

# **DEVELOPMENT AND OPTIMIZATION OF PRESSURE SWING ADSORPTION FOR BIOGAS UPGRADATION**

**GOLDY SHAH**



**CENTRE FOR RURAL DEVELOPMENT AND TECHNOLOGY  
INDIAN INSTITUTE OF TECHNOLOGY DELHI, INDIA**

**APRIL 2022**

© Indian Institute of Technology Delhi (IITD), New Delhi, 2022

**DEVELOPMENT AND OPTIMIZATION OF  
PRESSURE SWING ADSORPTION FOR BIOGAS  
UPGRADATION**

*by*

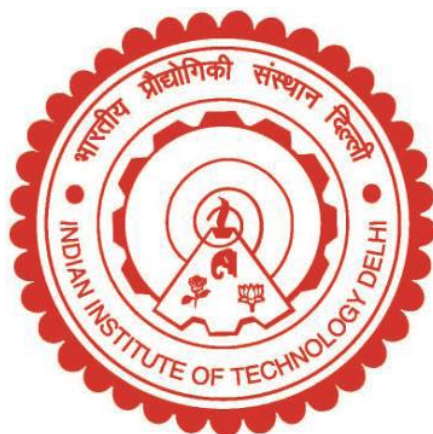
**GOLDY SHAH**

**CENTRE FOR RURAL DEVELOPMENT AND TECHNOLOGY**

**Submitted**

*in fulfilment of the requirements of the degree of Doctor of Philosophy*

to the



**INDIAN INSTITUTE OF TECHNOLOGY DELHI, INDIA**

**APRIL 2022**

# CERTIFICATE

---

---

It is certified that the thesis entitled “**DEVELOPMENT AND OPTIMIZATION OF PRESSURE SWING ADSORPTION FOR BIOGAS UPGRADATION,**” being submitted by **Ms. GOLDY SHAH** to the Indian Institute of Technology Delhi, is a record of the student work carried out by her. She has worked under our supervision and guidance, and has fulfilled the requirements for the submission of this thesis, which has attained the standard required for a Ph. D. degree of the Institute.

The results presented in this thesis have not been submitted elsewhere for the award of any degree or diploma.

**Dated: 21 SEPTEMBER, 2021**

**(Prof. Virendra K. Vijay)**

Professor

Centre for Rural Development & Technology

Indian Institute of Technology, Delhi

Hauz Khas, New Delhi – 110016, INDIA

**(Prof Kamal Kishore Pant)**

Professor

Department of Chemical Engineering

Indian Institute of Technology, Delhi

Hauz Khas, New Delhi – 110016, INDIA

# ACKNOWLEDGEMENTS

---

---

A dissertation is not the outcome of the efforts of entirely one individual. Many people have contributed to its development. At this time, I take the opportunity to acknowledge those who have made some impact on my doctoral journey and accomplishment.

First and foremost, I wish to express my deepest gratitude and indebtedness to my *supervisors*, **Prof. K.K.Pant** and **Prof. V.K. Vijay** for their continuous guidance, encouragement, consistent, inspiring guidance, and utmost cooperation throughout the study. I must thank them for sharing their immense knowledge and for inculcating the basics of research in me. It was a highly educative and memorable experience working under their supervision which has provided deep insight into the world of research. The determination, dedication, innovativeness, resourcefulness, and discipline of Prof. Pant have inspired me to complete this work. The consistent encouragement, continuous monitoring, and commitments to the excellence of Prof. V.K. Vijay have always motivated me to improve my work and use the best of my capabilities. I express my deep gratitude to **Dr. Ejaz Ahmad**, who advised me to overcome hurdles, helped me through difficulties, and encouraged me to slow down. All of them provide me a long-lasting bearing on my understanding of life and thought process.

I express my deepest gratitude to the esteemed members of my Student Research Committee, **Prof. T.R.Sreekrishnan** (External Examiner), Professor, Department of Biochemical engineering and biotechnology, **Prof. S. N. Naik**, (Chairperson), and **Prof. Hariprasad P.** (Internal Examiner) for their valuable comments, reviews, and support.

