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SCREW COMPRESSOR: A STRONG LINK IN THE DEVELOPMENT CHAIN

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Professional paper

In any development, screw compressor has several prominent roles. One is its unavoidable application in infrastructure building of the road and railway networks, as well as in major housing developments. Other roles are introduction of new compressor manufacturing facilities and a consequential improvement of the existing compressor industry in which the screw compressor has a vital part as an effective, efficient and robust machine. Old compressor industry, which has experience in manufacturing of traditional compressors, is a valuable basis for direct application of new developments in area of screw compressors achieved in recent years. A role of screw compressors as a potential means in the local and world trade also must be seriously considered.

Key words: *screw compressor, design, development, efficient use of energy*

Vijčani kompresor: Snažna veza u razvojnom lancu

Stručni članak

U svakom razvojnom projektu, vijčani kompresor ima nekoliko istaknutih uloga. Jedna od njih je njegova neizbježna primjena u izgradnji infrastrukture cestovnih i željezničkih mreža i velikih stambenih projekata. Druge uloge su uvođenje novih načina za proizvodnju kompresora te slijedom toga unapređenje postojeće industrije kompresora u kojoj je vijčani kompresor bitan kao učinkovit, efikasan i robustan stroj. Stara industrija kompresora, koja ima iskustva u proizvodnji tradicionalnih kompresora, predstavlja važnu polaznu točku za direktnu primjenu novih razvojnih dostignuća u području vijčanih kompresora zadnjih godina. Uloga vijčanih kompresora u lokalnoj i svjetskoj trgovini se također mora ozbiljno razmotriti.

Ključne riječi: *vijčani kompresor, konstrukcija, razvoj, djelotvorno korištenje energije*

1 Uvod
Introduction

Industrial and domestic compressors consume staggering 17 % of the world power production. Their majority today is reciprocating compressors. However, many other types have their substantial share. Among them, screw compressors play a significant role because of their popularity and relatively large size and consequently large power consumption.

Screw compressor is a rotational machine of volumetric action, which transforms mechanical work of the electromotor, turbine or IC engine into potential energy of the working medium of higher pressure. They operate on gases, vapour or multi-phase mixtures with phase changes taking place within the machine with or without internal lubrication. The main users of compressed gases supplied by screw compressors are today building engineering, food, process and pharmaceutical industry, metallurgy and pneumatic transport. For optimum performance from such machines, a specific design and operating mode is needed for each application. They are simple machines capable of high-speed operation over a wide range of operating pressures and flow rates with high efficiencies. Favourable features of the screw compressor process and its design details give certain advantage compared with all other compression machines. Before others, these are a pure rotational movement of the compressor elements, which allows higher speeds and higher efficiency per compressor unit mass, less wear and longer life of the machine. Therefore, screw compressors are up to five times lighter than their reciprocating counterparts of the same capacity and their longevity can be almost ten times higher. Since they are both reliable and compact, consequently they comprise a large portion of all positive displacement compressors sold and currently in operation. However, volumetric and adiabatic efficiency of screw compressors is highly dependent upon the precision of manufacturing of their rotors as well as other component parts, housings and bearings. Such a precision can be achieved only by use of specialized machine tools.

The present world production rate of positive displacement compressors is in excess of 150 million units per year, the bulk of them being required for compressed air and refrigeration systems. During the past thirty years, for many applications, traditional reciprocating compressors have been replaced by those of the twin-screw type. The main reasons for this change are the development of improved rotor profiles, which have drastically reduced internal leakage, and machine tools, which can manufacture the most complex shapes to tolerances of the order of 5 μm at an affordable cost. Although advances have also been made in analytical methods, which are gradually being adopted by designers to predict compressor performance more reliably, their scope and accuracy lag behind that of modern NC machine tools and assembly procedures. Consequently improved methods of analysis can create, as yet unrealised, opportunities for improving the performance and reducing the cost of screw compressors and, thereby further extending the range of applications for which they may be suitable.

