Advancing sustainability: A comprehensive study on energy-efficient screw compressors for biogas applications

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ABSTRACT

In the pursuit of sustainable energy solutions to meet the 'net zero' demands of the modern era, biogas emerges as a promising renewable resource. Derived primarily from organic waste materials, biogas offers a cleaner alternative to traditional fossil fuels. Innovative engineering solutions are necessary to realize its full potential in terms of efficiency and reliability. This research addresses this critical need by developing and evaluating the performance of an energy-efficient screw compressor designed for biogas applications. The screw compressor plays a crucial role in the biogas utilization chain, serving as both a water scrubber and membrane separator to enhance biogas purity. The key innovation lies in integrating a chamber model-based numerical simulation, providing an in-depth understanding of the compressor's performance characteristics and enabling direct comparison with an industrial conventional reciprocating compressor. The study begins with comprehensive modeling of the screw compressor using the chamber model, analyzing efficiency, reliability, and energy consumption when handling biogas. A critical aspect of the research involves a comparative analysis between the screw compressor and the widely employed conventional reciprocating compressor in industrial applications. The performance and reliability of both systems are rigorously evaluated, highlighting the advantages of the screw compressor in terms of efficiency, environmental sustainability, and long-term cost-effectiveness. Future work involves developing a prototype of the screw compressor for experimental validation.

Keywords: Biogas, Efficiency, Reciprocating compressor, Screw compressor, Sustainability

1. INTRODUCTION

The quest for sustainable energy solutions has become increasingly urgent in the face of escalating environmental concerns and the need to mitigate climate change. Biogas, derived primarily from organic waste materials, offers a promising renewable resource that can help achieve 'net zero' emissions targets. Its utilization holds significant potential across various sectors, including electricity generation, heating, and transportation. However, realizing the full potential of biogas necessitates innovative engineering solutions tailored specifically for biogas applications. Unlike traditional energy sources, biogas composition and characteristics can vary significantly depending on feedstock and production processes, presenting unique challenges in its handling and utilization (Kapdi, Vijay, Rajesh, & Prasad, 2005). To address these challenges, a multifaceted approach is required, encompassing advanced technologies, novel design concepts, and sophisticated numerical simulation techniques. By leveraging these tools and methodologies, researchers and engineers can develop energy-efficient solutions that maximize the potential of biogas while minimizing environmental impact (Morini, Pinelli, & Venturini, 2009). The purification process of biogas is a crucial step in the compressed biogas (CBG) value chain, ensuring that the biogas meets quality standards for various applications. This process typically involves several stages, including water scrubbing, membrane separation, and pressure swing adsorption (PSA). Water scrubbing involves passing the biogas through a scrubbing solution, typically water, to remove water-soluble impurities such as hydrogen sulfide (H_2S) and other acidic gases. Membrane separation involves passing the biogas through semi-permeable membranes that selectively allow certain gases to pass through while blocking others based on their molecular size and properties. PSA works by adsorbing impurities onto a solid adsorbent material under high pressure and desorbing them under reduced pressure. By integrating these purification technologies into the biogas purification process, the compressed biogas value chain can yield high-quality biogas suitable for diverse applications. The selection of compressor technology becomes critical in this process, particularly due to considerations regarding the pressure ratio. Screw compressors emerge as a preferable choice over conventional reciprocating compressors, particularly for the specified suction and discharge pressures. The specifications guiding the selection of compressor technology are as follows:

1. P_{suc}: 1.08 bar
2. P_{dis}: 10 bar (water scrubber) and 17 bar (membrane)
3. Q: (250 - 1500) SCMH

Reciprocating compressors are typically favored beyond this pressure ratio to elevate the pressure to levels up to 250 bar, thereby transforming the biogas into compressed biogas (CBG) suitable for various downstream applications.