I am grateful to the Indian Institute of Technology, Delhi, for providing me the research facilities and financial support. My heartfelt thanks to all my colleagues and friends

of my laboratory, i.e., **Ms. Shivali, Mr. Himanshu Kumar, Ms. Swapna Sagarika Sahoo, Ms. Adya Isha, Mr. Sameer Ahmad Khan, Mr. Subodh Kumar, Mr. Komalkant, Mr. I. K. Biju**, and all biogas research lab group for their valuable support for creating a conducive work environment and helping me in the time of need. I want to thank all my seniors **Dr. Pooja Ghosh, Dr. Rimika Kapoor, Dr. Vandit Vijay**, for their guidance and informal support in pursuing this research work and providing me the mentorship opportunity in their research. I would like to use this opportunity to thank **Mr. Mahesh Verma** and **Mr. Vinod Kumar**. They have constantly helped me with all lab issues during experimental studies at various stages of work.

I would also like to thank **Prof. Subbarao** (Head, CRDT) and other faculty members of CRDT, IIT Delhi, with whom I interacted occasionally. My heartfelt thanks are due to all the staff members of the Centre, especially **Ms. Seema Bharti**, for her help during the research work.

I am likewise thankful to those who have directly or indirectly helped me to finish my dissertation study.

My mom (**Kiran Shah**) passed away 6 years ago, but the only thing that continuously haunted me during the failure was will I be able to make my mom proud. It was my mom's sacrifice and dream, and I am trying hard to fulfill it. She must be smiling seeing my efforts. I miss her at this moment, but I know her blessings are always there. I hope I will not break her hope and dream that she always had for me.

I owe thanks to a very special person of my life, *my husband*, **Aditya Singh Mandloi**, for his continued and unfailing love, never-ending encouragement, and understanding during my pursuit of a Ph. D degree that made the completion of the thesis possible. Your support

has meant more to me than you could possibly realize. Without your support in my times of need, I would not be in the position I am today. I am truly thankful for having you in my life.

I express my sincere gratitude to my grandmother – **Shanti Devi**, as I spent a major part of my childhood in her lap. My deepest love, appreciation, and indebtedness go to my father - **Mr. Rajesh Shah**, who sacrifices and wholeheartedly endorses his dreams. His trust in my capabilities has always motivated me to reach higher academic degrees. I would like to convey my unbounded love to my brother **Prateek Shah**, my bua **Mona Bakliwal**, **Alka Bakliwal**, my aunt **Abha Jain**, my sister **Pratiksha Bakliwal & Riddhi Jain**, and my bhabhi **Ayushi Shah** for listening to my never-ending woes and encouraging me during the most challenging phases of my work and life.

My sincere thanks to my In-Laws - **Mr. Ravindra Singh Mandloi & Mrs. Vimla Kuwar**, and my sister-in-law **Shikha Rajpurohit** for their love, countless blessings, affection, incessant inspiration, and support because of which I have made it through all the steps to reach this point in life.

I take this opportunity to thank the great assets of my life, my friends **Ms. Amita**, **Ms. Shivali**, and **Ms. Deepti**, for sharing my joy, sorrow, and happiness, who helped me *accomplish this arduous work*.

At last, I am beholden to the almighty for their blessings to help me raise my academic level to this stage. I pray for their benediction in my future endeavours. Their blessings may be showered on me for strength, wisdom, and determination to achieve in the future.

**Date: September, 2021**

**GOLDY SHAH**

# ABSTRACT

---

---

Biogas is futuristic renewable energy with high market potential due to the wide-scale availability of organic biomass and for facilitating countries in meeting sustainable development goals related to creating and providing access to renewable energy. It has the potential of being developed as a vehicular fuel or for generating electricity that can be injected into power grids. Despite its prospect, it faces criticism, such as limited contributions in reducing carbon emissions compared to solar and wind. However, raw biogas produced via the anaerobic digestion process contains many impurities such as hydrogen sulfide and carbon dioxide.