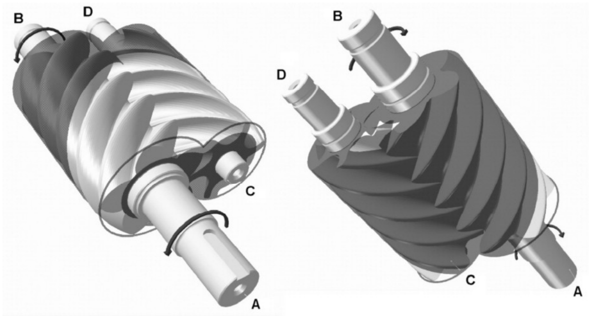
Rotor profile enhancement is still the most promising means of further improving screw compressors and rational procedures are now being developed both to replace earlier empirically derived shapes and also to vary the proportions of the selected profile to obtain the best result for the application for which the compressor is required. In addition, improved modelling of flow patterns within the machine can lead to better porting design. Also, more accurate determination of bearing loads and their fluctuation enables better choices of bearings to be made. Finally, if rotor and casing distortion, as a result of temperature and pressure changes within the compressor, can be estimated reliably, machining procedures can be devised to minimise their adverse effects.

Up to date modelling and analytical procedures now being developed to address all these possibilities are reviewed here together with examples of how their utilisation has led to improved designs and new applications.

As it was correctly pointed out in [1], a screw compressor is one of the great success stories of the last quarter of the twentieth century in which the increase in the number of units manufactured has been spectacular, due principally to the development of advanced manufacturing techniques, the fact which had limited the attractiveness of this machine in the first period of its modern existence.

2 Background
Pozadina

Screw compressors essentially consist of a pair of meshing helical lobed rotors, contained in a casing. Together, these form a series of working chambers, as shown in Fig 1, by means of views from opposite ends and sides of the machine. The dark shaded portions show the enclosed region where the rotors are surrounded by the casing and compression takes place, while the light shaded areas show the regions of the rotors, which are exposed to external pressure. The large light shaded area in Fig 1a) corresponds to the low-pressure port. The small light shaded region between shaft ends B and D in Fig 1b) corresponds to the high-pressure port. Admission of the gas to be compressed occurs through the low-pressure port, which is formed by opening the casing surrounding the top and front face of the rotors. Exposure of the space between the rotor lobes to the suction port, as their front ends pass across it, allows the gas to fill the passages formed between them and the casing. Further rotation then leads to cut off of the port and progressive reduction in the trapped volume in each passage, until the rear ends of the passages between the rotors are exposed to the high-pressure discharge port. The fluid then flows out through this at approximately constant pressure.



a) b)

Figure 1. Screw compressor main components (a - view from front and top, b - view from bottom and rear)
Slika 1. Glavni dijelovi vijčanog kompresora (a – pogled sprijeda i odozgo, b – pogled odozdo i straga)

In order to operate effectively a line of contact must be formed between the two rotors and between the rotors and the casing. The length of the contact line between the rotors varies according to the angle of rotation and must be maintained throughout the working chamber formed between the two lobes and the casing. As shown in Fig 2, a small gap occurs between the cusp of the casing and the rotors which extends along the length of the casing to form a "blowhole" through which the gas being compressed or expanded leaks. The aim of the designer is to select profiles for the rotor lobes, which maximise the flow area between them while minimising the blowhole area, the sealing line length and the contact forces between the male and female rotors. Although the principle of the screw compressor has been known for over 100 years, it is only since the development of the SRM "A" profile in 1973, which met these criteria far better than any of its predecessors, that screw compressors began to be commercially viable.

The mechanical design of such machines is relatively simple in that the moving parts comprise only two rotors rotating in their bearings. They can therefore operate reliably at high speeds. High accuracy profile milling and grinding now enable rotors to be manufactured with interlobe clearances of 30-50 μm at an economic cost. Hence, internal leakage is far less than in earlier machines of this type. Consequently, they are both compact and efficient and, in addition, they can operate over a wide range of operating pressures and flow rates.

Screw machines are used today for different applications both as compressors and expanders. Their geometry may vary depending on the number of lobes in each rotor, the basic rotor profile and the relative proportions of each rotor lobe segment. It follows that there is no universal configuration, which would be the best for all applications. Hence, detailed thermodynamic analysis of the compression process and evaluation of the influence of the various design parameters on performance is more important to obtain the best results from these machines than from other types which could be used for the same application. A set of well-defined criteria governed by an optimisation procedure is therefore a prerequisite for achieving the best design for each application. Such guidelines are also essential for the further improvement of existing screw machine designs and broadening their range of uses.

Screw compressors in normal commercial usage today have main rotors whose outer diameters vary between 75 mm and 620 mm. These deliver between 0.6 m^3/min and 600 m^3/min of compressed gas. The normal pressure ratios attained in a single stage are 3.5:1 for dry compressors and up to 15:1 for oil flooded machines. Normal stage pressure differences are up to 15 bars, but maximum values sometimes exceed 40 bars. Typically, for oil flooded air compression applications, the volumetric efficiency of these machines now exceeds 90 % while specific power inputs, which are both size and performance dependent, have been reduced to values which were regarded as unattainable only a few years ago.