Screw compressors are widely used due to their excellent efficiency and reliability in various fields, including HTHP, MVC/MVR, and natural gas. They are known for their ability to handle high pressures and temperatures while maintaining high efficiency (Stosic, Smith, & Kovacevic, 2005). The performance of screw compressors can be further improved through the optimization of rotor lead, refrigerant extracting, and BigData (Kumar et al., 2022) (Kumar, Patil, Kulkarni, & Patil, 2023) (Kumar, Patil, Kovacevic, & Ponnusami, 2024). However, screw expanders often present unsatisfactory performance, which is a crucial problem for their commercialization. More efforts are needed to investigate the loss mechanisms and further reduce various losses, such as suction pressure loss, leakage loss, friction loss, and under/over-expansion loss (Abdan, Stosic, Kovacevic, Smith, & Asati, 2022). Biogas compressors are becoming increasingly important for rural areas in developing countries, where biogas is produced by biodigesters. The design of a biogas compressor includes a glass bottle filled with steel wool to act as an H2S scrubber (Baron, Leginski, Malek, Murphy, & Smith, 2008). The use of biogas as a fuel source is driven by the availability of biomass, making it a promising alternative energy source (Baron et al., 2008). Reciprocating compressors are also widely used in various applications, including natural gas and biogas compression. They are known for their versatility and ability to handle a wide range of pressures and temperatures (Lu, Sultan, & Phung, 2023) (Wang, Wu, Ma, Liu, & Yu, 2011). The performance of reciprocating compressors can be optimized through the optimization of port shape, intake pressure, and rotational speed. In summary, screw compressors and reciprocating compressors are essential components in various applications, including natural gas and biogas compression. Their performance can be optimized through various design and operational strategies, including the optimization of rotor lead, refrigerant extracting, BigData, port shape, intake pressure, and rotational speed. However, there are still challenges in improving the performance of screw expanders, which require further investigation (Stosic, Smith, & Kovacevic, 2003).

In this context, this paper focuses on the development and performance evaluation of an energy-efficient screw compressor block designed specifically for biogas purification technology for water scrubber applications. The integration of a chamber model-based numerical simulation approach enables a detailed analysis of the compressor's performance characteristics using the SCORG (Screw Compressor Rotor Grid Generation) software from PDM Analysis was employed. SCORG is an industry-leading tool for grid generation and performance analysis of positive displacement screw machines, conducting thermodynamic calculations through a multi-chamber model (Kovacevic, Rane, & Analysis, 2024). This facilitates direct comparison with conventional reciprocating compressors commonly used in industrial applications.

By addressing the critical need for innovative engineering solutions tailored for biogas applications, this research aims to contribute to the advancement of sustainability goals and the transition towards a more environmentally conscious energy landscape. Through a comprehensive study of energy-efficient screw compressors for biogas applications, this paper seeks to highlight the importance of engineering innovation in realizing the full potential of renewable energy resources like biogas.

2. MODELLING AND METHODOLOGY

To facilitate a comprehensive understanding of the compressed biogas (CBG) value chain, Figure 1 provides a visual representation of the entire process. The current analysis focuses on the water scrubber technology for a discharge pressure of 10 bar. The following subsections outline the working specifications and modelling methodology for both screw and reciprocating compressors.

