	Analysis of variance
BET	-	Branauer Emmett Teller
CCD	-	Central composite design
CCS	-	Carbon capture and storage
CDM	-	Clean development mechanism
CER	-	Certified emission reduction
CFCs	-	Chlorofluorocarbons
CHNSO	-	Carbon, hydrogen, nitrogen, sulphur and oxygen
C_i	-	Resistance to mass transfer
CNG	-	Compressed natural gas
CNTs	-	Carbon nanotubes
D_{avg}	-	Average pore size
DEM	-	Double exponential model
DTG	-	Derivative thermo-gravimetric
3-D	-	3 Dimensional
ECBM	-	Enhanced coal bed methane
EOR	-	Enhanced Oil Recovery
ESA	-	Electric swing adsorption
ERUs	-	Emission reduction units
FA	-	Fly ash
FC	-	Fixed carbon

FTIR	-	Fourier transform infrared spectroscopy
GHG	-	Greenhouse gas
HSDM	-	Homogeneous solid diffusion model
HTCs	-	Hydrotalcites
IEP	-	Isoelectric point
Ils	-	Ionic liquids
JI	-	Joint implementation
K_{int}	-	Intra-particle diffusion rate constant
K_F	-	Freundlich constant
KL	-	Langmuir constant
K_{LF}	-	Sips constants
KBr	-	Potassium bromide
l	-	Loading cell
LNG	-	Liquefied natural gas
M	-	Molar mass
m	-	mass
M4P0	-	Microwave Palm sorbent prepared at 400 W, 6 min
M4P2	-	Microwave Palm-PEEK sorbent prepared at 400 W, 6 min, PEEK 20 wt%
M5P2	-	Microwave Palm-PEEK sorbent prepared at 500 W, 6 min, PEEK 20 wt%
MEA	-	Monoethanolamine
MOFs	-	Metal organic frameworks
MWCNTs	-	Multiwall carbon nanotubes
n	-	Adsorption intensity
N	-	Number of experiment
P	-	Pressure
PC	-	Porous carbon
PCs	-	Porous Carbons
PEEK	-	Polyetheretherketone
PEKC	-	Polyetheretherketone char
PKC	-	Palm kernel char

PKC1	-	Palm kernel char, carbonized for 1 h
PKC2	-	Palm kernel char carbonized for 2 h
PKC3	-	Palm kernel char carbonized for 3 h
PKS	-	Palm kernel shell
PPBC	-	Palm-polyetheretherketone blended char
PSA	-	Pressure swing adsorption
q	-	Amount adsorbed
q_m	-	Maximum amount adsorbed
q_d	-	Desorption capacity
q_e	-	Adsorption equilibrium
q_{exp}	-	Experimental amount adsorbed
q_p	-	Predicted amount adsorbed
q_r	-	Desorption rate
q_t	-	Amount adsorbed at time t
R^2	-	Correlation coefficient
$R^2{}_{adj}$	-	Correlation coefficient adjusted
RSM	-	Response surface methodology
RSMD	-	Root mean square deviation
R&D	-	Research and Development
S_i	-	Ideal selectivity
SEM	-	Scanning electron microscopy
S_{BET}	-	Surface area, BET
TG	-	Thermo-gravimetric
TSA	-	Temperature swing adsorption
UNFCCC	-	United nations framework convention on climate change
V	-	Volume
VM	-	Volatile matter
VOCs	-	Volatile organic hydrocarbons
V_{micro}	-	Micropore volume
V_{tot}	-	Total pore volume
W	-	Watts
W_c	-	Weight of char

W_p - Weight of precursor

W_{pc} - Weight of porous carbon

XRD - X-Ray diffraction

Ypc - Yield of porous carbon

Yc - Yield char

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Fossil fuel, a major world source of energy is associated with emission of toxic and greenhouse gases into the environment; this is a source of serious concern. The control of anthropogenic CO_2 emission is a crucial matter due to assertion that CO_2 gas contributes hugely to global climate change (Boonpoke et al., 2011; Molina and Bouallou, 2012). The best option for reducing CO_2 emission is to capture it from point source, transport it and then store it in an environment isolated from the atmosphere. Carbon Capture and storage (CCS) technology can be applied to large carbon point sources like: electric power-generation or cogeneration (CHP) facilities, synthetic fuel plants, natural gas fields and chemical industrial facilities (IPCC, 2007). Emissions from electricity and heat production and Stationary CO_2 sources associated with fossil-fuel energy use produce the bulk of the world's CO_2 emissions (IEA, 2008).

