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Contribution of modern rotor profiles to energy efficiency of screw compressors

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Abstract. Screw rotors are the heart of screw compressors. And the energy efficiency of industrial machines is a matter of tremendous significance now more than ever. Historically, rotor profile developments have played a key role in making screw compressors energy efficient and commercially viable. Further attention to manufacturing aspects of rotor profiles and the invention of the rack generated rotor profiles led to rotor profiles having good manufacturability. The principles of rotor profile generation and manufacturing are available in open literature since 1960's. But more and more literature on rotor profiling has been published since then. Modern screw rotor profiles (patented close to and in the 21st century) have all the principles of a good profile incorporated in their design. Hence the industry and profile designers at large are aware of the increasing difficulty to further make the twin screw compressor rotor profiles more energy efficient. This paper tries to quantify the contribution of rotor profile to energy efficiency of a typical twin screw compressor by comparing the most recent (hence modern) screw compressor rotor profiles. In order to fairly compare different rotor profiles, all are retrofitted to a single size, lobe combination, rotor length, and helix angle. Only the curves constituting the profile, as dictated in the patent documents of the respective profiles, have been changed. Tools such as SCORPATH and SCORG have been used to do the geometric and thermodynamic calculations on the profiles. Keeping the working conditions same for all the retrofitted but different profiles, a comparison has been made. This comparison sheds some light on how much is the energy efficiency of a particular twin screw compressor influenced by a mere change of profile. This analysis can be further extended to establish reasonable targets for twin screw compressor manufacturers to improve energy efficiency of their machines via improving their rotor profiles. This remains the future scope of this work.

1. Introduction

Twin screw compressors have evolved for almost a century since their invention in 1930's. Rotor profiles being an essential element of these machines, have gone through a similar evolution over these years. Advancements in rotor profile design and manufacturing played crucial role in putting the twin screw compressors on par with the other compression technologies. Energy efficiency of compressors could be talked about in terms of either their specific power which is power consumed to deliver a unit of compressed medium or the adiabatic or isothermal efficiencies of compression process evaluated for that machine. Early rotor profiles were not very energy efficient due to large leakage areas between the rotors. This scenario changed with the invention of asymmetric rotor profiles, first by Lysholm [1] and later with the SRM-A profile by Schibbye [2] which led to significant reduction of internal leakages with respect to total throughput of the rotors. The developments in manufacturing technology for making the helical rotors with precision also played a key role in making screw compressors energy efficient and hence commercially viable. Only by maintaining the tight form of rotor profiles in manufacturing, the internal clearances could be kept to minimum and thereby internal leakages were minimized too. There's a long and interesting history to how these principles of generating viable rotor profiles were discovered, patented and then re-discovered by other manufacturers. It is very well summarized by Stosic *et al.* [3]. By and large, most of the major screw compressor manufacturers had their own profile patents by 1980's [4] [5] [6] [7]. All these profiles were based on principles similar to SRM-A profile, wherein curves of choice were defined on either rotor to derive the conjugate curves on the other rotor using gearing condition. Efforts were put into choosing most suitable curves which would facilitate larger throughput area and minimize the leakage areas keeping manufacturability in consideration.

In the period that followed, the principle of rack generation was introduced in rotor profiling for screw compressors first by Menssen [8] followed by Rinder [9]. The principle of rack generation had several advantages over previous method such as better manufacturability by design, involute contact and a simplicity in the design. Still, the rack generated profiles had ample scope of improvement which was steadily and incrementally realized in later profiles such as Stosic [10] and as latest as Cavatorta and Tomei [11]. The rack generated profile by Rinder [9] though ingenious; had a problem of slightly larger blow hole area and poor sealing on the portion of rotors generated by the high pressure side of the rack. This particular shortcoming of the rack generated profile was overcome by Stosic and Hanjalic [12] through introduction of cycloids in this region of rack which could also be seen as a combined rotor-rack generation method. N-rotors are stronger yet lighter and also facilitate high throughput to leakage area ratio resulting in a higher energy efficiency of the machine.

Later and more recent contributions to the field of rotor profiling came through applications of finer design principles such as variable clearance distributions on rotors, controlling torque characteristics of the gate rotor [13] and an extensive work on optimisation techniques applied to rotor profile designs [14] [15] [16] [17]. The wealth of all this literature available in modern times has made the principles of good rotor profiling accessible to the majority of rotor profile designers.

