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Impact of rotor geometry and fluid injection on screw compressor performance

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Abstract. Screw compressors are widely used in industrial and commercial applications due to their high efficiency, reliability, and durability. However, there is still room for improvement in terms of energy efficiency and performance. To address this, the current study investigates the impact of screw rotor geometrical parameters: wrap angle, relative length, and built-in volume ratio and fluid injection methods (oil, and water injection) on the performance of screw compressors. The research offers a detailed analysis of these parameters, with a focus on the empirical validation of water injection's influence through experimental testing on an industrial screw compressor. The findings reveal that water injection reduces specific power consumption by 4.78 % compared to oil injection, highlighting its potential for improving compressor efficiency. This work contributes valuable insights into optimizing screw compressor design for enhanced performance and energy efficiency.

Nomenclature

P	power (kW)	Q	volume flow rate (m^3/min)
SPC	specific power consumption ($kW/m^3/min$)	P_{dis}	discharge pressure (bar)
L/D	relative length	ϕ	wrap angle (deg)
VI	built-in volume ratio	W_{tip}	tip speed (m/s)

1. Introduction

Screw compressors have been a cornerstone of industrial and commercial applications since their inception in the mid-20th century. The innovative designs of Heinrich Krigar and Alf Lysholm laid the foundation for these efficient, reliable, and durable machines. Over the years, advancements in materials, manufacturing techniques, and computational methods have continued to refine screw compressor performance. As the demand for more energy-efficient and high-performance systems grows, optimizing screw compressors has become crucial. This optimization requires a comprehensive understanding of the various parameters influencing compressor operation, including profile clearances, geometrical configurations, thermodynamic behaviors, and fluid injection strategies. Each parameter plays a vital role in determining the overall performance and efficiency of the compressor [1][2][3].

For instance, managing profile clearances is critical to minimize gas leakage while maintaining mechanical robustness, as demonstrated by Dhayanandh et al. [4]. Optimizing oil injection parameters is also essential, as Dundagekar et al. showed that oil improves lubrication and thermal management [5]. Kumar et al. have demonstrated the effectiveness of optimizing design and fluid parameters using Bayesian and evolutionary algorithms to enhance the performance of screw compressors. Their studies, as reported in [6] and [7], highlight the potential of these advanced optimization techniques in improving the efficiency and reliability of screw compressors by systematically adjusting design and fluid parameters to achieve optimal performance.

Recent studies have focused on the impact of geometrical parameters on compressor efficiency. Tian et al. developed a thermodynamic model highlighting the role of rotor profiles and clearances in achieving optimal volumetric efficiency and pressure dynamics [8]. The influence of fluid injection, particularly water injection, has also been a key area of research. Li and Wang's theoretical work on water-injected compressors demonstrated how water enhances cooling and sealing, leading to improved compressor performance and longevity [8].

Experimental investigations, such as those by Dhayanandh, have validated these theoretical findings by empirically demonstrating the performance improvements brought by optimized oil and water injection techniques [4]. The interplay between thermodynamic and geometrical parameters has also been scrutinized, revealing complex dependencies that dictate the overall operational efficiency of screw compressors [9]. In addition to the screw parameters, the choice of rotor materials is crucial for optimizing performance. The material properties, such as strength, durability, and thermal conductivity, significantly impact the compressor's efficiency and reliability. For instance, Kumar et al. have investigated the influence of rotor materials on screw compressor performance, highlighting the importance of selecting materials that can withstand the high temperatures and pressures within the compression chamber [10].

The literature review underscores the necessity of optimizing screw compressor parameters. However, before optimization, it is crucial to understand the impact of these parameters—including rotor profiles, geometrical dimensions, and fluid injection methods—on compressor performance. This study focuses on analyzing the effects of key geometrical parameters, laying the groundwork for future optimization efforts. Additionally, the research explores the impact of water injection, as opposed to traditional oil injection, within the compression chamber, highlighting the thermodynamic improvements and potential challenges in developing a water-injected screw compressor.

The paper is structured as follows: Section 2 presents the modelling of the KAS-200 industrial screw compressor block, incorporating both experimental and analytical approaches using a chamber model-based methodology with oil and water as the injected fluids. Section 3 explores the impact of key geometrical parameters on compressor performance, as well as the thermodynamic effects of varying fluid injections. Concluding insights are provided in Section 4.