On the other hand, Natural gas is receiving attention due its low price with less toxic gas emission compared to conventional fuels. Storage of natural gas with methane being the major component is important. Adsorbed natural gas (ANG) has advantage in methane storage over compressed natural gas (CNG) and liquefied natural gas (LNG). This is due to its low cost, energy efficiency, and safety

(Sren´scek-Nazzal et al., 2013). Porous carbonaceous materials are good candidates for natural gas storage due to large surface area, large pore volume and low density (Delavar et al., 2014).

Post combustion carbon capture is seen as a viable option for CCS because it can be retrofitted to existing power plants (Samanta et al., 2012).The methods used for carbon capture includes: absorption, adsorption, bio-processes, membrane separations and cryogenic separations. Currently, absorption using amine solutions is the technology that is more studied (Tuinier et al., 2011; Deguchi et al., 2011) and it's commercially used for CO_2 capture in power plants. The major drawback in using amine solutions are: High energy consumption, degradation and vapourization of solvent and corrosion of process equipment (Plaza et al., 2010, Shafeeyan et al., 2010; Hsiao et al., 2011; Hisb-ur-Rahman et al., 2012). Adsorption is considered to be a promising method (Su et al., 2009) because of its low energy consumption, low cost, high stability over wide range of pressure and temperature (Fenrong et al., 2010; Shafeeyan et al., 2010) and the sorbent could be dispose safely after use.

Adsorbents such as silica, metal oxides, metal organic frame works, zeolites and activated carbon have been tested for CO_2 capture (Kim et al., 2010; Shen et al. , 2010, Choi et al., 2009). These adsorbents are evaluated in terms of their adsorption/desorption rates, equilibrium CO_2 capabilities, Stability, regeneration abilities (Choi et al., 2009), Selectivity for CO_2 and sorbent cost (Samanta et al., 2011). Carbon based materials are considered to be promising CO_2 capture adsorbents due to their low cost, high surface area, high amenability to surface functionalization and pore structure modifications (Wang et.al., 2011a). Currently, researches showed that carbon based materials are capable of removing CO_2 together with other gaseous pollutants individually and simultaneously (Liu and Liu, 2011; Callen et al., 2007).

Commercial activated carbons can be manufactured from various carbonaceous precursors like lignite and coal (42%), peat (10%), wood (33%) and coconut shell. Nevertheless, its usage is limited because of the relative prices of commercially activated carbons. For this reason, research interest in the production of activated carbons from agricultural and industrial wastes grows rapidly (Tan et al., 2008). Some of agricultural wastes that were successfully converted into activated on a laboratory scale include: coconut shell (Wan Daud et al., 2004), palm wild olive cores (Kaouah et al., 2013), coconut coir (Etim et al., 2012), saw dust (Sevilla et al., 2011), saw dust, bamboo (Boonpoke et al., 2011, Kow et al., 2014) coconut husk (Foo and Hameed, 2012a), cashew nut shells (Tsamba et al., 2006), apricot shell (Xu et al., 2010) empty fruit bunch (Alam et al., 2009), waste tea, almond shells, tomato stems and leaves (Yagmur, 2012). Another prospective low cost precursor for the production of qualitative activated carbon is oil-palm shell (or called endocarp), an agricultural by-product from palm-oil processing mills. This is due to its high carbon content, high density and low ash content. The oil- palm shell is abundant in tropical countries like Malaysia and Thailand (Guo and Lua , 2002*)*. Therefore it will be of paramount importance to convert this less expensive agro waste into activated carbon for contaminants removal.