The intent of this paper is to review the more recent or modern rotor profiles from last 25 years. These modern rotor profiles are based on the body of literature and knowledge briefly outlined hereby. The state of the art rotor profile patents owned by major compressor manufacturers are reviewed in light of their uniqueness and differences. Their contribution to energy efficiency of modern screw compressors is discussed. Based on the review and discussion, a general outline of what may lie in future for the screw rotor profiling is drawn.

2. Modern screw rotor profiles

Fu Sheng's [18], Gardner Denver's [11], City's [19] and Kaeser's [20] are some of the major rotor profile patents in last 20 years. They are chosen particularly to highlight the features of the state of the art rotor profiles. There are obviously more patents to be found on rotor profiles in this time period but these profiles are assumed to be representatives of good rotor profiling principles applied in the design of energy efficient screw compressors by the respective assignees.

Figures 1, 2 and 3 depict the mentioned modern rotor profiles as represented in their respective patent documents. The patent [19] is mainly about the N-profiled rotors designed for better torque characteristics and reduced noise. Geometrically, the profile curves in this patent are same as that of [10].

Two of the three profiles depicted herein (figures 1 and 2) are based on the principle of rotor-

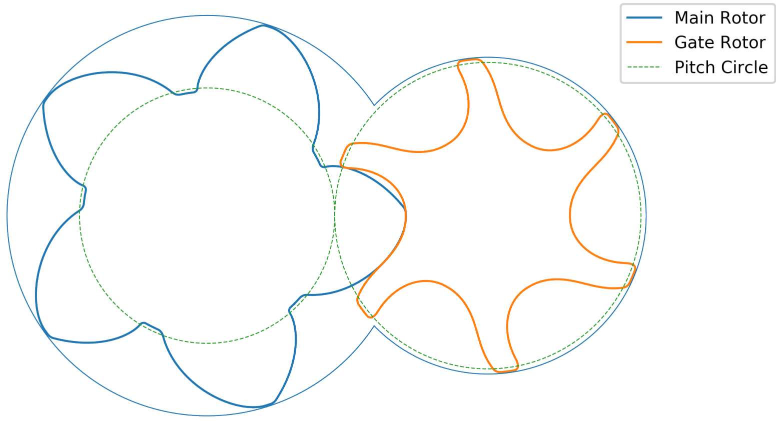

Figure 1. Fu Sheng Profile [18]

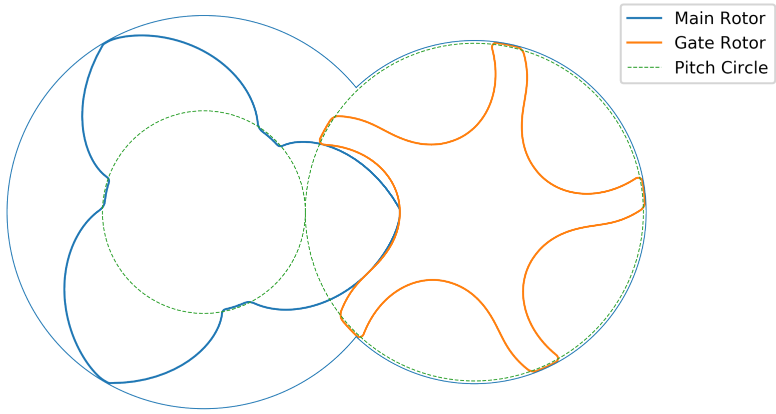

Figure 2. Gardner Denver Profile [11]

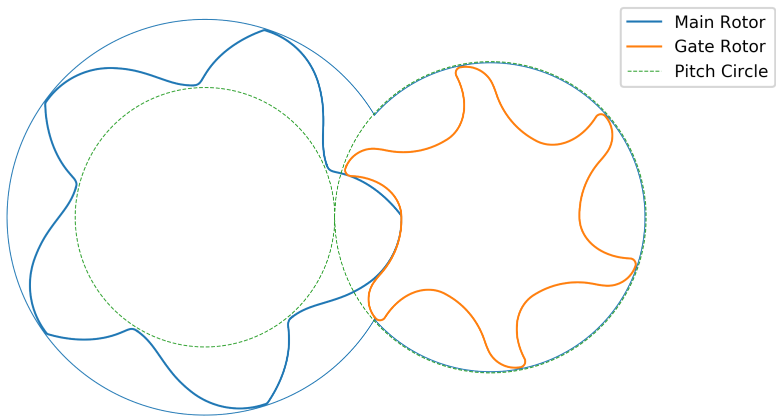

Figure 3. Kaeser Profile [20]

