Screw vacuum pumps

The state of the art

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Introduction

Dry-compressing screw vacuum pumps have been used as backing pumps to an increasing extent since the 1980s. Like the screw compressor that had already been introduced around 30 years earlier, the screw vacuum pump takes its name from the two screw-shaped rotors that rotate at high speed without contacting. As a result of the “dry” compression there is no mutual contamination of the gas and the lubricating oil.

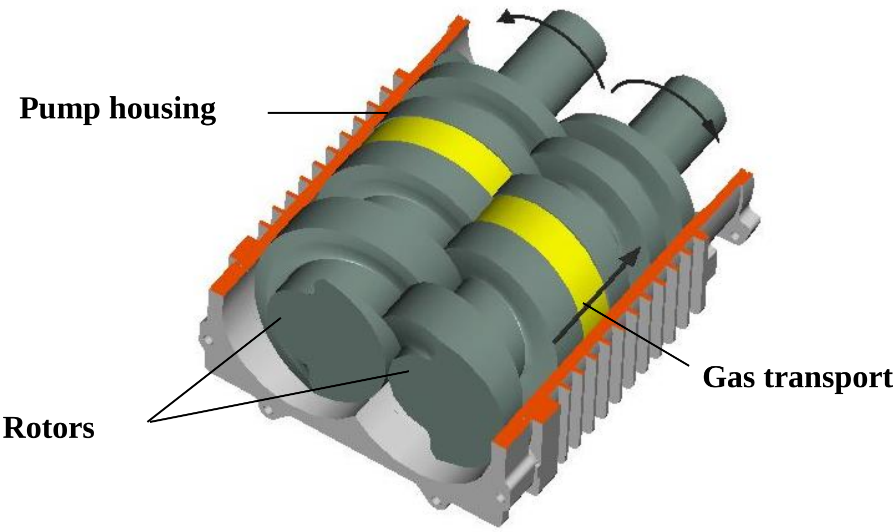

Fig. 1: Operating principle of a screw vacuum pump

In recent years screw vacuum pumps have become widely used and have reached a high technical level. In addition to the semiconductor industry and the chemical industry [1 to 2] they are increasingly appearing in industrial vacuum markets such as, for example, surface, metallurgy, packaging technology and drying processes [3, 4, 9, 10, 12, 13]. Screw vacuum pumps are also used in technologies of the future such as solar cell production and OLED coating technology [12].

The trend towards dry-compressing solutions has been pushed forward in most applications by the desire to have increased reliability and by omission of the oil as an operating medium. The savings in the “total cost of ownership” (maintenance, oil, oil filter, disposal of the oil, pump shutdown, etc.) can be considerable. Above all, in the semiconductor and coating industries the demand for a “clean” vacuum is crucial.

Structure and pumping mechanism

Like the claw pump or the Roots pump, the screw pump belongs to the class of two-shaft rotating displacement pumps. The gas is trapped in the thread of the screw rotors and transported axially from the inlet to the outlet by the rotation of the rotors, Fig. 1.

Compared to screw compressors, screw vacuum pumps have a large number of wraps. Due to this feature high pressure ratios between the inlet and outlet of the pump are achievable, which are necessary for vacuum pumps. Their area of application ranges from inlet pressures between 10^{-3} mbar and 1000 mbar and pumping capacities from 20 to 2,000 m³/h.

An important design feature is the arrangement of the bearings, Fig. 2. Cantilevered rotors (c) and double-flow rotors (b) make it possible to avoid bearings and shaft seals at the inlet side of the pump.

The simply-supported configuration (a) requires a more sophisticated seal design at the inlet side (see Fig. 3). In particular, in cyclic operation of the pump the seal is subjected to rapidly changing pressure gradients that must be tolerated. The suction-side bearings are lubricated either with oil or grease.