The surface chemistry of activated carbon strongly affects its adsorption capacity. Because CO_2 is acidic it’s expected that introduction of lewis base on to the activated carbon surface may improve the CO_2 adsorption (Shafeeyan *et al*, 2010*)*. The formation of the surface groups is carried out by reaction of carbon with oxidising gases, hydrogen gas, ammonia, carbon di sulphide and halogens. In addition, carbon surface can also be modified by degassing and by impregnation of metals on the surface (Bansal and Goyal, 2005). The nature of adsorption/desorption process also affects the overall energy savings and economy of the process. Therefore, adsorption of CO_2 on activated carbon can be enhanced by playing around with activated carbon pores and surface chemistry. In this work, K_2CO_3 was used as impregnating agent and subsequent activation was carried out in microwave oven.

In microwave heating, treatment time can be considerably reduced, it also offers low consumption of inert and energy. Microwave heating is internal and volumetric, which provides the advantages of uniform temperature distribution, rapid temperature rise and saving of energy. Microwave system was found to be effective in removal of oxygenated functionalities making the activated carbon surface more basic (Mendez et al., 1999). This property is highly required when using the activated carbon for uptake of acidic gas like CO_2. Microwave system was found to be effective in improving surface properties without much negative impact on the physical properties. Due to the aforementioned advantages of microwave (MW) system, it was selected for the activation of the sorbents in this work.

But adsorption is effective, only when optimum process parameters are employed. This necessitates the study of optimisation of process parameters for CO_2 and CH_4 uptake. Single dimensional methods of optimization, which involves varying only one factor at a time, do not give accurate prediction of optimum conditions (Kannan et al., 2010). Response surface methodology is a multivariable technique that simultaneously optimizes the process parameters (Montgomery, 2001; Utami et al., 2013) to get best response within the experimental region under study. In this study, microwave assisted heating was used in preparation of hybrid palm-PEEK porous carbons as CO_2 sorbents. Three numerical variables (Microwave power, irradiation time and amount of PEEK) were the dependent variables while the amount of CO_2 and CH_4 adsorbed were the dependent parameters. To the best of my knowledge, there is no previous work conducted on CO_2 and CH_4 adsorption on microwave palm shell-PEEK hybrid porous carbons.

Equilibrium relationships correlate the amount of gas adsorbed on a solid sorbate with the applied gas pressure (adsorption isotherms). Modelling of adsorption isotherm data is important for predicting and comparing adsorption performance (Al-Hajjaj et al., 2011) it gives the adsorbent adsorbate relation. The analysis of the equilibrium data by fitting them to different isotherm models is an important step to find the suitable model that can be used for design purposes. Adsorption kinetics is also useful in the design of fixed bed adsorbers, finding mechanism of adsorption process, finding the residence time required for adsorption reaction and for pilot application (Qiu et al., 2009).

Adsorption of carbon dioxide on adsorbent materials at high temperature is becoming increasingly significant in the field of energy and environment, such as, controlling carbon dioxide emissions from fossil-fuelled power systems, natural gas treatment, purification of hydrocarbons, production of hydrogen gas, and aerospace industry (Yong et al., 2002) and sub marines (Przepiorski et al., 2004). Overall, the success of the adsorbents is also dependent on the development of a material that, at flue gas temperatures (room temperature up to 150^0C), has a high CO_2 selectivity and adsorption capacity. Such sorbent is the one is the one desired for efficient CO_2 separation by adsorption (Drage et al., 2008; Xu et al, 2003). That overcomes the need to cool the fuel gas to ambient temperature prior to the removal of carbon dioxide (Yong et al., 2002).

