Optimization of Internally Geared Screw Machine Geometry for Air Compression Application

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ABSTRACT

Gerotor machines are commonly used as oil and fuel pumps, and as hydraulic pumps and motors. They also have the potential to be used as positive displacement compressors, which is the focus of current research. The mechanism consists of an inner and outer rotor which rotate in the same direction but are each centered on offset parallel axes. The rotor profiles are specified such that multiple continuous contact points occur between them forming several separate working chambers, whose volume varies from minimum to maximum and back to minimum during a single rotation of the outer rotor. For a gas or two-phase working fluid, varying the discharge port geometry allows internal compression to occur prior to discharge. Furthermore, adding helical twist to the rotors allows the forces and torques acting on the rotors to be modified in order to minimize contact forces and power transfer between the driven and idler rotors. Previous research has investigated the operation of these internally geared screw machines via characterization of key geometrical properties and simplified analysis of the compression process. To compare the performance of an internally geared screw machine with the performance of the conventional twin screw machine, it is important to provide optimum design for a specific application. The current paper is focused on providing initial multivariable geometry optimization of the internally geared screw machine for compression of air from 1 to 8 bar. Number of lobes, outer rotor diameter and wrap angle are optimized and the existing quasi one-dimensional chamber model within the in-house performance prediction software is used.

1. INTRODUCTION

Twin-screw compressors, characterized by their use of two inter-meshing rotors, are a prevalent type of positive displacement compressor used in various industries, including oil and gas, chemical processing, food and beverage, and HVAC (Heating, Ventilation and Air Conditioning) systems. Renowned for their high efficiency, reliability, and compact design, twin-screw compressors excel in managing diverse operating conditions while ensuring a consistent flow of compressed gas, making them particularly suitable for continuous operation requirements.

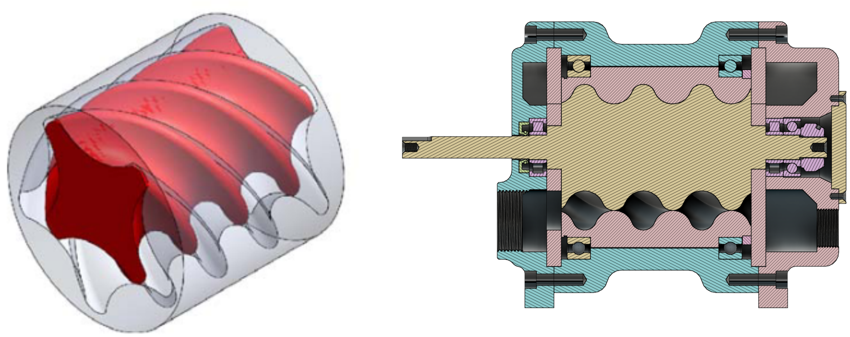
In contrast, internally geared positive-displacement machines, though not extensively explored for compressor applications, are widely used as liquid gerotor pumps. Gerotor pumps feature two straight-cut rotors rotating in the same direction about non-coincident parallel axes. The outer rotor's profile forms a conjugate pair with the inner rotor, maintaining continuous contact during rotation and enabling the separation of the volume between the rotors into multiple working chambers. These chambers' volume varies with rotor position, offering flexibility in achieving zero or non-zero minimum volumes based on the chosen rotor geometry. Control of the periods at which the fluid is allowed to enter or exit the machine is achieved by fixed porting within the machine's casing.

Methods for generating rotor geometry for gerotor applications have been detailed by various authors, including Colbourne (Colbourne, 1974), Beard et al (Beard, Yannitell, & Pennock, 1992), Vecchiato et al (Vecchiato, Demenego, Argyris, & Litvin, 2001), and Hsieh et al (Hsieh & Hwang, 2006), with several numerical approaches available for analyzing gerotor pump performance. While alterations to inlet and discharge port shapes can enable the gerotor configuration to achieve internal compression or expansion, rigorous investigations of these machines' performance are lacking in the literature.