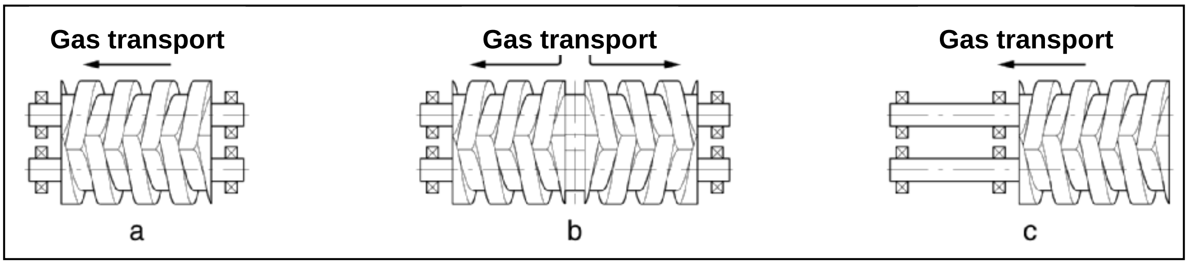

Fig. 2: Bearing concepts for screw vacuum pumps
a: “simply-supported”, b: “double-flow” and c: “cantilevered”

Both symmetrical and asymmetrical profiles are used for the rotors, and these are produced by milling, turning or grinding. Since the gas forces on the rotors are limited to the pressure range from 0 to around 1200 mbar, generally only single- or two-start screw profiles are used to attain the highest possible theoretical pumping capacity.

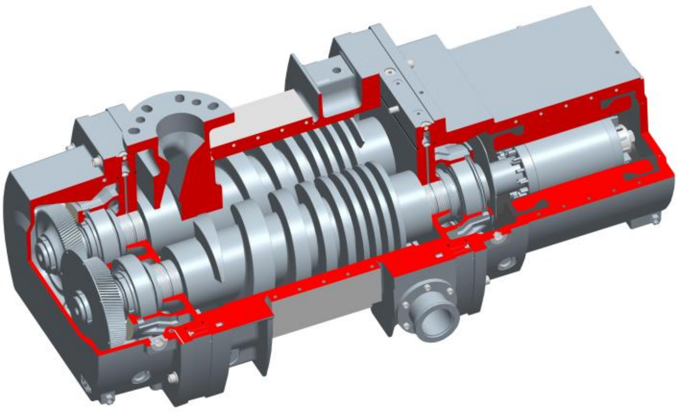

Fig. 3: Cross section through a screw vacuum pump with simply supported bearing arrangement and cantilevered motor rotor on a rotor shaft

Pumping capacity

The most important characteristic of a screw vacuum pump is its effective pumping speed in relation to the inlet pressure, Fig. , [3, 12]. If the internal back-flow is ignored, this is a linear function of the swept volume and the rotating speed of the pump. However, due to the complex three-dimensional shape of the screw rotors the internal clearance cannot be made as close as desired. This leads to a considerable amount of back-flow between the chambers of the screw rotors, depending on the pressure ratio involved [5 to 8]. If the same amount of gas flows back through the clearances as is transported forward by the pump, the effective pumping speed is zero; the pump runs at ultimate pressure. This is a characteristic value for the internal sealing capability of a vacuum pump and is specified in the catalogues of the manufacturers.

In order to estimate the pumping capacity of a screw vacuum pump, the expected clearance back-flow is compared to the theoretically transported gas flow. A reduction in the back-flow through smaller tip clearances likewise leads to a higher effective pumping capacity as does an increased theoretical pumping capacity by higher rotational speed. In good pumps the theoretical pumping capacity should be at least an order of magnitude greater than the expected back-flow. A reduction in rotational speed can drastically reduce the pumping speed of a screw vacuum pump.

Single-start screw profiles have a greater tooth gap width compared to two-start configurations, so a greater tooth height can be manufactured. Generally, this results in a better ratio of pump body volume to pumping capacity. Furthermore, two-start profiles exhibit more unfavourable leakage paths, so most screw vacuum pumps are of single-start type. However, an advantage of two-start profiles is their symmetry, which means that their rotors are inherently free of unbalance. This makes them suitable for high-speed pumps and they are used in such cases [11].

The (single- or two-start) cycloid profile or the asymmetrical, single-start Quimby profile have established themselves as common profile types, Fig. 4. The latter has the advantage of providing better sealing, although it is more difficult to manufacture due to the deep undercut and the sharp sealing edge.