rack generation which is known have several advantages over classical rotor generation or rack generation principle. The racks used to define these profiles are very similar to the N-rack [10]. They all differ essentially by the curve used to define the low pressure side of the rack. Figure 4 depicts a general rack profile for rotor-rack generated profiles with nodes representing end points of the constituent curves. Table 1 then lists the individual curves to show how the patents are different. The respective conjugates on rotors are simply roulettes of the curves defined on rack calculated by solving the envelope gearing condition.

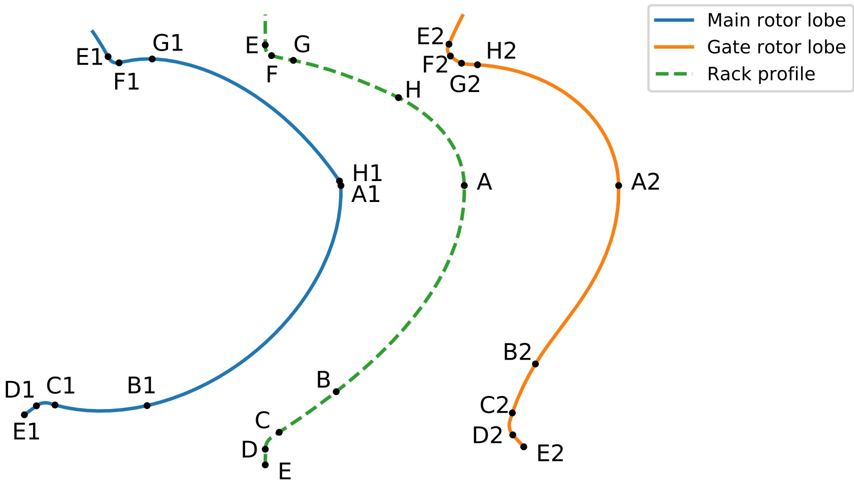

Figure 4. A general rack profile generating main and gate rotor profiles

Table 1. The curves constituting rack of the N-profile, Fu Sheng profile and the Gardner Denver profile

Rack curve	N-profile	Fu Sheng profile	Gardner Denver profile
D-E	Vertical straight line	Vertical straight line	Vertical straight line
E-F	Circular arc	Circular arc	Circular arc
F-G	Straight line	Straight line	-
G-H	Cycloid	Cycloid	Cycloid
H-A	Cycloid	Cycloid	Cycloid
A-B	**General arc***	**Elliptic arc**	**Hyperbolic arc**
B-C	Straight line	Straight line	Straight line
C-D	Circular arc	Circular arc	Circular arc

*Parabolic, Elliptic or Hyperbolic arc, depending upon the arc exponents [10]

The key change in the three similar profiles in table 1 is in the curve A-B. This particular portion of the rack determines what would be main and gate rotor lobe thicknesses which influence the total combined throughput area of the rotor pair. It also affects the sealing line length of the meshing rotor pair. Hence, the changes in arc to get various conic sections such as ellipse and hyperbola are probably done for striking a good balance between total throughput area and the sealing line leakage area. Curve A-B does not affect high pressure side blow-hole area but all the curves above horizontal axis do. In this context, it is interesting to note that the straight line F-G is omitted in the Gardner Denver profile. This slight change of directly connecting the cycloid with circular arc on high pressure side helps marginally reduce the blow hole area.

Only the Kaeser profile out of most of the modern profiles is based on the principle of rotor generation. Majority of this profile's curves are defined on the gate rotor and the remaining on the main rotor. It is largely based on its predecessor SIGMA profile by Bammert [4]. The latest profile has made amendments with the targets of improving gate rotor torque characteristics, minimizing blow-hole area, strengthening gate rotors and optimizing the profiles with respect to multi-objective criteria. Especially the profile version of Kaeser's new profile depicted in figure 3 has up to four times smaller blow-hole than an equivalent rack-generated profile due to slightly negative gate rotor addendum combined with a well designed sharp gate rotor tip. This however comes at a price of relatively lesser throughput area due to smaller profile depth. Such trade-offs are ubiquitous in rotor profile design. Therefore, one has to weigh in the role of operating conditions and application of the screw compressor to make the best trade-offs.