Internally geared screw machines are considered a novel type of positive displacement machines which can be used in various applications. 3D model and cross-sectional view of a prototype internally geared screw machine is presented in Figure 1. Unlike gerotor pumps, these machines require zero minimum volume of the working chamber. Internal compression can be achieved by varying the helix pitch or profile along the rotor's length as it was first proposed by Moineau (Moineau, 1932) or by using constant pitch and profile with stationary porting on the inlet and outlet side of the machine as proposed by Read (M. G. Read, Smith, & Stosic, 2017). In this study, internally geared screw machine with fixed porting is considered and investigated through optimization procedure. Design of these machines begins with rotor profiling where continuous contact between the outer and inner rotor and a zero minimum working chamber volume represent conditions on profile shapes that need to be satisfied to allow compression and provide better sealing between the working chambers. Pin-generation method for generating rotor profiles for gerotor pump (Vecchiato et al., 2001) is suitable for internally geared screw machine rotor profiles and used in this study.

For compression applications, the gerotor profiles with a helical twist have demonstrated a reduction in power transfer between rotors (M. G. Read, Stosic, & Smith, 2019). Similar to conventional twin-screw machines, low power transfer is anticipated to play a crucial role in minimizing friction and wear on the rotors, thereby enhancing durability and limiting performance degradation over time. While previous studies have investigated the geometry of internally geared screw machines (M. Read, Stosic, & Smith, 2017; M. G. Read, Smith, & Stosic, 2019), the exact performance and comparison with conventional twin-screw machines remain unknown and further investigation is needed. Performance prediction of internally geared screw machines using a one-dimensional chamber model has been discussed in prior studies (Lacevic, Kovacevic, & Read, 2024), and the same chamber model will be utilized for performance prediction in this study.

To comprehensively understand the exact performance of internally geared screw machines, it is essential to compare them with well-known conventional twin-screw machine configurations. This study represents the initial step towards comparison, focusing on optimization of the internally geared machine geometry for this purpose. Compression of air from 1 to 8 bar has been selected as a focal application for comparing the two machine types. The objective of this study is to enhance understanding of the influence of various parameters on the machine's performance by optimizing its geometry for air compression applications. The outcomes of this study will provide foundation for conducting detailed comparisons between internally geared and conventional twin-screw compressors in the future, thereby enriching the understanding of the role of internally geared screw machines in the field of compressors.



(a) Internally geared screw machine model (M. G. Read, Stosic, & Smith, 2019)

(b) Cross-sectional view of the internally geared screw machine prototype (Lacevic et al., 2024)

Figure 1: Internally geared screw machine

2. OVERVIEW OF INTERNALLY GEARED SCREW MACHINE GEOMETRY

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2.1 Rotor Profiles

The design process of a compressor machine initiates with the specification of rotor profile shape and size, crucial factors influencing the working chamber volume, leakage paths, and overall machine performance. An internally geared screw machine is consisted of two helical rotors with internal meshing, subject to certain conditions for effective compression. Continuous meshing between the inner and outer rotors is essential for achieving compression, with a zero minimum volume being imperative for optimal machine performance. As the inner and outer rotors rotate around parallel axes, enclosed working chambers are formed, their volume varying from zero to maximum and back to zero. Compression is achieved by controlling the periods of fluid entry or exit from these chambers.

The inner rotor of an internally geared screw machine must have one fewer or one more lobe than the outer rotor and various methods for rotor profiling have been proposed in the literature, including those described by Colbourne (Colbourne, 1974) and Beard (Beard et al., 1992), however for this study, a well-established pin-generation technique is adopted, as outlined by Vecchiato (Vecchiato et al., 2001). Here, the inner rotor is assumed to have one fewer lobe than the outer rotor, with coordinate systems defined relative to the outer rotor.