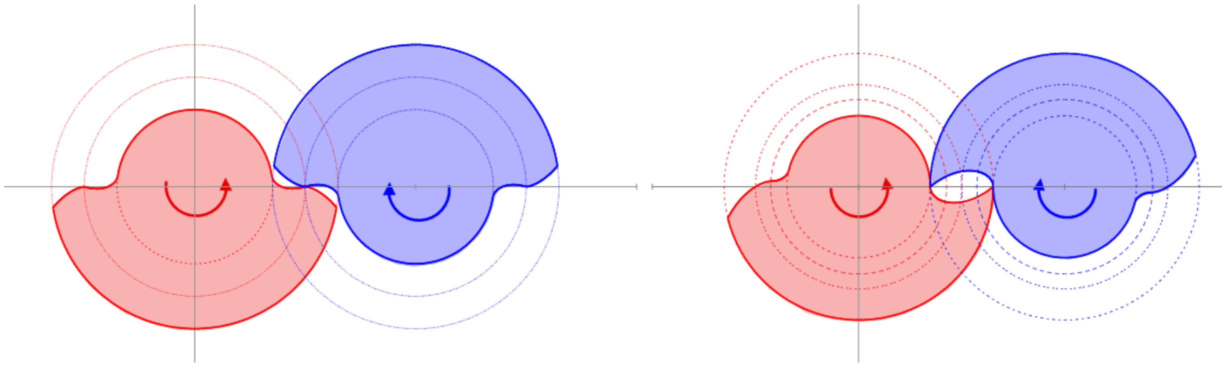

Fig. 4: Single-start cycloid profile (left) and Quimby profile (right)

When designing screw vacuum pumps the expected back-flow must be determined to optimise the geometry with regard to the desired operating behaviour of the pump. Simulation programs are used for this, which are typically developed by the pump manufacturer himself.

Influence of clearance heights

Fig. 5 shows the influence of the tip clearance on the simulated pumping capacity of a typical screw vacuum pump. A small change of 10% in the tip clearance already affects the pumping speed substantially throughout the entire inlet pressure range and changes in the ultimate pressure about one decade. Among the clearances, the rotor tip to housing clearance shows the greatest influence. It is therefore necessary to define the shape and positioning tolerance carefully for series production.

Wear of the rotors can likewise have a considerable effect on both ultimate pressure and pumping speed. Coatings on the rotor with soft materials (e.g. “grinding-in” of lubricant varnishes) need to be assessed critically if dust and particles need to be pumped.

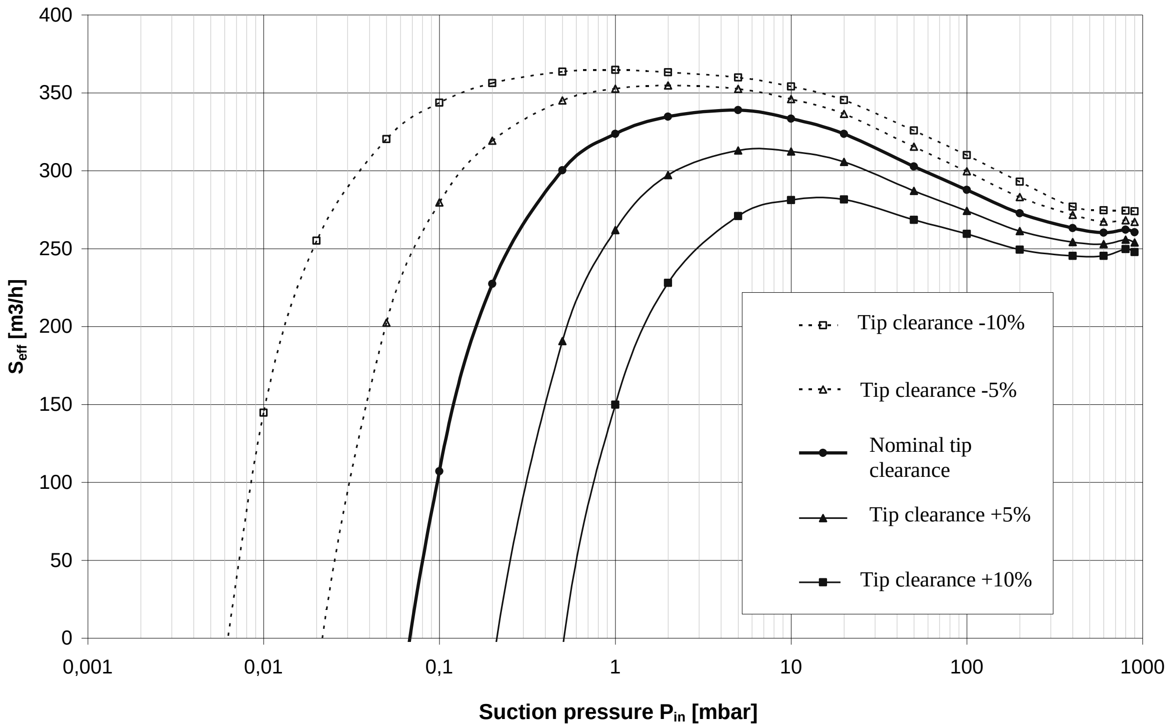

Fig. 5: Simulated pumping capacity of a typical screw vacuum pump with simultaneous variation of all clearances

Working process

The simplest configurations of rotors have constant pitch and constant tip and root diameter along the entire profiled section and an open axial outlet.