2. Experimental and analytical modelling of KAS-200 screw compressor

This study focuses on the KAS-200 industrial screw compressor block, manufactured by Kirloskar Pneumatic Company Limited (KPCL), Pune, India. The KAS-200 is an oil-flooded air screw compressor with a power rating of 22 kW, operating at a pressure ratio of 8.5, and a nominal tip speed of approximately 35 m/s, delivering a volume flow rate of around 4m^3/min. Key geometrical parameters of the 4/5 lobe combination screw rotors include:

- Rotor Length-to-Diameter Ratio (L/D) = 1.55

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- Male Rotor Wrap Angle (ϕ) = 306.647°
- Built-in Volume Ratio (VI) = 4.6
- Working Fluid: Air
- Maximum Chamber Volume = 175,259 mm^3

Due to proprietary restrictions, detailed size and profile specifications are not disclosed. The KAS-200 compressor block was produced and assembled at KPCL for experimental validation using two fluid injection types—oil and water. An isometric view of the KAS-200 compressor block is shown in Figure 1.

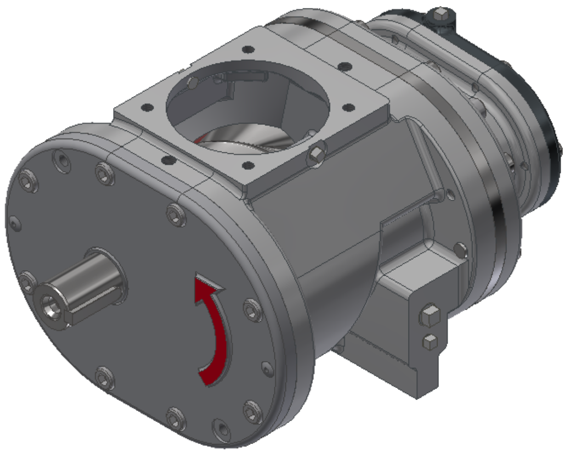

Figure 1: Isometric view of the KAS-200 compressor block

A customized testing package was developed for the KAS-200 compressor, featuring different separator tanks depending on the fluid injection type. The oil injection system uses an air-oil separator based on centrifugal and gravity principles, while the water injection system employs an air-water separator equipped with a demister pad to remove entrained liquid droplets effectively, as shown in Figure 2 . All components in direct contact with water, including the air-water separator tank, pipes, and small parts, were fabricated from corrosion-resistant stainless steel (SS304L) to ensure durability.

The compressor block, including the rotors and housing, remained consistent for both oil and water injection tests. The rotors are made from normalized medium carbon steel, and the housing is constructed from grey cast iron. Anti-friction bearings were used to ensure smooth operation.

The complete setup for the water-injected screw compressor is shown in Figure 2.

Following the experimental tests with both oil and water injections, the data obtained was utilized to develop an analytical model of the KAS-200 using SCORG (Screw Compressor Rotor Grid Generation) software from PDM Analysis. SCORG is a leading tool for grid generation and performance analysis of positive displacement screw machines, conducting thermodynamic calculations through a multi-chamber model [11] [6]. This analytical model was used to evaluate the impact of key geometrical parameters and to validate the experimental results of fluid injection on the screw compressor's performance, keeping the other input conditions and the rotor profile constant.

3. Results and Discussion

Following the completion of the experimental setup, tests were conducted under steady-state conditions at specified operating points, ensuring that the compressor reached stable parameters