Thus, the upgradation and purification of the raw biogas by capturing CO<sub>2</sub> before its application are necessary. Consequentially, for higher efficiency and better commercialization, it is important to upgrade raw biogas and utilize the energy value of off-gas. This dissertation aims to present the state-of-art upgradation technologies currently available and the ones that are promising for rural India. It also discusses the future perspectives for overcoming the challenges associated with upgradation.

Therefore, various techniques have been investigated to remove carbon dioxide from biogas from the production of a gas with a high methane content called biomethane. The current study focuses on one such process where biogas enrichment is carried out through equilibrium-based adsorption, particularly a process called Pressure Swing adsorption using a special grade of carbon molecular sieves used as an adsorbent.

PSA is the second-most commonly employed technique for biogas upgrading, has received considerable attention from the research community worldwide compared to other methods because of flexibility in operation, high auto-control degree, low energy consumption, and less capital investment. Portable or small-scale pressure swing adsorption (PSA) systems have gained increasing popularity in the rural area. While these processes have much in common with larger PSA systems, significant differences make understanding process limitations difficult. These include faster cycle times, smaller adsorbent particles, and reduced column size.

Thus, this study provides a detailed mechanistic insight into the design of the portable pressure swing adsorption reactor, the effect of various factors such as type of adsorption technologies, different kinds of adsorbents, bed configuration, source and composition of the biogas, time cycle, and operating conditions on the efficiency of biogas purification process via pressure swing adsorption technologies. Moreover, an overview of the fundamentals of the pressure swing adsorption (PSA) process is provided by focussing on different innovative engineering approaches that contribute to the continuous improvement in process performance.

Initially, the breakthrough experiments were performed in a single column filled with SG CMS. The range of adsorption step time was derived from the results of preliminary breakthrough experiments and selected at nearly 30%–60% of the breakthrough time. To understand the adsorption characteristics of the CH<sub>4</sub> and CO<sub>2</sub> gases, the Langmuir isotherm model was used to determine the isotherm of a mixed gas containing 55% CH<sub>4</sub> and 45% CO<sub>2</sub>. A different cycle configuration was designed and optimized the best configuration to get the high methane purity. The six-step cycle includes two pressure equalization steps that achieved the highest methane purity after the cycle design and configuration, the design of

experiments by central composite design for the small-scale PSA. We obtained a CH<sub>4</sub> purity of 94.6% and a recovery of 85.6%. At last, a full-scale proposed design was conducted for the commercial application.

बायोगैस जैविक बायोमास की व्यापक पैमाने पर उपलब्धता के कारण उच्च बाजार क्षमता के साथ भविष्य की अक्षय ऊर्जा है और अक्षय ऊर्जा के निर्माण और पहुंच प्रदान करने से संबंधित सतत विकास लक्ष्यों को पूरा करने में देशों की सुविधा के लिए है। इसमें वाहनों के ईंधन के रूप में विकसित होने या बिजली पैदा करने की क्षमता है जिसे पावर ग्रिड में इंजेक्ट किया जा सकता है। इसकी संभावना के बावजूद, इसे आलोचना का सामना करना पड़ता है, जैसे कि सौर और पवन की तुलना में कार्बन उत्सर्जन को कम करने में सीमित योगदान। हालांकि, अवायवीय पाचन प्रक्रिया के माध्यम से उत्पादित कच्चे बायोगैस में हाइड्रोजन सल्फाइड और कार्बन डाइऑक्साइड जैसी कई अशुद्धियाँ होती हैं।

इस प्रकार, कच्चे बायोगैस के उपयोग से पहले CO<sub>2</sub> को कैप्चर करके उसका उन्नयन और शुद्धिकरण आवश्यक है। नतीजतन, उच्च दक्षता और बेहतर व्यावसायीकरण के लिए, कच्चे बायोगैस को अपग्रेड करना और ऑफ-गैस के ऊर्जा मूल्य का उपयोग करना महत्वपूर्ण है। इस शोध प्रबंध का उद्देश्य वर्तमान में उपलब्ध अत्याधुनिक उन्नयन तकनीकों और ग्रामीण भारत के लिए आशाजनक प्रौद्योगिकियों को प्रस्तुत करना है। यह उन्नयन से जुड़ी चुनौतियों पर काबू पाने के लिए भविष्य के दृष्टिकोण पर भी चर्चा करता है।