Screw vacuum pumps with a volume change during the transport phase [11] are used almost exclusively these days in order to reduce the required compression power and the resulting exhaust gas temperatures. This is termed a “pump with internal compression”.

The change in volume can be achieved in various ways. The simplest way is to limit the outlet area on the discharge side in such a way that the start of the discharged phase is delayed until the volume of the discharging tooth gaps chamber has already become smaller. This is called compression against an end plate. In addition, the rotors can be assembled from several sections with different pitch, resulting in reduction of volume in discrete steps. Due to advances in manufacturing technology, it has been possible for a number of years to manufacture rotors with a variable pitch, which allows a continuous transition of the tooth gap volume from the inlet to the discharge side, Fig. 3, Fig. 8, [11]. Also, conical rotors with a reducing tip diameter (and hence an increasing root diameter) make it possible to bring about internal compression. The volume ratios (the volume at the inlet to the volume at the outlet) that can be achieved by such measures lie within the range from 2 to 15 for screw vacuum pumps [11].

The theoretical compression power in relation to the inlet pressure of screw vacuum pumps with varying internal volume ratios is shown in Fig. 6. The power consumption per theoretical pump capacity at ultimate pressure is often taken as a quality criterion for the energy efficiency of a pump. This is primarily influenced by the achieved internal volume ratio. A higher degree of internal compression leads to a lower compression power for the same pumping capacity, since it reduces the volume to be displaced against atmospheric pressure.

An internal volume ration of around 2.3 gives to an approximately constant compression power over the entire inlet pressure range (*flat power curve*), so that the drive motor is loaded constantly in all operating conditions. Pumps with this volume ration are used in rough vacuum applications or in cyclical operation with small vacuum chambers.

In the case of smaller volume ratios the compression power drops as the inlet pressure rises because the pressure difference across the pump becomes smaller and no or only little over-compression occurs. For volume ratios greater than 2.3 the compression power increases with rising inlet pressure as more compression work is done in the bigger stages and over-compression becomes significant for high inlet pressures.