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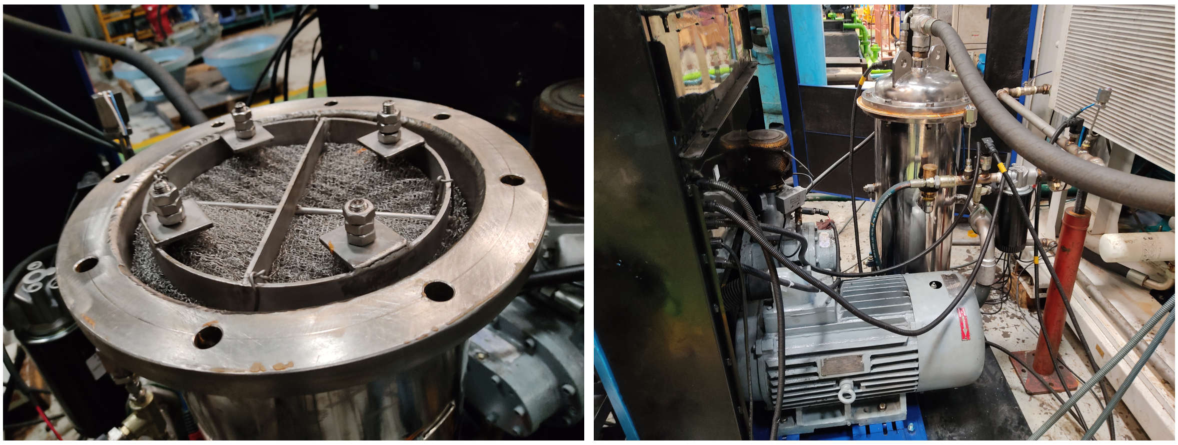

Figure 2: Demister pad and complete package of the water-injected screw compressor

before recording data. For each steady-state condition, data was recorded for a minimum of 10 minutes. The results at each test point were averaged from 10 data samples and normalized to the required values of pressure ratios and speeds, in accordance with the ISO 1217 standard for displacement compressor testing.

The following sub-sections present the experimental results for the KAS-200 compressor using water and oil as the injected fluids.

3.1. Experimental results

The performance of the KAS-200 compressor was evaluated under varying operating conditions, focusing on key performance parameters such as discharge pressure, tip speed, power consumption, specific power consumption (SPC), and volumetric flow rate. Table 1 summarizes the testing results for both water and oil as the fluid injected into the compression chamber.

Table 1: Testing Results for KAS-200 Compressor Block

P_{dis} (bar a)	W_{tip} (m/s)	P (kW)	SPC (kW/m^3/min)	Q (m^3/min)
Fluid Injection: Water				
8.00	32	23.56	7.032	3.35
Fluid Injection: Oil				
8.00	32	24.74	7.385	3.35

The experimental results indicate that the water-injected screw compressor demonstrated an improvement in efficiency compared to the oil-flooded variant. Specifically, the water-injected configuration achieved a 4.78% reduction in specific power consumption, signifying a more energy-efficient operation under consistent operating conditions.

However, the introduction of water in a compressor traditionally designed for oil flooding resulted in notable challenges. After approximately 25 hours of operation, signs of corrosion, bacterial pollution and scaling were observed on the compressor components, as shown in Figure 3. These issues underscore the complexities involved in developing a reliable water-flooded screw compressor and highlight the necessity for further research and development to address these challenges effectively.

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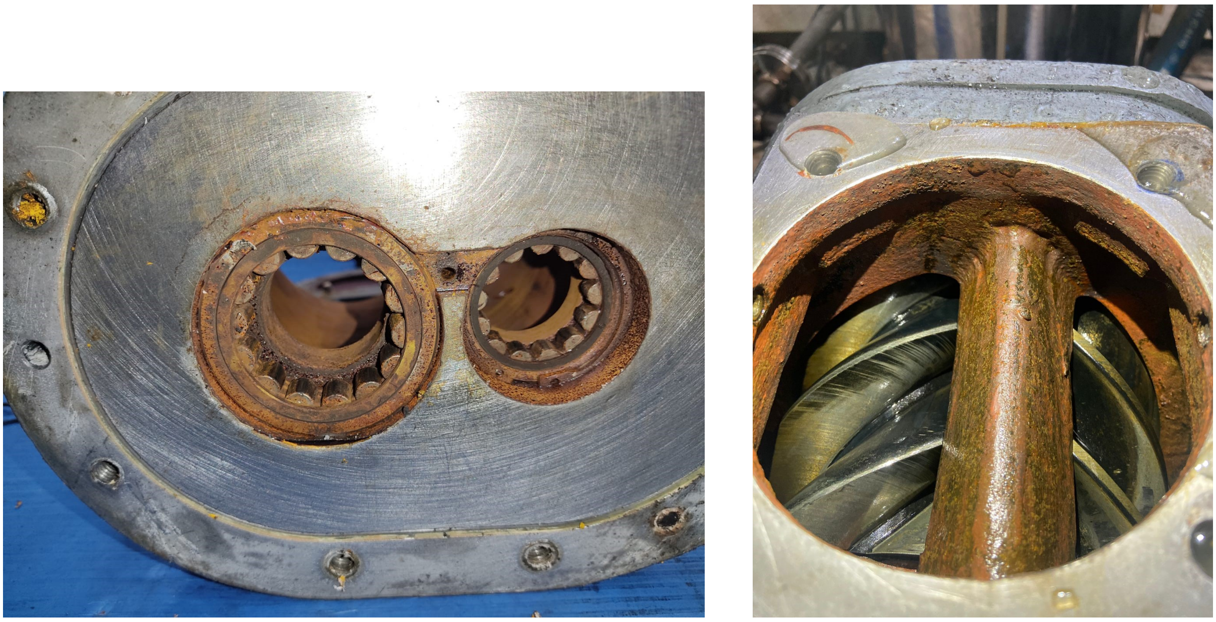