In both, dry and oil free air compression, screw compressors are used almost exclusively. This is also gradually becoming the case for process gas compression. In the field of refrigeration, the use of reciprocating and vane compressors is decreasing and a continuing increase in favour of screw machines is expected in forthcoming years.

Typically, refrigeration and process gas compressors, which operate for long periods, must be designed to have a high efficiency. In the case of air compressors, especially for mobile applications, efficiency may be less important than size and cost.

3
Screw compressor market and industry
Tržište i industrija vijčanih kompresora

Svenska Rotor Maskiner, SRM, a Swedish company, was the pioneer and they are still being leaders in the field of screw compressor design and development practice. Other companies, such as Compair in the U.K, Atlas-Copco in Belgium, Ingersoll-Rand and Denver Gardner in the USA and GHH in Germany are the main air compressor manufacturers. York, Trane and Carrier in the USA lead in refrigeration and air conditioning applications. Japanese screw compressor manufacturers, such as Hitachi, Mycom and Kobe-Steel are also well known. In recent years there have been a number of mergers and buy-outs of smaller companies by these larger ones. New markets in China, India and other developing countries in the Middle and Far East have led to new screw compressor companies being founded there as well as factories being built there by the major manufacturers. Although they do not manufacture compressors, Holroyd, a British company is the world's largest screw rotor manufacturer. They are also world leaders in tool design and machine tool production for the manufacture of screw compressor rotors. Recently a need was expressed for centres of excellence in screw compressor research and development. One such centre was established 8 years ago at City University London to provide services for large or small, renown or new companies manufacturers of screw compressors. A main contemporary development in screw compressor industry happens in the Far East where new companies redirect a great proportion of their profits into acquiring a new knowledge in compressor technologies. A number of the Western compressor companies, facing a fact of fresh competition, follow their examples.

In spite of the increasing screw compressor popularity, a public knowledge on screw compressors is still limited. Early reference textbooks were published in Russian, [2]-[4], later in German, [5] and [6] and recently in English [7] and [8]. There are a substantial number of patents dealing with various aspects of screw compressors, specially their profiles. Only SRM claims 750 patents, 1946 (symmetric), 1970 (unsymmetrical) and 1982 ("D" profile) are classical reference literature presenting state of the art in screw compressor profile generation. Successful profiling patents are also applied by Atlas-Copco, Compair, Denver Gardner, Hitachi, Fu Sheng, Ingersol-Rand. Journals surprisingly lack in screw compressor literature. Three compressor conferences deal exclusively or partly with screw compressors: Purdue compressor technology conference in the U.S.A, IMechEng conference on industrial compressors in England and "VDI Schraubenkompressoren Tagung" in Germany. A valuable contribution at these conferences can be recognized in [9]-[13]. Many reference textbooks in gears are useful background for a screw rotor profiling, one of them, [14] is used as a reference in [15], where a new concept of the rack generation of the screw compressor rotors is presented.

The search for new screw compressor profiles has been both stimulated and facilitated by recent advances in mathematical modelling and computer simulation. These analytical methods may be combined to form a powerful tool for process analysis and optimisation and thereby eliminate the earlier approach of intuitive changes, verified by tedious trial and error testing. As a result, this approach to the optimum design of screw rotors lobe profiles has substantially evolved over the past few years and is likely to lead to further improvements in machine performance in the near future. However, the computer models and numerical codes reported in the open literature often differ in their approach and in the mathematical level at which various phenomena are modelled. A lack of comparative experimental verification still hinders a comprehensive validation of the various modelling concepts. In spite of this, computer modelling and optimisation are steadily gaining in credibility and are increasingly employed for design improvement. These models have been abundantly used in the screw compressor designs, as presented in [16]-[18].

The efficient operation of screw compressors is mainly dependent on proper rotor design. An additional and important requirement for the successful design of all types of compressors is the ability to predict accurately the effects on performance of the change in any design parameter such as clearance, rotor profile shape, oil or fluid injection position and rate, rotor diameter and proportions and speed. Now that tight clearances are achievable, internal compressor leakage rates become small. Hence, further improvements are only possible by the introduction of more refined design principles. The main requirement is to improve the rotor profiles so that the internal flow area through the compressor is maximised while the leakage path is minimised and internal friction due to relative motion between the contacting rotor surfaces is made as small as possible.