3. Contribution of modern profiles to the energy efficiency of screw compressors

The literature has several clues and reportings of the improvement in energy efficiency of screw compressors with the onset of rotor-rack generation method along with the application of finer design principles such as variable clearance distributions and multi-variate optimisation to rotor profiles. That is to say, contribution of the modern screw rotor profiles replacing the older profiles of late 20^{th} century to the energy efficiency of screw compressors can be pinned down with evidence. Stosic *et al.* [21] presents a case of retrofitting old SRM-A profiled rotors in an oil flooded twin screw compressor with the N-profiled rotors and thereby improving the energy efficiency of the machine by 2.5%.

From a purely geometric point of view, profile does not solely contribute to the energy efficiency of screw machine. Other characteristics of the rotors such as lobe combination, diameter, length, helix angle, speed and also the suction and discharge ports affect the performance to a significant degree. Hence, only a holistic approach to optimum choice of all the geometric and operating parameters would lead to substantially efficient compressors. The combined profile and geometry optimisation with Kaeser's new profile [20] is claimed to have improved upon the old SIGMA profile [4] by up to 3%. Similarly, Fu Sheng's rack generated profile (figure 1) is claimed to have improved on their own old rotor generated profile [22] by 1.32% in terms of the energy efficiency [17].

Nevertheless, all three of the presented examples arise from a comparison of the modern profiles with old profiles. But, if one wishes to gauge the contributions of only modern rotor profiles into improvements of energy efficiency of screw compressors in last 25 years, only the modern profiles must be compared starting from N-profile [10]. As elaborated in the previous section, majority of the modern screw rotor profiles have incorporated the principles of designing good profiles. This could be the reason for minimal differences among their designs. But to what extent do these minimal changes affect the energy efficiency of machines? To answer this, Fu-Sheng profile [18] and the Gardner Denver profile [11] can be compared through retrofitting and numerical evaluation of their geometric and thermodynamic properties. The profile with 5/6 lobe combination of rotors as depicted in figure 1 true to Fu Sheng's patent description is generated and taken as a reference for calculation. The Gardner Denver profile's patent depiction (figure 2) is in 3/5 lobe combination of rotors. In order to retrofit with Fu Sheng profile, a Gardner Denver profile with 5/6 lobe combination is generated based on the patent description of curves and other details of the profile. The two profiles are set at the same centre distance of approximately 100 mm and have a 140 mm main rotor outer diameter. The length to diameter ratio is set to 1.55 and the wrap angle is set to 300° for both rotor pairs. Figure 5 is a representation of these two retrofitted profiles.