इसलिए, बायोमीथेन नामक उच्च मीथेन सामग्री वाली गैस के उत्पादन से बायोगैस से कार्बन डाइऑक्साइड को हटाने के लिए विभिन्न तकनीकों की जांच की गई है। वर्तमान अध्ययन एक ऐसी प्रक्रिया पर केंद्रित है जहां बायोगैस संवर्धन संतुलन-आधारित सोखना के माध्यम से किया जाता है,

विशेष रूप से एक प्रक्रिया जिसे एक सोखना के रूप में उपयोग किए जाने वाले कार्बन आणविक छलनी के एक विशेष ग्रेड का उपयोग करके दबाव स्विंग सोखना कहा जाता है।

पीएसए बायोगैस उन्नयन के लिए दूसरी सबसे अधिक नियोजित तकनीक है, संचालन में लचीलेपन, उच्च ऑटो-नियंत्रण डिग्री, कम ऊर्जा खपत और कम पूंजी निवेश के कारण अन्य तरीकों की तुलना में दुनिया भर में अनुसंधान समुदाय से काफी ध्यान मिला है। पोर्टेबल या छोटे पैमाने पर दबाव स्विंग सोखना (पीएसए) सिस्टम ने ग्रामीण क्षेत्र में बढ़ती लोकप्रियता हासिल की है। जबकि इन प्रक्रियाओं में बड़े पीएसए सिस्टम के साथ बहुत कुछ है, महत्वपूर्ण अंतर प्रक्रिया की सीमाओं को समझना मुश्किल बनाते हैं। इनमें तेज चक्र समय, छोटे सोखने वाले कण और कम स्तंभ आकार शामिल हैं।

इस प्रकार, यह अध्ययन पोर्टेबल दबाव स्विंग सोखना रिएक्टर के डिजाइन में एक विस्तृत यंत्रवत अंतर्दृष्टि प्रदान करता है, विभिन्न कारकों जैसे सोखना प्रौद्योगिकियों के प्रकार, विभिन्न प्रकार के सोखना, बिस्तर विन्यास, बायोगैस के स्रोत और संरचना, समय चक्र, और दबाव स्विंग सोखना प्रौद्योगिकियों के माध्यम से बायोगैस शोधन प्रक्रिया की दक्षता पर परिचालन की स्थिति। इसके अलावा, दबाव स्विंग सोखना (पीएसए) प्रक्रिया के मूल सिद्धांतों का एक सिंहावलोकन विभिन्न नवीन इंजीनियरिंग दृष्टिकोणों पर ध्यान केंद्रित करके प्रदान किया जाता है जो प्रक्रिया के प्रदर्शन में निरंतर सुधार में योगदान करते हैं।

प्रारंभ में, सफलता के प्रयोग एसजी सीएमएस से भरे एकल कॉलम में किए गए थे। सोखना चरण समय की सीमा प्रारंभिक सफलता प्रयोगों के परिणामों से ली गई थी और सफलता समय के लगभग 30% - 60% पर चुना गया था। CH<sub>4</sub> और CO<sub>2</sub> गैसों के सोखने की विशेषताओं को समझने के लिए, लैंगमुइर इज़ोटेर्म मॉडल का उपयोग 55% CH<sub>4</sub> और 45% CO<sub>2</sub> युक्त मिश्रित गैस के इज़ोटेर्म को निर्धारित करने के लिए किया गया था। उच्च मीथेन शुद्धता प्राप्त करने के लिए एक अलग चक्र विन्यास को सर्वोत्तम विन्यास के लिए डिजाइन और अनुकूलित किया गया था। छह-चरणीय चक्र में दो दबाव