(a) Suction side view (b) Top view

Figure 3: Condition of the compressor block after 25 hours of operation

3.2. Analytical results

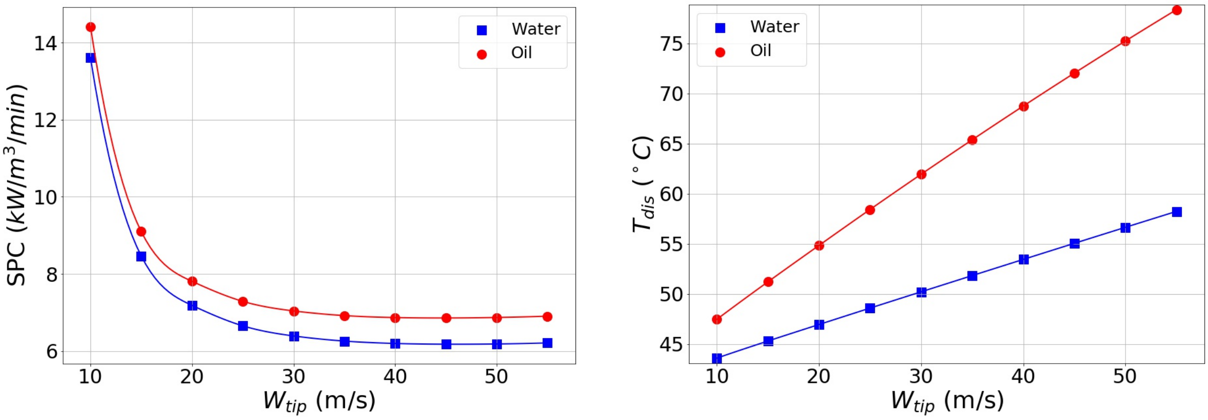
3.2.1. Effect of fluid injection To validate the experimental testing results with oil and water as fluid injection, analytical simulations were conducted using the SCORG software. The analytical model employed a chamber-based approach to evaluate the influence of fluid injection on the compressor's specific power consumption and discharge temperature.

The results, presented in Figures 4a and 4b, illustrate the impact of using water and oil in the compression chamber. The water-injected air screw compressor demonstrated lower specific power consumption compared to the oil-injected variant. Additionally, the discharge temperatures for the water-injected compressor were significantly lower, typically ranging between 45°C and 60°C, whereas the oil-injected compressor exhibited higher discharge temperatures.

The superior cooling performance of the water-injected system can be attributed to the higher specific heat capacity of water compared to oil. This results in more effective heat absorption, reducing the amount of fluid required for injection into the compression chamber. Furthermore, water's lower viscosity compared to standard compressor oils (such as ISO VG 68 Grade) leads to reduced viscous drag, which in turn lowers frictional power losses [12]. These factors collectively contribute to improved compressor performance and lower discharge temperatures.

3.2.2. Effect of geometrical parameters This research explores the effects of key geometrical parameters—such as the relative length of the rotor (L/D), wrap angle (ϕ), and built-in volume ratio (VI) on the performance of the KAS-200 compressor. These parameters were varied while keeping the rotor profile and clearances constant to achieve the desired volume flow rate at a fixed tip speed. The individual impacts of these parameters on compressor performance are discussed below:

Relative length of rotor: The length-to-diameter (L/D) ratio of the male rotor significantly influences compressor performance. Increasing the rotor length enhances the total displacement



(a) SPC vs. W_{tip} (b) T_{dis} vs. W_{tip}

Figure 4: Impact of fluid injection type on specific power consumption and discharge temperature.

volume, which generally improves performance. However, larger rotors are heavier, requiring more power to maintain the same RPM as smaller rotors, as shown in Figure 5. There are also practical constraints, such as the maximum power capacity of the compressor frame. A higher L/D ratio can lead to greater rotor deflection, potentially compromising the reliability of the compressor. Therefore, the L/D ratio must be chosen carefully, considering deflection analysis. A useful guideline is to limit the maximum rotor deflection to within one-third of the machine's radial clearance [13], as illustrated in Figure 6.