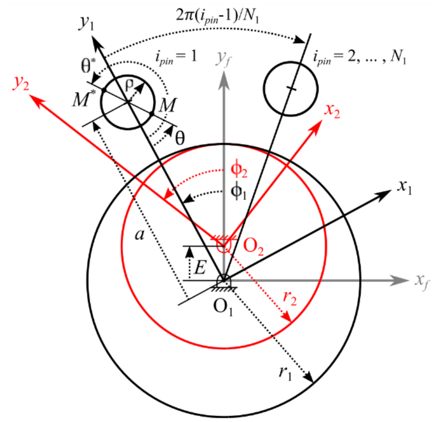


Figure 2: Pin-generation method for generating internally geared rotor profiles (M. G. Read, Stosic, & Smith, 2019)

The pin-generation procedure starts by specifying the radius (ρ_c) and center distance (a_c) of a circular pin, along with the number of lobes and diameter for either the outer or inner rotor. A circular pin is defined on the outer rotor within coordinate system S_1 which is fixed to the initial position of the outer rotor. By rotating this profile in the coordinate system of the inner rotor (S_2), which is fixed to its initial position with parallel but non-coincident axes, and applying the meshing equation described by (Vecchiato et al., 2001), the inner profile is defined. The inner rotor, as mentioned previously, has one fewer or one more lobe compared to the outer rotor ($N_2 = N_1 \pm 1$) and gearing ratio $m_{21} = N_1/N_2$ defines the angle between the coordinate systems S_1 and S_2 when rotating. Once the inner rotor is fully defined, it is rotated and transformed back to coordinate system S_1, and by applying the second meshing condition described by Vecchiato (Vecchiato et al., 2001), the outer rotor profile is formed. Geometry and position of a circular pin in pin-generation method is presented in Figure 2.

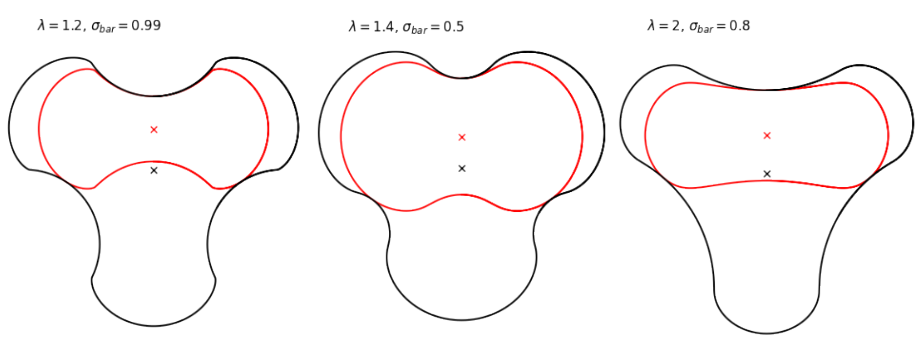


Figure 3: Example of various rotor profile shapes generated using pin-generation method

For a more convenient software implementation of the pin-generation method, non-dimensional parameters $\lambda = a_c/r_1$ and $\sigma = \rho_c/r_1$ are employed, where r_1 denotes the radius of the outer rotor pitch circle. These parameters directly influence rotor profile shape, allowing for the generation of a variety of profile shapes by varying the values of λ and σ. It is worth noting that the pin-generation method has limitations on σ values to prevent the occurrence of undercuts on either outer or inner rotor, as described by Read (M. G. Read, Stosic, & Smith, 2019). Examples of internally geared screw machine profiles produced using pin-generation method are presented in Figure 3.

2.2 Screw Machine Geometry

The previously described pin-generation method for rotor profile generation provides profiles suitable for positive displacement machines. In the case of internally geared screw machines, which feature helical rotors designed to reduce power transfer between the rotors (M. G. Read, Stosic, & Smith, 2019), an additional parameter known as the wrap angle (Φ) is introduced. This angle represents the rotation of the profile along the length of the rotor. It is crucial that the ratio of inner and outer wrap angles matches the gearing ratio, ensuring $\Phi_1/\Phi_2 = m_{21}$. Similar to conventional twin-screw machines, the wrap angle influences the swept volume and the forces exerted on the rotors (Adams & Soedel, 1995; Hanjalic & Stosic, 1997).

The continuous contact between the inner and outer rotor enables the formation of separate working chambers within the internally geared screw machine. Understanding the geometry of an internally geared screw machine requires identifying and tracking contact points during rotor rotation, enabling the investigation of variations in working chamber shape (presented in Figure 4). Geometrical analysis involves tracking a single working chamber throughout its life cycle, beginning when the working chamber is first formed and ending when its volume reaches zero. Previous studies have focused on detailed geometrical analyses of internally geared screw machines, with significant contributions from Read (M. G. Read et al., 2017; M. G. Read, Smith, & Stosic, 2019; M. Read et al., 2017).