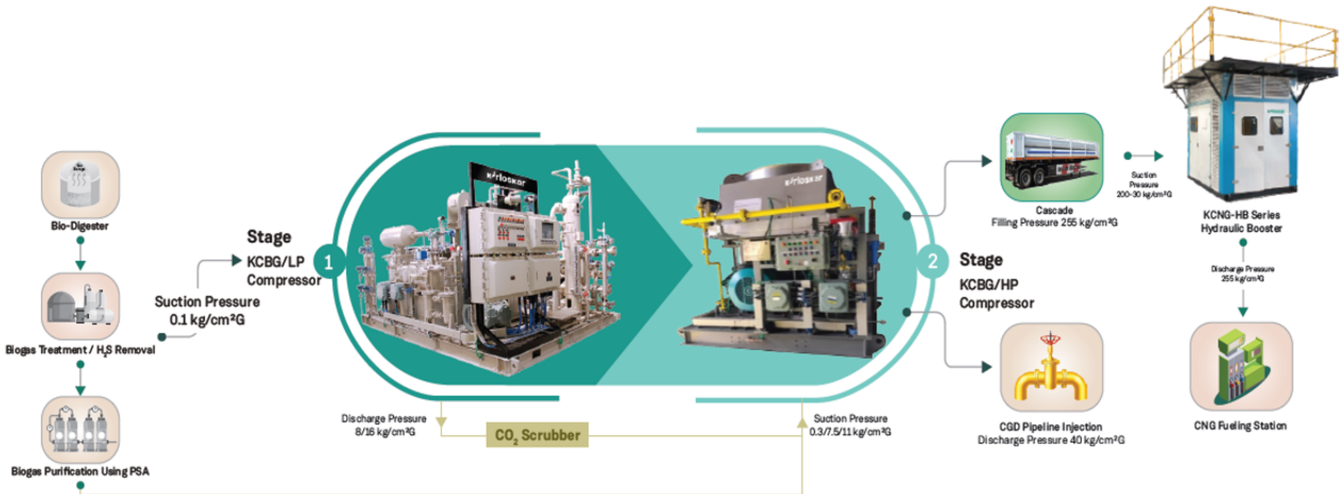

Figure 1: Compressed Biogas value chain

2.1 Working conditions

After biogas generation from biowastes, the initial step undertaken by the client involves the extraction of H_2S gas. Following the removal of H_2S gas, the biogas attains the following gas composition at the designated site (Table 1):

Table 1: Composition of Biogas at specific site location

Component	Mole %
CH_4	(55-60)%
CO_2	(38-40)%
H_2S	0.01%
H_2O	(1-4)%

The molecular weight and specific heat ratio (γ) for this gas composition are as follows:

- $R = 27.82$
- $\gamma = 1.3069$

The atmospheric pressure at the site location is 1.002 bar.

2.2 Screw Compressor Model

The KGS-1000 screw compressor block, manufactured by Kirloskar Pneumatic Company Limited (KPCL) in Pune, India, was utilized in this study. This oil-flooded screw compressor features a built-in volume ratio of 3 and operates at a tip speed of (10-35) m/s. Due to confidentiality reasons related to its industrial nature, detailed specifications are limited. However, key parameters including dimensions, weight, and motor rating are provided below:

- Weight: 665 kg
- Compressor Envelope Dimensions (LBH): 1070 x 604 x 440 mm^3
- Motor kW Rating: 160 kW

A 3-D model of the KGS-1000 is presented in Figure 2. This screw compressor was digitally replicated in SCORG software for performance analysis and further comparison (Kovacevic et al., 2024).

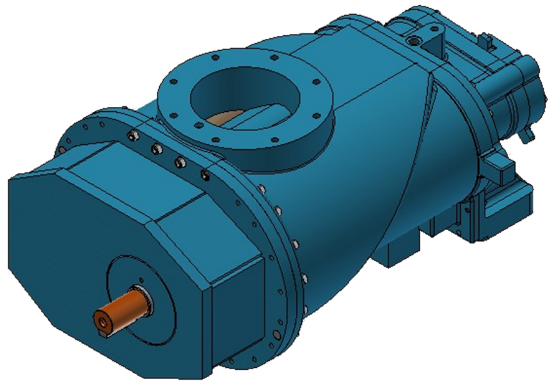

Figure 2: 3-D model of the KGS-1000 screw compressor block

2.3 Reciprocating Compressor Model

The reciprocating compressor utilized in this study is the SGT/BIO model, manufactured by KPCL. Due to proprietary considerations, detailed specifications are limited. However, key operational parameters are provided below:

- Stroke: 150 mm
- Speed: 750 RPM
- Piston Speed: 3.65 m/s

A 3-D model of the SGT/BIO compressor is depicted in Figure 3. This compressor was digitally modeled using Gas Reciprocating Performance Assessment Tool (Gas-RPAT), an in-house software developed by KPCL. The enhanced Gas-RPAT model will be used for performance analysis and comparison with the screw compressor.

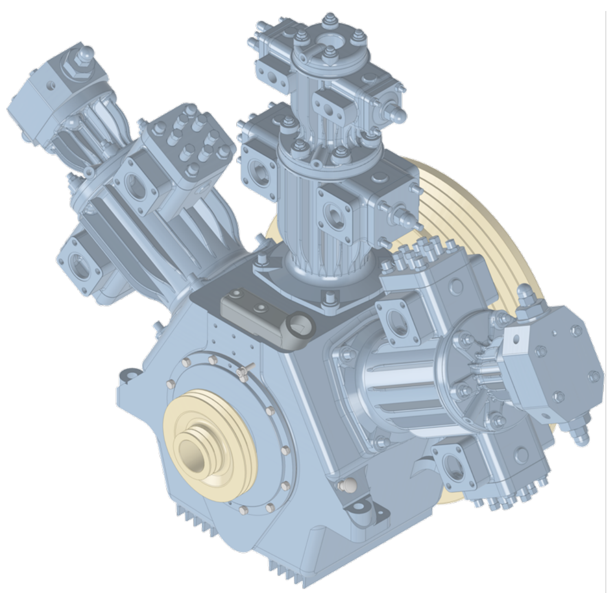

Figure 3: 3-D model of the SGT/BIO reciprocating compressor block

3. RESULTS AND DISCUSSION

To validate the performance of both reciprocating and screw compressors, both bare compressors were analyzed based on numerical simulations. The performance details of the KGS-1000 screw compressor are provided in Table 2. Both