Although rotor-profiling procedures may appear to be fully defined, substantial improvements are still possible. The most promising approach for this seems to be through rack profile generation, which gives stronger but lighter rotors with higher throughput and lower contact stress. The latter enables fluids with lower viscosity than oil to be used for lubrication. Rotor housings with better-shaped ports can be designed using multivariable optimisation techniques. Flow losses may thereby be reduced permitting higher rotor speeds and hence more effective compressors. Recent improvements in bearing design make process fluid lubrication possible in some applications. Also seals are more efficient today. All these developments can be utilised to produce more efficient, lighter and cheaper screw compressors.

Increase in number of screw compressors manufactured has recently been significant mainly due the advancement in their manufacturing. A high accuracy profile grinding reduces linear tolerances permitting rotors to be manufactured with small clearances and economic cost. Internal leakages have thus been reduced to a small fraction of their values in earlier designs and as a result screw compressors are now more efficient than other types of compressors as well as being smaller.

Screw compressors are used in infrastructure building of the road and railway networks, as well as in major housing developments. Another is a consequential improvement of compressor industry, where the screw compressor has a vital part as an effective, efficient and robust machine. A role of screw compressors as a potential means in the local and world trade also must not be neglected. Old compressor industry, which has experience in manufacturing of traditional compressors, is a good basis for a direct application of new developments in screw compressors achieved in recent years.

4 Recent Screw Compressor Developments

Skorašnji razvoj vijčanih kompresora

The efficient operation of screw compressors is mainly dependent on proper rotor design. An additional and important requirement for the successful design of all types of compressors is an ability to predict accurately the effects on performance of the change in any design parameter such as clearance, rotor profile shape, oil or fluid injection position and rate, rotor diameter and proportions and speed.

Now, when tight clearances are introduced and internal compressor leakage rates become small, further improvements are only possible by the introduction of more refined design principles. The main requirement is to improve the rotor profiles so that the internal flow area through the compressor is maximized while the leakage path is minimized and internal friction due to relative motion between the contacting rotor surfaces is made as small as possible. Although it seems that everything was done in the rotor profiling, there is a lot of room for substantial improvements. The most promising appears to be a rack profile generation, which gives stronger but lighter rotors with higher throughput and lower contact stress. The latter enables a lower viscosity fluid than oil to be used for lubrication.

Rotor housings with better-shaped ports can be designed using a multivariable optimisation technique. This reduces flow losses enabling higher rotor speeds giving more effective compressors. A fascinating improvement in the compressor bearing design is achieved in recent years enabling a process fluid lubrication. Also seals are more efficient today. All these give a good foundation for more effective and more efficient screw compressors.

4.1 Rotor Profiles

Profili rotora

An efficient screw compressor needs a rotor profile, which has a large flow cross-section area, a short sealing line and a small blowhole area. The larger the cross section area the higher the flow rate for the same rotor sizes and rotor speeds. Shorter sealing lines and a smaller blowhole reduce leakages. Higher flow and smaller leakage rates both increase the compressor volumetric efficiency, which is the rate of flow delivered as a fraction of the sum of the flow plus leakages. This in turn increases the adiabatic efficiency because less power is wasted in the compression of gas, which is recirculated internally.

As precise manufacture permits rotor clearances to be reduced, despite oil flooding, the likelihood of direct rotor contact is increased. Hard rotor contact leads to deformation of the female rotor increased contact forces and ultimately rotor seizure. Hence the profile should be designed so that the risk of seizure is minimized.

Figs. 2 and 3 show a pair of a rack-generated rotors [15]. The selection and distribution of primary curves on a rack, which was used to create these rotors, give a larger cross section area with stronger female rotor lobes than any other known screw compressor rotor.

Two additional favourable features characterize these rack-generated rotors. Firstly they maintain a seal over the entire contact length while maintaining a small blowhole. Secondly, the two contact bands B-C and G-H are straight lines on the rack, which form involutes on the rotors. Hence the relative motion between the rotors is the best it could be.