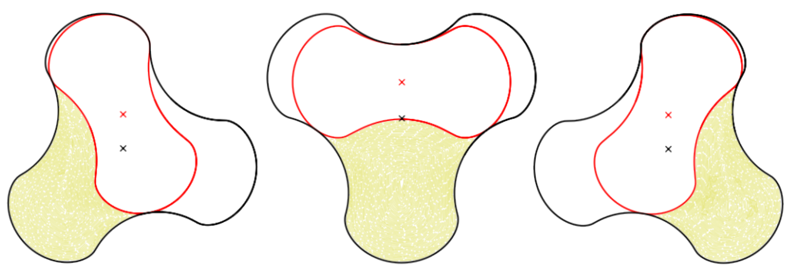


Figure 4: Example of tracked working chamber area through cross-sections at three different rotational positions

To understand how the volume of a single working chamber changes with rotor position, thereby enabling investigation of the overall capacity of the machine, two different calculation procedures are described by Read (M. G. Read, Stosic, & Smith, 2019), depending on whether the rotors are straight-cut or helical. In this study, helical rotors are employed, and the working chamber volume can be calculated by integrating the working chamber area along the longitudinal length of the chamber. This calculation requires specifying the wrap angle Φ along with the rotor length L.

2.3 Leakage Areas

The pressure difference across sealing lines of a single working chamber is a key factor in determining the internal leakage to and from a chamber during the compression process. 'Blow hole' leakage path is not present in the internally geared screw machine geometry, thus it is not considered in this study (M. G. Read, Stosic, & Smith, 2019). However, for the purposes of using the existing one-dimensional chamber model geometry simplifications have been made for the interlobe and axial end-face leakage paths as it was described by Lacevic (Lacevic et al., 2024). The leakage areas at the end face can be approximated by evaluating the perimeter of the end faces of the working chamber when they are exposed to the suction and discharge ends of the rotor. Future research on the geometry of internally geared screw machines should prioritize gaining a deeper understanding of their leakage paths and comparing them with those in conventional twin-screw machines.

3. INTERNALLY GEARED SCREW MACHINE PERFORMANCE ANALYSIS

3.1 Performance Prediction Model

Understanding the performance of a compressor and simulating its behavior is crucial for detailed investigations into its effectiveness and for producing better designs for real-world applications. Compressor performance is assessed based on factors such as power consumption, flow rates, leakages, and overall size. Utilizing performance prediction tools enables quicker and more cost-effective evaluations of machine designs. Previous studies on conventional twin-screw machines have employed either 1D performance prediction tools like the quasi one-dimensional chamber model (Hanjalic & Stosic, 1997) or 3D tools such as Computational Fluid Dynamics (CFD) (Kovacevic, Stosic, & Smith, 2006).

A performance calculation and design software known as SCORG, developed at City, University of London (Kovacevic et al., 2006), employs a one-dimensional chamber model and serves as a performance prediction tool in this research. Recent work on internally geared screw machines has involved adapting this one-dimensional chamber model, commonly used for conventional twin-screw machines, to the geometry of internally geared screw machines (Lacevic et al., 2024). Rotor profiling and geometry analysis for internally geared screw machines have been integrated into the SCORG software, enabling the efficient execution of numerous simulations within a short timeframe. The same procedures have been employed to provide performance predictions for internally geared screw machines using the one-dimensional chamber model in the current study. Apart from the oil drag power loss, other mechanical losses are not considered in this research, but will be investigated as part of current research programme.

3.2 Screw Machine Geometry Optimization

Pareto optimization, also known as multi-objective optimization, is a method used to find the best possible solutions when dealing with conflicting objectives. The core principle of Pareto optimization is derived from Pareto efficiency, where a solution is considered optimal if no other feasible solution can improve one objective without worsening another (Deb, Pratap, Agarwal, & Meyarivan, 2002). In essence, Pareto optimization seeks to identify a set of solutions known as the Pareto front, which represents the trade-off relationship between multiple objectives. This approach enables decision-makers to explore and select from a range of solutions that offer different compromises between conflicting goals.