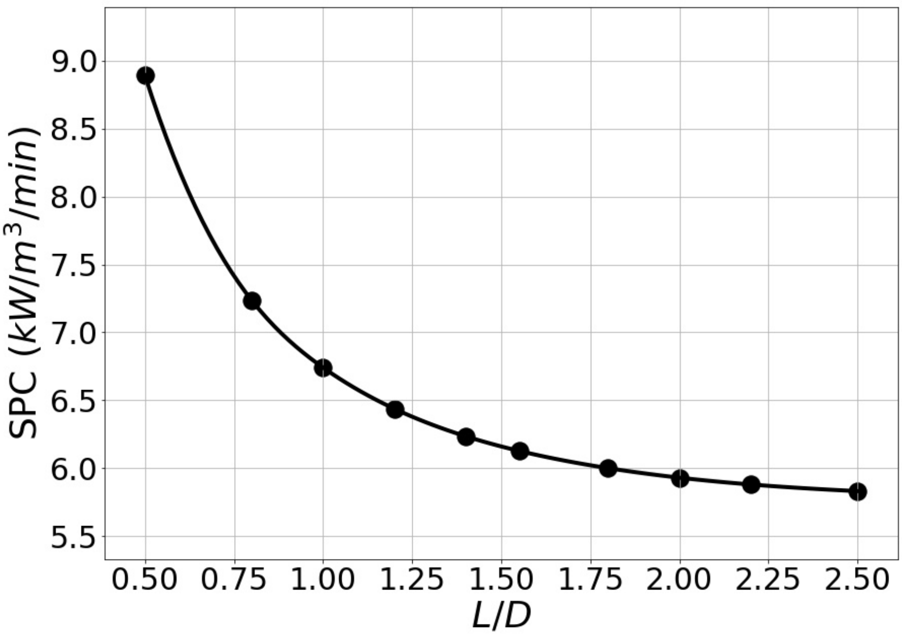


Figure 5: Effect of L/D ratio on KAS-200 compressor performance.

Wrap angle: The existing wrap angle of the male rotor in the KAS-200 compressor is 306.647°. Figure 7 shows the variation in specific power consumption as a function of the wrap angle. The

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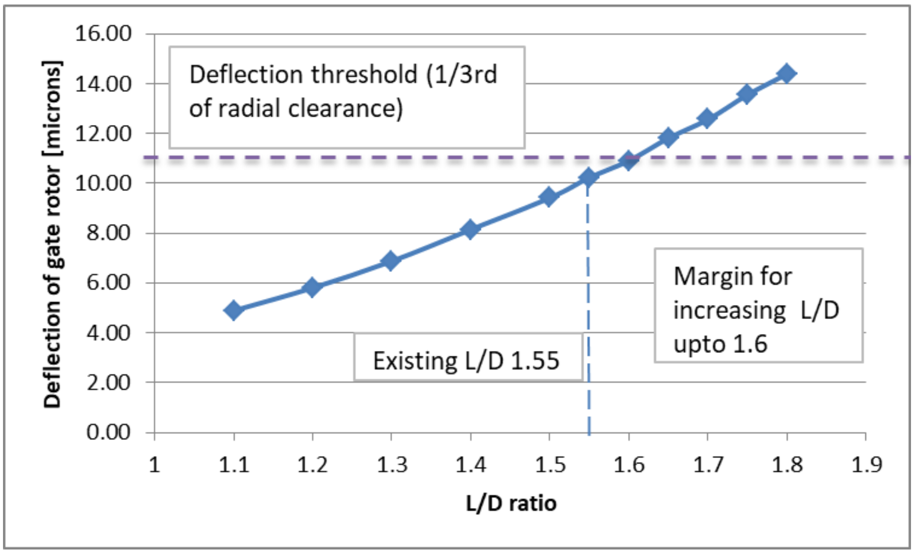

Figure 6: Effect of L/D ratio on deflections in the gate rotor at an 8.5 pressure ratio.