1.2 Problem Statement

One of the main issues related to the energy sector is finding the best way to curb CO_2 emission, which is implicated to be global warming contributor. The current system for CO_2 capture involves absorption in amine-based solutions. The major setback of this method is degradation and vapourization of the amine solvent, corrosion of equipment's and huge energy requirements for solvent regeneration. Adsorption with porous carbon is considered a promising option due to adsorbent low cost, easy to regenerate, low energy requirement, susceptible to surface chemistry modification and high surface area. However, most activated carbon demonstrated low to moderate CO_2 uptake necessary to compete with amine absorption system. Most previous research efforts are geared towards surface chemistry and pore modifications of activated carbon for enhanced CO_2 adsorption and increased in selectivity to CH_4. Not much has been done on high temperature application of the sorbents and improvement in stability of the carbonaceous materials to be used in several adsorption cycles at various temperatures. Good sorbent performance at low and high temperature will save the cost of cooling the streams before adsorption. Ease of regeneration and long term cyclic adsorption characteristics of a sorbents are also critical properties to be considered in designing gas sorbents, since they determine the sorbent lifetime, cost and potential industrial applications. PEEK (Polyetheretherketone) is a semi-crystalline and thermoplastic material with excellent thermal, physical and chemical properties which are retained over wide temperature. It was reported to have excellent properties desirable for high temperature and gas storage applications. However, material cost, non-availability and non-sustainability of PEEK activated carbon will limit its commercial application. In order to produce low cost adsorbent, palm shell ago-waste that is produced in millions of tonnes per year in Malaysia alone was used as the main precursor. However adsorption capacity of these sorbents is reduced after several adsorption cycles. Sorbents were modified via impregnation with K_2CO_3 and optimization of sorbents preparation variables such as microwave power, irradiation time and amount of PEEK.

It's on this note that this research focuses on blending PEEK char and palm shell char in order to have a combine desirable properties of these two carbonaceous materials. The novelty of this work is formulation and modification of PEEK-Palm blended activated carbon as sorbent for the enhanced carbon dioxide capture and methane adsorption. Development of adsorbent with high adsorption capacity and good regeneration efficiency will reduce cost and makes the sorbent feasible to be used in the CO_2 capture facilities and as an ANG (adsorbed natural gas) material.

1.3 Hypotheses

- CO_2 and CH_4 adsorption performance is related to the optimum preparation conditions such as microwave power, irradiation time, amount of PEEK and impregnation with base.
- Temperature affects adsorption performance of sorbents.
- Established adsorption isotherm and kinetic models correlates the CH_4 and CO_2 adsorption data.
- Sorbents stability depends on its performance after several adsorption cycles.

1.4 Aim and Objectives of the Work

The aim of this work is to synthesise a CH_4 and CO_2 capture sorbents from palm shell and PEEK. The specific objectives of the research work are:

1. To synthesize and exploit properties of porous carbons from palm shell and polyetheretherketone.

2. To use response surface methodology (RSM) for the experimental design, statistical analysis and optimization of the sorbent preparation for enhanced CO_2 and CH_4 adsorption.

3. To determine the adsorption performance of the sorbents produced towards CH_4 and CO_2 uptake.

4. To find the appropriate kinetic and equilibrium isotherm models that best describes the CH_4 and CO_2 adsorption process.

5. To evaluate the CO_2 desorption capacity and stability of the sorbents after seven adsorption regeneration cycles.

1.5 Scope of Work

In order to achieve the above objectives the research was limited to the following:

1. The precursors for the synthesis of porous carbons were palm kernel shell and PEEK. Palm shell and PEEK carbonization was carried out at 700^0C and 800^0C respectively. Modification of chars was carried out by impregnation with potassium carbonate (impregnation ratio, 1:1) and microwave irradiation for enhanced CO_2 and CH_4 uptake. The

characterization covers: surface chemistry (functional groups, pH and elemental composition), thermogravemetric analysis (TG, DTG, fixed carbon, ash and volatile matter), morphology and texture (BET Surface area, scanning electron microscopy).

2. Design Expert Version 7.1.6 software specifically; Central Composite Design (CCD) coupled with Response Surface Method (RSM) was used for the experimental design, optimization and statistical analysis. The sorbent preparation parameters considered were microwave power (200 – 600W), irradiation time (0- 12 min) and amount of PEEK char (0- 40 wt%). The responses were CO_2 and CH_4 adsorption capacity of the sorbents.

3. Adsorption and desorption were measured using static volumetric technique, by temperature and pressure measurement across dual cells. The CO_2 adsorption temperature are 303.15, 343.15, 378.15 and 443.15 K, while pressure were chosen from 1- 4 bar. The CH_4 adsorption was carried out at 303.15 K under the same pressure range.