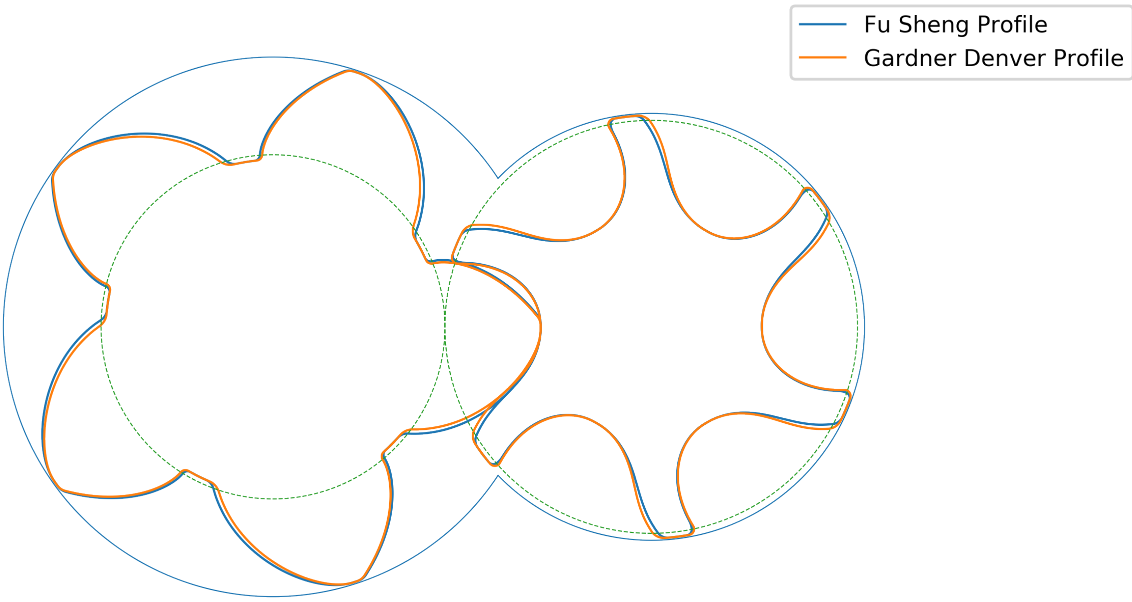

Figure 5. Retrofitted rotor profiles with 5/6 lobe combination-[18] and [11]

As elaborated earlier, the high pressure side of these profiles is identical except the absence of straight line in Gardner Denver profile. A closer look at the leading edge tip of the gate rotors of Gardner Denver profile shows that it would have a smaller blow hole area compared to Fu Sheng profile on account of this small change. The low pressure sides of these profiles have Ellipse and a Hyperbola respectively. That makes them look slightly different on leading edge of the main rotor. The throughput area and the leakage areas for these two profiles are calculated and given in table 2. It is worth noting that both, FuSheng and Gardner Denver profiles can be generated through the N rotor form by choosing coefficients and exponents in its general curve to resemble circles, ellipses, parabolas or hyperbolas.

Table 2. Geometric profile characteristics for retrofitted Fu Sheng and Gardner Denver profiles

Profile Characteristic	Fu Sheng Profile	Gardner Denver Profile
Throughput area (mm^2)	8507	8621
Interlobe sealing area (mm^2)	4.693	4.876
Blow hole area (mm^2)	1.852	1.191

The Gardner Denver profile has a slight advantage in throughput area as well as blow hole area on account of the finer details elaborated in previous section. If these profiles are subjected to a thermodynamic simulation for an oil injected screw compressor air application, the difference in energy efficiency of these machines is observed to be of the order of 0.3% to 0.5% only. The simulation was done in SCORG software within the envelope of operating conditions - tip speed 10 m/s to 40 m/s, suction pressure 1 bar absolute (bara) and discharge pressure 6.5 bara to 12.5 bara. The oil injection parameters and other peripheral details were set to practically reasonable values and same for both setups to avoid their influence on evaluation. The observed order of difference shows that the modern profiles which are more or less equivalent in application of good design principles do not make a big difference in terms of energy efficiency. Even the gap of 0.3% could be minimized if the profile with larger leakage area is allowed to compensate using other characteristics such as rotor size, sharper tips or rotor speeds, etc. If an N-profile were designed for similar size, it wouldn't be any different because structurally both the profiles in figure 5 are equivalent to it. Either FuSheng or Gardner Denver profiles can be generated through the N rotor patent definition by changing the curve A-B exponent n [10]. No more than 0.5% of difference in energy efficiency would be observed by only interchanging curves such as-parabola, ellipse and a hyperbola.

4. Conclusion & Future scope

Most of the known features of a good rotor profiles are already incorporated in all the modern rotor profiles. Hence, an advantage by a mere change of curves or their placement in a profile is practically not possible at least in modern profiles. Unlike the leap in energy efficiency of screw compressors first by introduction of asymmetric profiles in 1960's and then through the principle of rotor-rack generation in 1990's, modern profiles are unlikely to come by such leap through only change of profile curves and shapes.

Screw compressor manufacturers already in possession of a good modern profile should expect improvements from any new profiles only in the order of 1% at maximum. More improvements are only going to come from either innovations in optimisation techniques or a scientific disruption in the methods of profile generation and manufacturing. One example of such an innovation which could improve rotor profiles if combined with good optimisation framework is application of topology inspired by path homotopy in profiling [23].

Since all modern profiles are more or less equally efficient, the weight of designing more efficient screw compressors lies with the ability of profile designer. Use of the state of the art optimisation algorithms, understanding of the machine application and underlying physics of compression is paramount if one wishes to fine tune any good profile for the desired duty. Energy efficiency of not only operation but also during manufacturing of screw compressors until the end of complete product life-cycle should be the focus for future of rotor profiling.

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