समकारी चरण शामिल हैं जो चक्र डिजाइन और विन्यास के बाद उच्चतम मीथेन शुद्धता प्राप्त करते हैं, छोटे पैमाने के पीएसए के लिए केंद्रीय समग्र डिजाइन द्वारा प्रयोगों का डिजाइन। हमने 94.6% की CH<sub>4</sub> शुद्धता और 85.6% की रिकवरी प्राप्त की। अंत में, वाणिज्यिक अनुप्रयोग के लिए एक पूर्ण पैमाने पर प्रस्तावित डिजाइन आयोजित किया गया था।

# TABLE OF CONTENTS

---

---

<b>SECTION</b>	<b>TITLE</b>	<b>PAGE NO.</b>	
Certificate		I	
Acknowledgements		II	
Abstract		V	
Table of Contents		XI	
List of Figures		XX	
List of Tables		XXIII	
List of Symbols and Abbreviations		XXV	
<b>CHAPTER</b>	<b>I</b>	<b>INTRODUCTION</b>	<b>1-19</b>
1.1	What is biogas		7
	1.1.1	Biogas composition and technologies for production	7
	1.1.2	Need for biogas upgradation	13
1.2	Why Bio-CNG?		15
1.3	Biogas upgradation technologies		16
1.4	Structure of thesis		17

1.5	Aim and scope	18
<b>CHAPTER</b>	<b>II (A) REVIEW OF LITERATURE</b>	<b>20-66</b>
2.1	Introduction	21
2.2	Biogas upgradation technologies	22
	2.2.1 Scrubbing technologies for biogas enrichment	23
	2.2.2 Membrane technology for biogas enrichment	24
	2.2.3 Cryogenic technology for biogas enrichment	25
	2.2.4 In situ technologies for biogas enrichment	26
	2.2.5 Swing adsorption technologies for biogas enrichment	26
	2.2.6 Comparison of Biogas Upgradation Technologies and Selection Criteria for Pressure Swing Adsorption	28
2.3	Challenges accomplished by existing biogas plants and from research worldwide	31
	2.3.1 Technical Challenges	31
	2.3.2 Financial challenges	32
	2.3.3 Social challenges	32
	2.3.4 India Case Study	33
	2.3.5 The need and availability of appropriate technology	34
	2.3.6 Benefits of biogas for rural areas in India	34

<b>2.4</b>	<b>Bio-CNG—Vehicle Fuel for a Green Future</b>	<b>35</b>
2.4.1	Bio-CNG uptake in India	36
2.4.2	Growth Areas	36
2.4.3	Government initiative scheme for Biogas	37
2.4.4	Key Challenges faced in adoption of Bio-CNG	39
2.4.5	Key findings	40
<b>2.5</b>	<b>What is adsorption?</b>	<b>40</b>
2.5.1	Adsorption Technology	40
2.5.2	Adsorption Kinetics	41
2.5.3	Adsorption Isotherm	42
	2.5.3.1 Henry’s (Linear) isotherm	42
	2.5.3.2 Langmuir isotherm	43
2.5.4	Mathematical models and scale-up	44
2.5.5	Adsorption column dynamics	46
<b>2.6</b>	<b>Swing adsorption technologies for biogas enrichment</b>	<b>47</b>
2.6.1	Temperature swing adsorption (TSA)	48
2.6.2	Electric swing adsorption (ESA)	50
2.6.3	Vacuum swing adsorption (VPSA)	55
2.6.4	Pressure swing adsorption (PSA) technologies	56
	2.6.4.1 Applications of the PSA technology	57

2.6.4.2	Historical developments of the PSA technology	58
2.6.4.3	Adsorbent configuration in PSA system	60
2.6.4.3.1	Double bed PSA system	61
2.6.4.3.2	Multi bed PSA units	62
2.7	Research gaps and motivation for the work	64
2.8	Research objectives	65
2.9	Summary	66
<b>CHAPTER</b>	<b>II (B) RATIONALE FOR CHOICE OF THE ADSORBENTS</b>	<b>67-76</b>
2(b).1	Adsorbent Material Selections	68
2(b).1.1	Zeolite	70
2(b).1.2	Carbon molecular sieves	72
2(b).1.3	Metal-organic framework (MOFs)	75
<b>CHAPTER</b>	<b>III MATERIALS AND METHODS</b>	<b>77-80</b>
3.1	Introduction	78
3.2	Raw Biogas	78
3.3	Adsorbents	80