The Python Multi-objective Optimization (*pymoo*) library provides convenient means for optimization tasks, making use of its robust functionalities for addressing multi-objective optimization challenges. Described by Blank and Deb (Blank & Deb, 2020), *pymoo* presents a user-friendly interface, seamlessly integrating into Python-based optimization workflows. With its extensive documentation and active community support, *pymoo* empowers users to navigate and resolve intricate trade-offs between conflicting objectives effectively, facilitating the identification of Pareto-optimal solutions across diverse domains.

Additionally, the Nondominated Sorting Genetic Algorithm II (NSGA-II) outlined by Deb (Deb et al., 2002) is implemented to address optimization challenges. NSGA-II is a significant advancement in multi-objective optimization, because it builds upon genetic algorithms and introduces new strategies to efficiently explore solutions. A notable feature is its sorting mechanism, which categorizes solutions based on their significance. By balancing exploration and exploitation, NSGA-II effectively converges towards the Pareto front, making it a valuable tool for solving complex optimization problems across various fields and especially suitable for this research objectives.

3.3 Screw Machine Performance Results

Prior research has focused on understanding the geometry of internally geared screw machines and providing optimal designs in terms of power transfer between the rotors (M. G. Read, Stosic, & Smith, 2019). Internally geared screw machines represent a novel type of compressor, and their exact performance remains unknown. To comprehend the role of internally geared screw machines in compressor technology, it is crucial to develop optimal designs tailored to specific applications and compare them with well-known conventional twin-screw machines or other compressor types intended for the same applications. In this study, the application of interest is the oil-injected compression of air from 1 bar to 8 bar. The objective is to provide optimal designs for internally geared screw machines designed for this application.

Geometry calculations, including working chamber volume, leakage, and end port areas relative to the main rotor's rotational position, have been implemented and integrated with the one-dimensional chamber model in the SCORG software. Additionally, a separate software written in the Python programming language, utilizing the Python Multi-objective Optimization library *pymoo*, has been employed to perform multi-objective Pareto optimization. Two distinct optimization problems have been defined:

- **Problem I:** Optimizing the configuration of internally geared screw machines to maximize volumetric flow $[m^3/min]$ and minimize specific power $[\frac{kW}{m^3/min}]$, with a fixed outer rotor diameter of $D_1 = 0.15m$ and a fixed outer rotor tip speed $u_1 = 30m/s$.
- **Problem II:** Optimizing the configuration of internally geared screw machines, with a fixed volumetric flow of 3.5 m^3/min, to minimize specific power $[\frac{kW}{m^3/min}]$ and outer rotor diameter (D_1).

For both optimization problems, various geometrical parameters presented in Table 1 were optimized. Upper and lower limits for each parameter considered in the optimization procedure are provided, and values within these ranges are selected for each iteration. As shown in Table 1, profile shapes and sizes were optimized through the number of lobes and the diameter of the outer rotor profile (N_1, D_1). Additionally, pin-generation specific non-dimensional parameters (λ) and normalized non-dimensional parameters (σ_{bar}), as described by Read (M. G. Read, Stosic, & Smith, 2019), were optimized.

The overall capacity and size of the machine were also taken into account in the optimization procedure through the outer rotor wrap angle (Φ_1), the outer rotor length-to-diameter ratio ($\frac{L_1}{D_1}$), and the volume index (VI). Oil injection considerations were addressed in optimization via the oil injection port diameter (d_{oil}) and the oil injection angle relative to the main rotor's rotational position (Θ_{oil}). Finally, the outer rotor tip speed (u_1) was optimized to enhance machine performance.

