DEVELOPMENT AND OPTIMIZATION OF PRESSURE SWING ADSORPTION FOR BIOGAS UPGRADATION

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by

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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

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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_2 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_4 and CO_2 gases, the Langmuir isotherm model was used to determine the isotherm of a mixed gas containing 55% CH_4 and 45% CO_2. 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_4 purity of 94.6% and a recovery of 85.6%. At last, a full-scale proposed design was conducted for the commercial application.

सार

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_2 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_4 और CO_2 गैसों के सोखने की विशेषताओं को समझने के लिए, लैंगमुइर इज़ोटेर्म मॉडल का उपयोग 55% CH_4 और 45% CO_2 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_4 शुद्धता और 85.6% की रिकवरी प्राप्त की। अंत में, वाणिज्यिक अनुप्रयोग के लिए एक पूर्ण पैमाने पर प्रस्तावित डिजाइन आयोजित किया गया था।

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%	percentage
&	and
/	per
<	lower than
>	greater than
^{0}	degree
ρ	density
^0C	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_l	Desorption Pressure
Conc.	Concentration
CH_4	Methane
CO_2	Carbon dioxide
H_2S	Hydrogen sulphide
NH_3	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