<b>CHAPTER</b>	<b>IV</b>	<b>DESIGN OF PSA COLUMN</b>	<b>81-103</b>
4.1		Introduction	82
4.2		PSA System	82
	4.2.1	PSA Flow Diagram	83
	4.2.2	PSA Instrumentation, Process Control, and Data Collection	85
	4.2.3	System Design	88
4.3		Design Parameters	89
	4.3.1	Purge/Feed Ratio	89
	4.3.2	Pressure Ratio	90
	4.3.3	Cycle Time	90
4.4		Performance Indicators	91
	4.4.1	Product Purity	91
	4.4.2	Methane recovery or Fractional recovery	92
	4.4.3	Working Capacity	93
	4.4.4	Energy requirement	93
	4.4.5	The concentration of trace impurities	93
	4.4.6	Scaling characteristics	93
4.5		Design of Pressure Swing Adsorption Column	95
	4.5.1	Determination of breakthrough time for gas adsorption	95

	calculation	
4.5.2	Measurement of adsorption isotherm	97
4.6	Results and Discussion	98
4.6.1	Breakthrough analysis	98
4.6.2	Measurement of adsorption isotherm	100
<b>CHAPTER</b>	<b>V CYCLE DESIGN &amp; OPTIMIZATION OF PROCESS PARAMETERS</b>	<b>104-126</b>
5.1	Introduction	105
5.2	Cycle sequencing	105
5.2.1	Case A: Basic 4-step PSA cycle	105
5.2.2	Case B: 4-step PSA cycle with light product pressurization	106
5.2.3	Case C: 6-step PSA cycle with counter-current blowdown, purge, pressure equalization	107
5.2.4	Case D: 6-step PSA cycle with co-current blowdown, purge, two pressure equalization step	109
5.2.5	Comparison of configuration	110
5.3	Optimization of Cycle time	111
5.4	Effects of process parameters and operating condition on PSA system	114
5.4.1	Effects of the time cycle	114

5.4.2	Effect of Adsorption Time on product purity and recovery	116
5.4.3	Effect of Adsorption and desorption pressure on Purity	119
5.4.4	Effect of Pressure fluctuations in the adsorption beds	121
5.4.5	Effect of Feed Flow rate	122
5.4.6	Effect of purge-to-feed ratio	123
5.5	Comparative PSA performances	125
<b>CHAPTER VI</b>	<b>OPTIMIZATION OF PSA SYSTEM BY RESPONSE SURFACE METHODOLOGY</b>	<b>127-140</b>
6.1	Introduction	128
6.2	The Design of Experiment method	129
6.3	PSA Process Optimization at the Laboratory Scale	131
6.3.1	Analysis of two bed six steps PSA process performances	132
6.4	Simulation of a dual PSA process for biogas upgrading and carbon capture	132
6.4.1	Results of ANOVA Analysis	133
6.4.1.1	CH <sub>4</sub> Purity	133
6.4.1.2	CH <sub>4</sub> Recovery	138
<b>CHAPTER VII</b>	<b>TECHNO-ECONOMICS OF THE OVERALL</b>	<b>141-150</b>

## **SYSTEM**

7.1	Proposed Design of Full Scale PSA Process	142
7.2	Biomethanation	142
7.2.1	Advantages of Anaerobic Digestion / Biomethanation	143
7.2.2	Bio-CNG Plant Description	145
7.2.3	Feeding Mechanism	145
7.2.4	Digester	145
7.2.5	Biogas Enrichment	146
7.2.6	Pressure Swing Adsorption process (PSA)	146
7.2.7	Purified Gas Storage Balloon	147
7.2.8	210 Bar MPA Compressor Gas Compressor and Cascade Gas storage and Filling	147
7.2.9	Bio-CNG Dispensing Unit	147
<b>CHAPTER</b>	<b>VII CONCLUSION &amp; DIRECTION FOR FUTURE WORK</b>	<b>151-158</b>
8.1	Introduction	152
8.2	Pressure Swing Adsorption	152
8.2.1	Superiority of PSA system designed in this study over commercially available	153
8.2.2	Thesis Summary and Contributions	153