Table 1: Internally geared screw machine parameters considered in optimization procedure

Parameter	Lower Limit	Upper Limit
N_1	3	7
D_1 [m]	0.05	0.2
λ	1.1	2.5
σ_{bar}	0.1	0.99
Φ_1 [°]	36	360
L_1/D_1	1	2.1
VI	3	8
d_{oil} [m]	0.005	0.04
Θ_{oil} [°]	0	150
u_1 [m/s]	10	30

The one-dimensional chamber model in the SCORG software serves as a performance prediction tool, with fixed thermodynamic parameters outlined in Table 2. Both optimization problems focus on oil-injected air compression from 1 bar to 8 bar, with a suction temperature of $19.85°C$ and an oil temperature of $36.85°C$. The NSGA-II algorithm within the *pymoo* library is utilized and integrated for both optimization problems.

In order to maintain discharge temperature within acceptable limits and ensure improved performance, a constraint is incorporated into the optimization algorithm. This constraint restricts the discharge temperature to a maximum of $70°C$. Additionally, considerations for bearing speed limits are addressed by imposing a maximum outer rotor tip speed of 30 m/s.

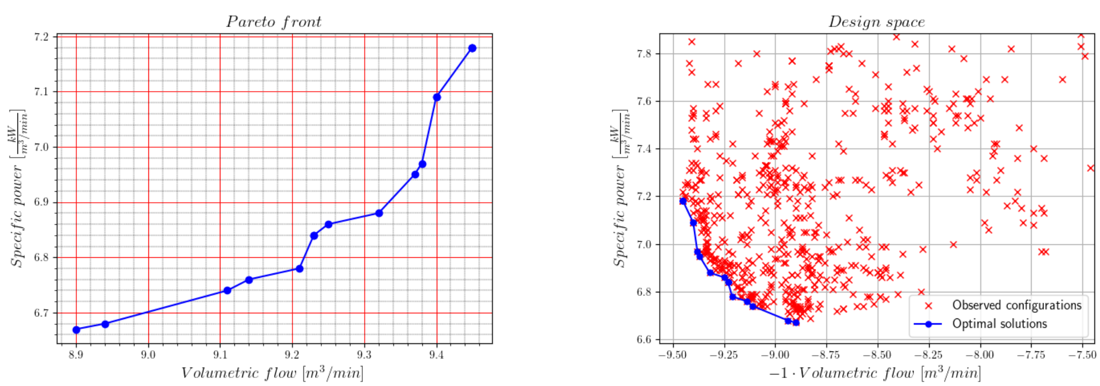
Table 2: Internally geared screw machine parameters considered in optimization procedure

Suction pressure [bar]	Discharge pressure [bar]	Suction temperature [°C]	Oil temperature [°C]
1	8	19.85	36.85

For both optimization problems examined in this study, the NSGA-II algorithm is employed to explore optimal solutions and derive the resulting Pareto front. In Figure 5 (a), the Pareto front for **Problem I** is presented, illustrating optimal solutions that balance maximizing volumetric flow and minimizing specific power. Figure 5 (b) showcases the configurations considered during the optimization process, revealing that solutions outside the Pareto front fail to improve one objective without compromising the other.

All optimal solutions on the Pareto front comply to the constraint limiting the discharge temperature to $70°C$. Figure 6 shows the internally geared screw machine design parameters for each solution on the Pareto front. Notably, optimal configurations feature a fixed number of lobes on the outer rotor ($N_1 = 3$) and relatively consistent values for other observed parameters.

Given the fixed outer rotor diameter ($D_1 = 0.15m$) and the objective of maximizing volumetric flow, it's evident that the ratio L_1/D_1 is maximized, reaching the upper limit of 2. The outer rotor wrap angle Φ_1 is represented in Figure 6 through the normalized parameter $\Phi_{1bar} = \Phi_1/360°$. Optimal configurations for **Problem I** feature slightly lower outer rotor wrap angles, approximately around 100°.