Table 2: Operational parameters for screw compressor: KGS-1000

P_{suc} (bar)	P_{dis} (bar)	**Q** (SCMH)	**P** (kW)	**N** (RPM)	Q_{oil} (LPM)
1.08	10	250	54.4	750	60.00
1.08	10	500	77.8	1100	86.00
1.08	10	1000	120.63	1800	139.00

the reciprocating and screw compressor performance are compared for the following given operating parameters, which are summarized in Table 3.

Table 3: Working conditions

Parameters	**Value**
P_{suc}	1.08 bar
P_{dis}	10 bar
T_{suc}	40 °C
Q	1000 SCMH

After analysis, the performance comparative analysis is presented in Table 4. The comparative analysis of the reciprocating compressor and the screw compressor block revealed a notable improvement in the specific power consumption of the screw compressor. Specifically, it was observed that the specific power consumption of the screw compressor improved by approximately 6.20% when operating at the same flow rate of 1000 SCMH. This represents a significant enhancement in efficiency for the screw compressor.

Table 4: Comparative performance of screw and reciprocating compressors

Compressor Model	**KGS-1000**	**SGT/BIO**
SPC (kW/SCMH)	0.1206	0.1286
η_v (%)	84.65	76.95
η_{ad} (%)	83.19	78.48

In evaluating the performance of both machines over a one-year duration, consideration of lifecycle costs becomes imperative. Lifecycle cost encompasses not only the initial investment but also operational expenses incurred throughout the machine's lifespan, including maintenance, repair, and energy consumption costs. This comprehensive approach to cost analysis highlights the significant advantages of the KGS-1000 screw compressor in terms of energy efficiency and cost savings. The lifecycle cost comparison for both machines is summarized in Table 5, providing valuable insights for decision-makers in selecting the most cost-effective and efficient compressor option. The results indicate that the screw compressor outperforms the reciprocating compressor in terms of specific power consumption and efficiency, resulting in significant energy savings and cost reductions.

Table 5: Lifecycle Cost Comparison for 1 Year

Compressor Models	**KGS-1000**	**SGT/BIO**
Total Energy Consumption (kWh)	715,272	761,234
Energy Cost (INR)	8,583,258	9,134,813
% Difference in Energy Savings	6.04%	-

4. CONCLUSIONS

In conclusion, the performance numerical validation conducted for both screw and reciprocating compressors in biogas applications has yielded insightful results. It was evident that the screw compressor outperformed the reciprocating compressor, demonstrating a significant improvement in specific power consumption by approximately 6.20% at a flow rate of 1000 SCMH. Additionally, the lifecycle cost analysis revealed cost savings of approximately 6%, further highlighting the economic benefits of utilizing screw compressor technology. The results of this study demonstrate the potential of screw compressors in biogas applications, particularly in terms of energy efficiency and cost savings. The improved performance of screw compressors can be attributed to their design, which allows for more efficient compression and reduced energy consumption.

Future work includes experimental validation of the performance of screw compressors through prototype development. This will involve designing and building a prototype screw compressor and testing its performance under various operating conditions. The results of this experimental validation will provide further insights into the performance of screw compressors and help to confirm the numerical results obtained in this study.

Overall, this study highlights the potential of screw compressors in biogas applications and provides a comprehensive analysis of their performance. The results of this study can be used to inform the design and development of screw compressors for biogas applications, and the experimental validation of the performance of screw compressors through prototype development will provide further insights into their performance.

NOMENCLATURE

P	power	(kW)
Q	flow	$(SCMH)$
SPC	specific power consumption	$(kW/SCMH)$
P_{suc}	suction pressure	(bar)
P_{dis}	discharge pressure	(bar)
T_{suc}	suction temperature	(°C)

Subscript

v	volumetric
th	theoretical
ad	adiabatic

Abbreviations

SCMH	standard cubic meters per hour
LPM	litres per minute
INR	Indian Rupee

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