4. Kinetics of the adsorption was described using pseudo-first-order, pseudo-second order and Elovich model. The CO_2 adsorption equilibrium data were correlated with Langmuir, Freundlich, Sips and Toth's isotherm models.

5. Reusability and stability of the sorbents was determined after seven successive adsorption-desorption cycles at 1 bar and temperature of 303.15, 343.15, 378.15 and 443.15 K. Sorbents desorption capacity at these temperatures and pressure of 4 bar was also evaluated.

1.6 Research Contribution and Significance

The main contribution of this work is synthesis of a new CO_2 and CH_4 sorbent material from palm shell and PEEK via chemical and microwave assisted activation. The palm-PEEK sorbent demonstrated good CO_2 adsorption capacity and was stable after seven adsorption cycles.

In Malaysia there is huge amount of palm shells from palm processing mills. Converting this agro-waste to valuable product would serve as a way of minimizing the negative environmental effect of these wastes. Not only that, any industry that is involved in conversion of this waste would serve as an indirect way of revenue generation and employment creation.

Use of microwave offers advantages in the synthesis and modification of the sorbents within short period of time which in many cases represents a reduction in the energy and inert consumption. Chemical impregnating and microwave assisted modification method will enhance the sorbent CO_2 and CH_4 capabilities. Achieving these, consequently leads to lower emission of greenhouse gases (e.g. CO_2) into the atmosphere and lower cost of flue gas capture from plants using fossil fuel as a major energy source. The Porous carbon will serve as a candidate for adsorbed natural gas (ANG).

In addition, improvement in thermal stability of sorbent materials is particularly important during reactivation and in gas-phase adsorption applications. It enables the sorbent material to be used in repetitive manner for adsorption and desorption at high temperature without damage or degradation of the sorbent. Not only that, high temperature sorbent will save the cost of cooling the flue gas to lower temperature before adsorption

Equilibrium relationships correlate the amount of gas adsorbed on a solid sorbate with the applied gas pressure (adsorption isotherms). Modelling of adsorption isotherm data is important for predicting and comparing adsorption performance (Al-Hajjaj et al., 2011). The adsorption kinetics models are important in predictive modelling, design of fixed bed adsorbers, identification of the rate-determining step of the adsorption process (Balachandran, 2004), finding the residence time required for completion of adsorption process and for pilot application (Qiu et al., 2009).

1.7 Organization of the Study

The thesis is organised in five chapters, each focused on specific area as indicated below:

Chapter One: Introduction

This chapter presents the background of the study. The purpose of and the problems related to the research were highlighted. Aims, objectives, scope, significances and contribution of the research were covered in this chapter. The summary of the thesis outline was also given in this chapter.

Chapter Two: Literature Review

This chapter highlights issues related to flue gas emission with emphasis on CO_2 emission. Issues related to policies and regulations on CO_2 were given. Various methods of CO_2 capture were highlighted; advantages of adsorption over other techniques were given. Review on activated carbon modification for CO_2 capture was carried out. Literatures on microwave irradiation for modification of AC were highlighted. Review on polyetheretherketone its properties and applications were presented. Fundamentals of adsorption equilibrium and kinetics modelling were reviewed.

Chapter Three: Methodology

Materials and equipment used in this research were mentioned. The methods and procedures that were followed in conducting the research were stated. The condition of Palm-PEEK activated carbon synthesis, modification was elucidated.

Techniques and procedure for characterization of the sorbent were given. Research design, model fitting and optimization techniques for CO_2 and methane uptake were given. Methods followed in application of sorbent produced in CO_2 adsorption and desorption were explained. Adsorption isotherms and kinetic model used to correlate the data were stated.

Chapter Four: Results and Discussion

The results of activated carbon synthesis, modification and characterization were presented. The results of CO_2 and CH_4 uptake on the activated carbon were presented. Response surface methodology, statistical analysis and optimization results for CO_2 adsorption were given. Kinetics of the adsorption process was highlighted. Analysis and interpretations of the results obtained was carried out in this chapter. Sorbents regeneration and desorption capacity was tested and explained.

Chapter Five: Conclusions and Recommendations

In this chapter major findings and summary of the results were presented. Recommendation on how to improve on the research and conducting future studies were given.

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