(a) **Problem I:** Pareto front when maximizing volumetric flow and minimizing specific power

(b) **Problem I:** Design space presenting all machine configurations considered in Pareto optimization procedure

Figure 5: Problem I: Maximizing volumetric flow and minimizing specific power with fixed outer rotor diameter $D_1 = 0.15m$ and outer rotor tip speed $u_1 = 30m/s$

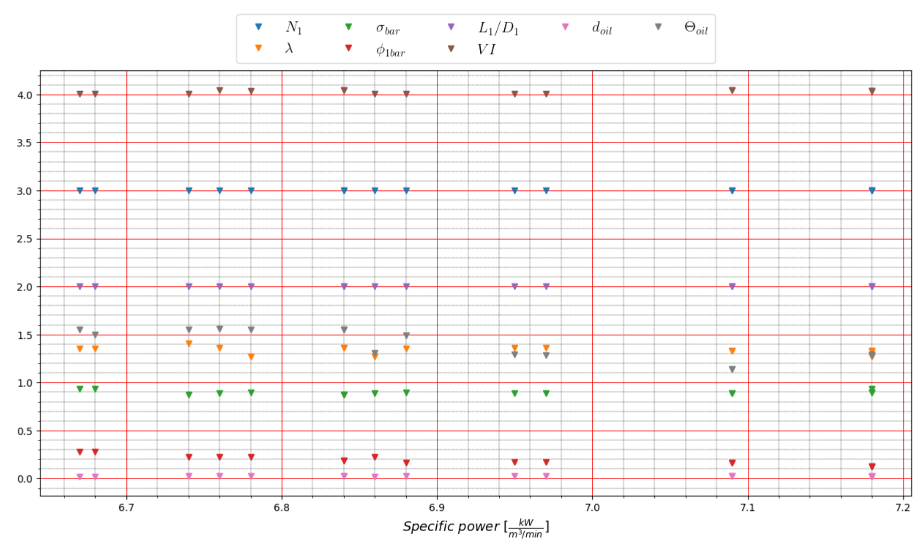


Figure 6: Problem I: Internally geared screw machine configurations for each optimal solution on pareto front

The second optimization problem targets a specific application where an internally geared screw machine aims to deliver a volumetric flow of $3.5m^3/s$ for oil-injected air compression from 1 to 8 bar. Unlike the prior problem, the outer rotor diameter can vary, with one objective being the minimization of the outer rotor diameter to reduce the overall size of the machine. Once again, the discharge temperature is limited at a maximum of $70°C$. The NSGA-II algorithm is employed to explore optimal solutions within a maximum of 100 iterations, resulting in the Pareto front for **Problem II**, as presented in Figure 7. Here, the specific power ranges from 7.36 to 7.46 $\frac{kW}{m^3/min}$, and each optimal solution on the Pareto front features a slightly different outer rotor diameter in millimeters.

Given that the overall size of the machine remains nearly constant across optimal solutions, the one with the minimum specific power ($7.36\frac{kW}{m^3/min}$) is selected as optimal for the specified oil-injected air compression application with the predetermined volumetric flow. The configuration of the internally geared screw machine for this application is outlined in Table 3. Here, the optimal solution showcases an outer rotor with 3 lobes, same as previous optimal solutions for **Problem I**, with a slightly reduced outer rotor wrap angle of 61.66°. The P-V diagram and mass flows with respect to the main rotor rotational position for the optimal solution detailed in Table 3 are illustrated in Figure 8. Notably, the injection of oil into the machine causes a minor pressure drop, and there is a slight overcompression observed on the discharge side. Additionally, the mass flow diagram indicates that there is approximately three times more oil within the machine compared to air.

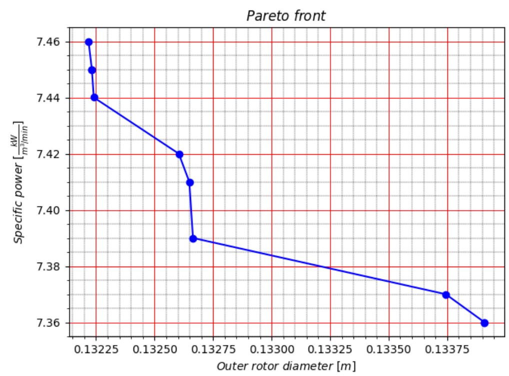
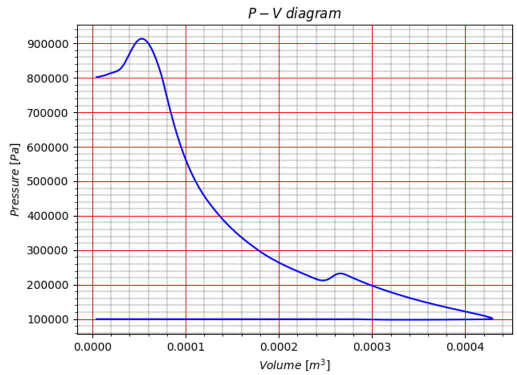