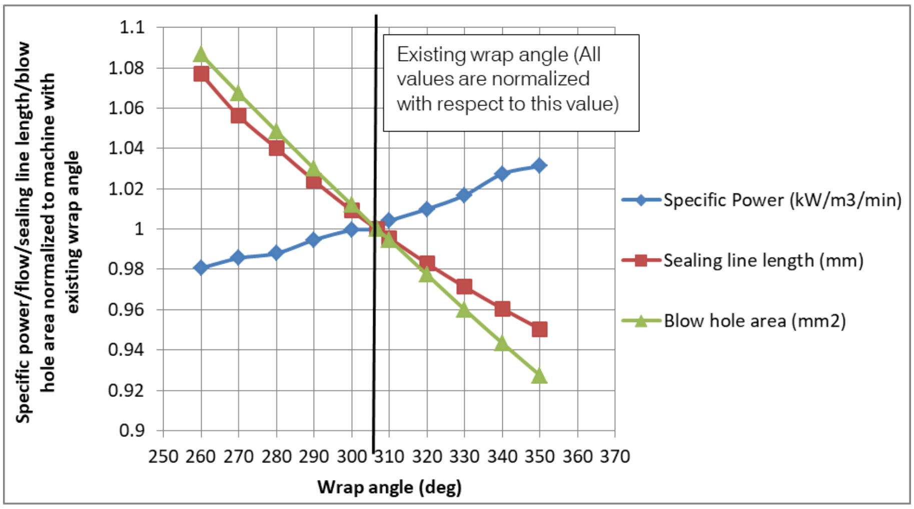

Figure 7: Variation in specific power and leakage areas with respect to wrap angle.

results indicate that specific power decreases as the wrap angle is reduced. Within the tested range of 350° to 200°, the specific power varies by 0.348 kW/m^3/min. However, reducing the wrap angle also increases leakage areas, which can negatively affect performance.

Other rotor characteristics, such as actual chamber volume and displacement volume, increase as the wrap angle decreases, counteracting the effects of increased leakage through blow holes and sealing line length (see Figure 8). While these changes can enhance performance under certain conditions, higher leakage rates could reduce efficiency, especially under high-pressure ratios or extreme working conditions. Deflection analysis of the rotors showed that changes in the wrap angle had an insignificant impact on deflection. The effective performance gain from reducing the wrap angle to 260° (beyond which further gains are minimal) is approximately 1.9%.

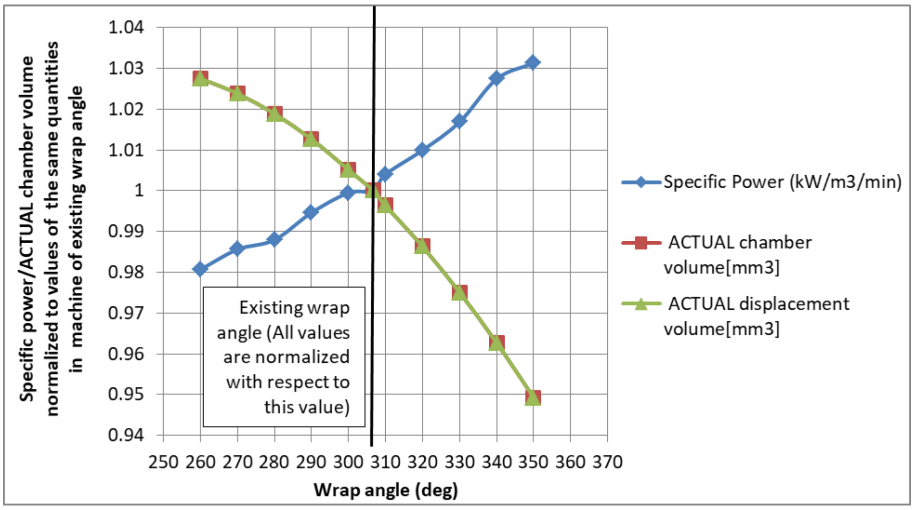

Figure 8: Variation in actual chamber volume and actual displacement volume with respect to wrap angle.