8.2.3	Concluding Remarks	154
8.3	Research Contribution to knowledge and practice	155
8.3.1	Contribution to the theory	156
8.3.2	Contribution to the society	156
8.3.3	Contribution to the industry	156
8.4	<b>Challenges and future outlook</b>	156
	<b>REFERENCES</b>	159-186
	<b>APPENDIX</b>	187-190
	<b>CV</b>	191-194

## LIST OF FIGURES

---

---

<b>Figure No.</b>	<b>Figure Title</b>	<b>Page No.</b>
Fig. 1.1	Energy consumption worldwide from 2000 to 2018, with a forecast until 2050*(in exajoules)	3
Fig. 1.2	Potential of biogas	6
Fig. 1.3	Anaerobic digestion process	8
Fig. 1.4	(a) Anaerobic digestion cycle (b) Schematic of four phases of biogas production	9-10
Fig. 1.5	Biogas annual production and leading producer countries	11
Fig. 1.6	Contributions of the biogas industry in various sectors	12
Fig. 1.7	Technologies used for biogas enrichment	17
Fig. 1.8	Flowchart of the thesis work.	19
Fig. 2.1	An overview of the separation processes	22
Fig. 2.2	Swing Adsorption Technologies	28
Fig. 2.3	Bio-CNG-generating biogas plants in Indore, Madhya Pradesh, India. (a) Choithram Mandi (b) Kabitkhedi plant	33
Fig. 2.4	Temperature Swing Adsorption Cycle	49
Fig. 2.5	(a) Electric swing adsorption cycle (b) Isotherm of ESA process, adapted from reference	51
Fig. 2.6	Advantages of PSA	56
Fig. 2.7	Benefits of PSA	57
Fig. 2.8	Different applications of pressure swing adsorption technique	58

Fig. 2.9	Chronological order for the historical developments of the PSA process	59
Fig. 2.10	Process diagram for the upgrading of biogas using PSA	63
Fig. 2(b).1	Size selective effect of adsorbent	69
Fig. 2(b).2	Principle of Pressure Swing Adsorption process	70
Fig. 2(b).3	Zeolite 13X adsorbent pellets	72
Fig. 2(b).4	Special Grade of Carbon Molecular Sieves adsorbent pellets	74
Fig. 3.1	Biogas plant from Kitchen Waste Operating at IIT Delhi	79
Fig. 4.1	Pressure swing adsorption flow integrated design (FID)	83
Fig. 4.2	Laboratory scale PSA equipment	84
Fig. 4.3	Complete setup of the experimental work	86
Fig. 4.4	Schematic of Column arrangement	94
Fig. 4.5	Breakthrough curve, where $C_0$ = initial concentration, $C$ = final concentration	96
Fig. 4.6	Breakthrough Experimental setup	97
Fig. 4.7	Experimental breakthrough curve for $CO_2$ removal using carbon molecular sieves at different adsorption pressure	99
Fig. 4.8	Experimental breakthrough curves for $CO_2$ removal using zeolite 13X adsorbent at different adsorption pressure	100
Fig. 4.9	Effect of pressure on adsorption at $25^\circ C$	103
Fig. 5.1	Basic 4 step Cycle	106
Fig. 5.2	4 step PSA Cycle with LPP	107
Fig. 5.3	6-step PSA cycle with purge and single pressure equalization	108
Fig. 5.4	6-step PSA cycle with purge and two pressure equalization	110
Fig. 5.5	Comparison of $CH_4$ Purity vs Time for different	111