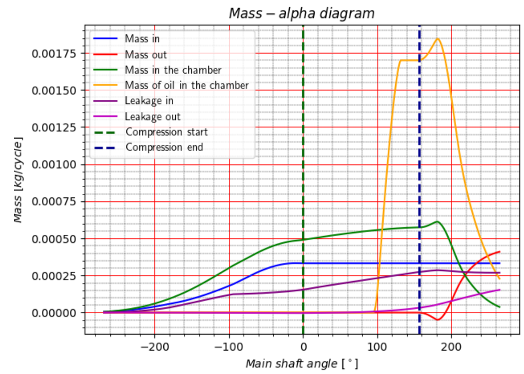
Figure 7: Problem II: Pareto front minimizing outer rotor diameter and specific power for a fixed volumetric flow of $3.5m^3/s$

Table 3: Problem II: Chosen optimal solution for a fixed volumetric flow of $3.5m^3/min$ while minimizing specific power and outer rotor diameter

Parameter	Optimum value
N_1	3
D_1 [m]	0.133744
λ	1.719013
σ_{bar}	0.89918
Φ_1 [°]	61.66
L_1/D_1	1.05218
VI	3.468065
d_{oil} [m]	0.020916
Θ_{oil} [°]	95.1281
u_1 [m/s]	29.638



(a) **Problem II:** P-V diagram for optimal solution



(b) **Problem II:** Mass flows with respect to the main rotor rotational position for optimal solution

Figure 8: Problem II: Performance prediction results for optimal solution presented in Table 3

4. CONCLUSIONS

The internally geared screw machine presents a novel configuration among screw compressors, yet its precise performance remains unknown. While extensive research has investigated the geometry of these machines, it is essential to provide better understanding of their operational efficiency. To determine the precise role of internally geared screw machines within the compressor domain, it is important to optimize their designs for various real-world applications and compare their performance against cutting-edge compressor designs intended for the same applications. Previous studies have implemented existing quasi one-dimensional performance prediction models to simulate the performance of internally geared screw machines in specific applications. Similarly, in this study, the same one-dimensional performance prediction tool is used to optimize the design of an internally geared screw machine for oil-injected air compression from 1 to 8 bar.

This study addresses two distinct optimization problems. Firstly, **Problem I** aims to maximize the volumetric flow rate while keeping the outer rotor diameter fixed. On the other hand, **Problem II** focuses on minimizing the outer rotor diameter for a predetermined volumetric flow rate. Several observations are noted from the optimization of internally geared screw machine configurations in this study:

- Increasing the number of lobes on the outer rotor does not provide any benefits, as all optimal solutions feature the 2/3 configuration, with the number of lobes on the outer rotor (N_1) fixed at 3.
- All optimal solutions feature lower values of the wrap angle (Φ) and higher values of the normalized pin-generation parameter (σ_{bar}), thereby implementing a broader interlobe region on both the inner and outer rotor profiles.

The optimization results obtained in this study provide insights for the future design of internally geared screw machines for practical applications. By specifying a narrower range of values for certain geometric parameters, performance of internally gearead screw machine can be improved. To understand exact role of internally geared screw machine, future work should incorporate this research and provide detailed comparison between internally geared and conventional twin screw machine performance for the same application. Internally geared screw machine has various potential benefits compared to the conventional compressors, however their comparative effectiveness is yet to be investigated.

NOMENCLATURE

N	number of lobes on rotor	(–)
λ	rotor profile parameter	(–)
σ	rotor profile parameter	(–)
Φ	rotor wrap angle	(°)
L	rotor length	(m)
D	rotor outer diameter	(m)
u	rotor tip speed	(m/s)
Subscript		
1	outer rotor	
2	inner rotor	

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