Built-in volume ratio: Figure 9 demonstrates that the specific power consumption increases when the built-in volume ratio deviates from the optimal value of 4.6. When the VI is decreased below 4.6, the internal compression is insufficient to match the external pressure ratio, leading to under-compression. This results in a need for additional external compression, increasing the overall power consumption and thus the SPC. On the other hand, increasing the VI beyond 4.6 causes over-compression, where the discharge pressure inside the compressor exceeds the external discharge pressure. This excess pressure leads to increased leakage losses and additional frictional power consumption, which also raises the SPC. Thus, a VI of 4.6 strikes an optimal balance by closely aligning the internal and external pressures, minimizing both under-compression and over-compression losses, and optimizing the compressor's efficiency. The ideal VI is specific to the application and depends on the targeted pressure ratios, as shown in Figure 9 [13].

This detailed assessment of the geometrical parameters in the KAS-200 screw compressor underscores the need for a balanced approach to optimizing performance while maintaining reliability across various operating conditions. Based on this research, the optimal geometrical parameters for the KAS-200 compressor were determined to be:

- Rotor Length-to-Diameter Ratio (L/D): 1.55
- Male Rotor Wrap Angle (ϕ): 306.647°
- Built-in Volume Ratio (VI): 4.6

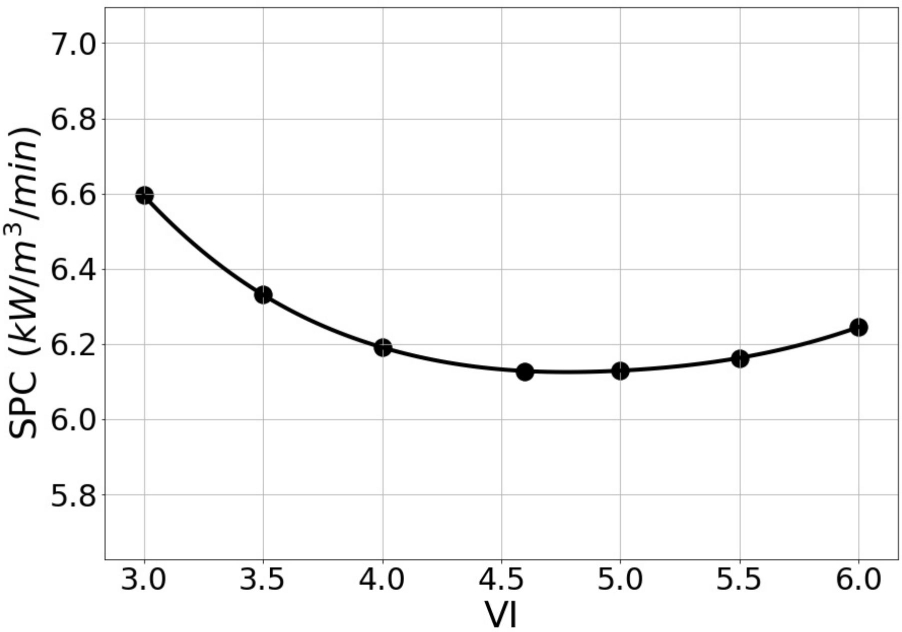

Figure 9: Effect of built-in volume ratio on KAS-200 compressor performance.

4. Conclusion

This study underscores the significant influence of rotor geometrical parameters and fluid injection on the performance of screw compressors. The analysis revealed that key geometrical parameters such as the built-in volume ratio, relative length, and wrap angle directly impact the compressor's specific power consumption. Optimizing these parameters is crucial for achieving maximum efficiency and performance. Additionally, the choice of fluid injection, whether oil or water, plays a pivotal role in determining compressor efficiency. The experimental results demonstrated that water injection led to a 4.78% reduction in specific power consumption compared to oil injection, highlighting its potential for improving compressor performance. This performance gain is attributed to the superior cooling properties of water and its lower viscosity, which reduce frictional losses within the compressor. While these findings provide valuable insights into optimizing screw compressor performance, future research should address potential challenges associated with water injection, such as corrosion, scaling, and bacterial contamination. Developing strategies to mitigate these issues will be essential for the long-term reliability and efficiency of water-injected screw compressors.

Declaration of competing interest

The authors declare no known competing financial interests or personal relationships that might have influenced the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

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