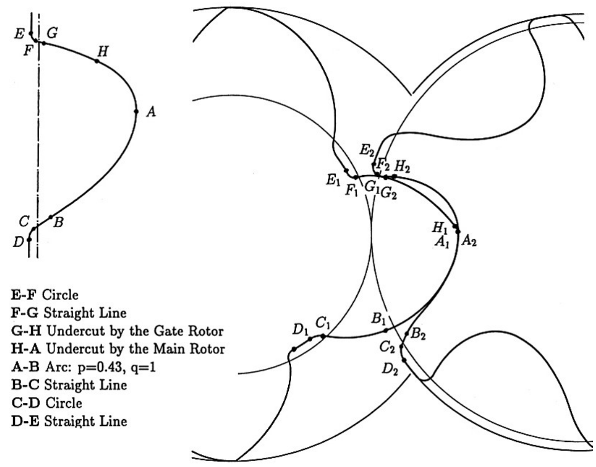


Figure 2. "N" rotor profile
Slika 2. "N" profil rotora

Figure 3. Screw compressor rotors with "N" profile
Slika 3. Rotori vijčanog kompresora s "N" profilom

Although advanced rotor profiles are a necessary condition for a screw compressor to be efficient, all other components must be designed to take advantage of their potential if the full performance gains are to be achieved. Thus rotor to housing clearances, especially at the high pressure end must be properly selected. This in turn requires either expensive bearings with smaller clearances or cheaper bearings with their clearances reduced to an acceptable value by preloading.

A screw compressor, especially of the oil-flooded type, which operates with high-pressure differences, is heavily loaded by axial and radial forces, which are transferred to the housing by the bearings. Rolling element bearings are normally chosen for small and medium screw compressors and these must be carefully selected to obtain a satisfactory design. Usually two bearings are employed on the discharge end of the rotor shafts in order to absorb the radial and axial loads separately. Also the distance between the rotor centre lines is in part determined by the bearing size and internal clearance. An assembly drawing of the compressor is shown in Fig. 2 in which the bearing arrangement can be seen.

4.2 Compressor design

Konstrukcija kompresora

The same oil is used for oil flooding and for bearing lubrication, but the supply to the bearings is separate to minimize the friction losses. Oil is injected into the compressor chamber at the place where thermodynamic calculations show the gas and oil inlet temperature to coincide. The position is defined on the rotor helix with the injection hole located so that the oil enters tangentially in line with the female rotor tip in order to recover as much as possible of the oil kinetic energy.

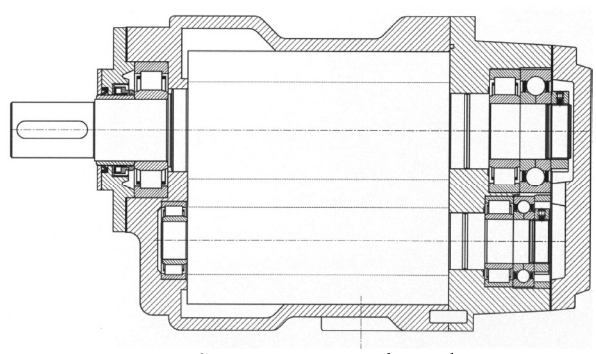


Figure 4. Screw compressor design layout
Slika 4. Izgled konstrukcije vijčanog kompresora

To minimize the flow losses in the suction and discharge ports, the suction port is positioned in the housing to let the gas enter with the fewest possible bends and the gas approach velocity is kept low by making the flow area as large as possible. The discharge port size is determined by estimating the built-in-volume ratio required for optimum thermo-dynamic performance. It is then adjusted in order to reduce the exit gas velocity and hence obtain the minimum combination of internal and discharge flow losses. The casing should be carefully dimensioned to minimize its weight, containing reinforcing bars across the suction port to improve its rigidity at higher pressures. It must be added that recent advances in the development of advanced low friction rolling element bearings highly contribute to the efficiency and reliability of the modern screw compressor.

The rotors and compressor designed following such principles are presented in Figs. 3 and 4. More information about that particular design can be found in [16].

Figure 5. Oil flooded screw compressor
Slika 5. Uljem potopljen vijčani kompresor

5 Conclusion
Zaključak

The screw compressor is established as a mature product at the beginning of the 21st century. Simultaneous efforts of a large number of companies driven by market forces in the local and world trade resulted in the compact and efficient compressor machine. Every detail in compressor design counts today. A small difference gives a small, but distinctive improvement, which may be used as an individual advantage. Although only continuous and evolutionary improvements will move the screw compressor forward, there is still place left for more or less revolutionary methods or procedures to result in a better product. The promising appears to be a rack profile generation, which gives stronger but lighter rotors with higher displacement and lower contact stress. Screw compressors are widely applied in building of roads and railways and in housing developments. Screw compressors as a product of high technology improve the existing compressor industry. Since any serious research and development in screw compressors requires serious investment in the workforce, machinery and procedures, a need is expressed universally for a consortial effort which puts all interested parties together to achieve the best use of the existing potentials and to develop a strong basis for application of new achievements in industry.

Literature
Literatura

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