	configurations	
Fig. 5.6	Solenoid valves arrangement in the PSA experimental setup	112
Fig. 5.7	Effect of cycle time on the methane purity	115
Fig. 5.8	Effect of adsorption time on CH <sub>4</sub> Purity	118
Fig. 5.9	Effect of adsorption pressure on CH <sub>4</sub> purity and recovery	120
Fig. 5.10	Effect of desorption pressure on CH <sub>4</sub> purity and recovery	121
Fig. 5.11	Pressure variation for the first and second column when cycle time 180s	122
Fig. 5.12	Effect of flow rate on CH <sub>4</sub> purity and recovery	123
Fig. 5.13	Effect of P/F (Purge/Feed) ratio on CH <sub>4</sub> purity and recovery	125
Fig. 5.14	Product gas purity as a function of operation cycles	126
Fig. 6.1	Relationship between experimental and predicted values; CH <sub>4</sub> purity	136
Fig.6.2. (a)	Response surface for CH <sub>4</sub> purity as function of the independent variables: adsorption step time and cycle time	137
Fig.6.2. (b)	Response surface for CH <sub>4</sub> purity as function of the independent variables: adsorption pressure and desorption pressure	138
Fig.6.3	Response surface for CH <sub>4</sub> Recovery as function of the independent variables: adsorption time and Cycle time	140
Fig.7.1	Process flow diagram of Bio CNG Plant	144

## LIST OF TABLES

---

---

<b>TABLE NO.</b>	<b>TITLE</b>	<b>PAGE NO.</b>
1.1	Hazardous effects of contaminants present in biogas	14
2.1	Comparative study of the different biogas purification technologies	29
2.2	Total energy consumption, purity, and recovery of the swing adsorption technologies	54
2.3	Government initiative scheme for Biogas	38
3.1	Typical components of a biogas	79
3.2	Physical properties of adsorbent	80
4.1	Characteristics of the Adsorbent Beds and the experimental condition used in the PSA column	95
4.2	Models details used in the adsorption isotherm	102
4.3	Langmuir constant and their regression coefficient and thermodynamic parameters for the adsorption of CO <sub>2</sub>	102

5.1	Automatic solenoid valves operation of the 6-step PSA system	113
5.2	Cycle description of the PSA experimental setup	114
5.3	Bio methane purity, recovery and number of cycles necessary to reach the CSS as a function of the adsorption time.	118
6.1	Independent variables and their levels	131
6.2	The ANOVA table for the top product CH <sub>4</sub> purity	134
6.3	The ANOVA table for the top product CH <sub>4</sub> Recovery	139
6.4	Components of the PSA setup	146
6.5	Cost Benefit Analysis	148
6.6	Adsorption bed parameters and operating conditions for the full scale process.	149
6.7	Simulation results of the full scale PSA process	142

## LIST OF SYMBOLS AND ABBREVIATIONS

---

---

%	percentage
&	and
/	per
<	lower than
>	greater than
°	degree
$\rho$	density
°C	degree Celsius
D	Bed diameter
L	Bed length
R	Universal gas constant
s	second
h	hour
min	minute
P	Total pressure
$P_H$	Adsorption Pressure
$P_1$	Desorption Pressure
Conc.	Concentration
CH <sub>4</sub>	Methane
CO <sub>2</sub>	Carbon dioxide
H <sub>2</sub> S	Hydrogen sulphide
NH <sub>3</sub>	ammonia

CNG	Compressed natural gas
LPG	Liquefied petroleum gas
Bio-CNG	Bio compressed natural gas
$C_{in}$	Inlet concentration
$C_{out}$	Outlet concentration
PSA	Pressure swing Adsorption
TSA	Temperature swing Adsorption
VPSA	Vacuum pressure swing Adsorption
CSS	Cyclic steady state
ESA	Electric swing Adsorption
RSM	Response Surface Methodology
CCD	Central Composite Design
ANOVA	Analysis of variance
P/F	Purge/Feed
SG-CMS	Special grade of carbon molecular sieves
LUB	Length of unused bed
PR	Pressurization
AD	Adsorption
DPE	Depressurization pressure equalization
BL	Blowdown
PU	Purging
PPE	Pressurization pressure equalization
BT	Breakthrough time