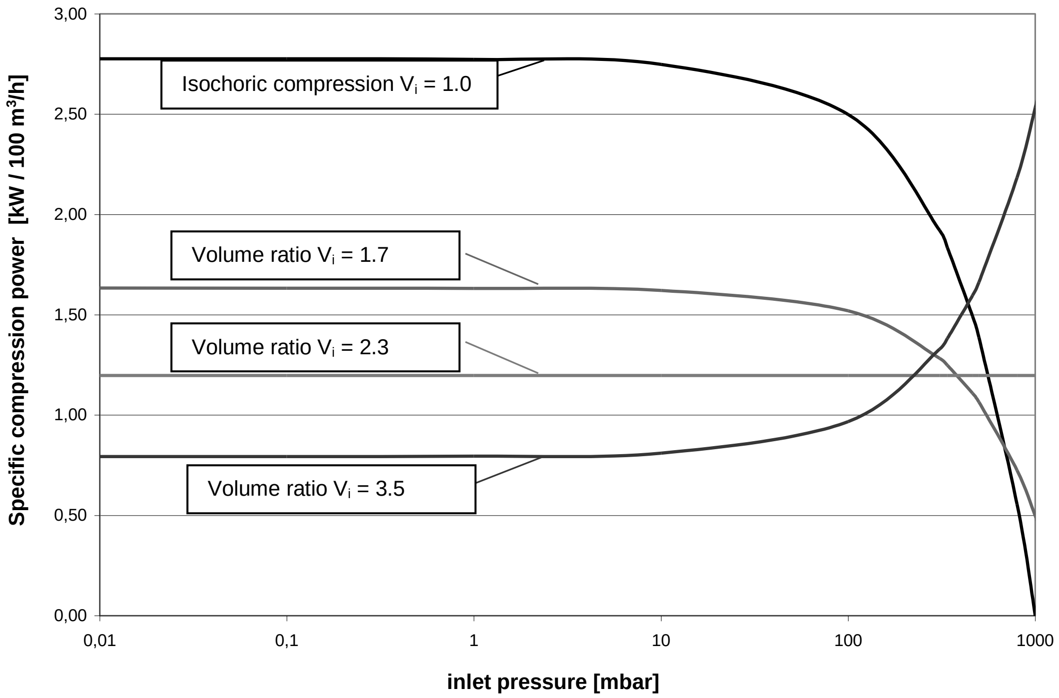

Fig. 6: Specific compression power in kW per 100 m³/h theoretical pumping speed for various inner volume ratios of v_i = 1.0 to 3.5 (isentropic, without internal leakage)

Design of the shaft seals

The shaft seals are one of the most difficult machine elements in dry-compressing vacuum pumps. The most important requirements for these seals are:

- Avoidance of oil leakage from the gearbox or motor area into the pumping chamber
- Avoidance of leakage of process media into the environment and the gearbox
- Circumferential speeds of up to 35 m/s
- Low production costs
- Pressure differential of up to 1000 mbar at the inlet side of the pump
- Very robust over many years of continuous operation

A wide variety of solutions have been used to meet these requirements. Mostly, combinations of several sealing principles are used in order to achieve satisfactory reliability and endurance.

Rotary shaft seals are primarily used (contacting at moderate rotating speeds and grinding-in at higher speeds), floating ring seals (only in selected applications due to very high cost), and labyrinth, piston ring and gap rings. In difficult applications these seals are frequently protected against process media and hence against wear and corrosion through the use of purge gas [15].

Noise reduction

Just like all displacement machines, vacuum pumps also generate a considerable amount of noise. This problem was very noticeable in screw pumps of the first generation, because the compression was done against an end plate with a small discharge area. Here the outlet is opened abruptly at each rotation of the rotor. Machines with an open rotor discharge side are better as the discharging is done continuously.

However, a silencer is still required if the pump is operated with an open exhaust. However, very good acoustic damping can be attained by the use of an absorption silencer.

In the case of air-cooled machines the cooling air is an additional source of noise, while the water jacket of water-cooled machines damps the noise. In the case of air-cooled pumps the pump casing can guide the cooling air and damp the noise at the same time. In this way a pump of this type attains the noise level of water-cooled screw vacuum pumps or the same as large rotary vane pumps.

Technical state of the art of screw vacuum pumps for industrial applications

By now, virtually all leading European manufactures of vacuum pumps offer their own models [9,11,12,14]. There are several makers in Japan and Korea as well. The advantages of screw pumps as opposed to multi-stage claw and Roots pumps are primarily:

- Small number of components for a high number of stages (Fig. 1)
- No diversion of the flow of gas and hence good particle transport capability
- Low noise level

Typical pump sizes range from a pumping capacity S = 70 m^3/h up to 1000 m^3/h. In the industrial markets there is the widest variety of models up to around 350 m^3/h. The range under 200 m^3/h is dominated by multi-stage Roots and claw pumps due to their wide distribution in the semiconductor market. For smaller pumping capacities there is still a big difference in price compared to rotary vane pump, which, in combination with the often simpler applications, is the main reason for the small market share of dry pumps.

Combinations of screw pumps and Roots pumps are used for very high pumping speeds, Fig. 7.

Fig. 7: Screw pump with directly flanged Roots pump, screw pump with frequency converter.

Drive units with frequency converters are increasingly used in newer models to allow a higher rotor rpm and hence to reduce the amount of space required, Fig. 7. A further advantage of the higher rpm is the more favourable ratio of the transported mass flow rate compared to the gap mass flow rate, i.e. the pump is “better sealed.” This makes the use of high volume ratios possible as the transport capacity of the exhaust stages in such pumps is inherently small.

In most pumps the rotors are synchronised with gears, certain solutions without gears need a separate motor for each rotor. In this case the synchronisation is done electronically via the motors [11].

Water cooling predominates as the cooling principle, Fig. **3** and 7. The main reason for water cooling is its ability to deal with the high heat flux rates in the exhaust area of the pump.

An example for an air-cooled screw vacuum pump is shown in Fig. 8. Here the heat of compression is drawn off through the rotors (cooled with oil) and the surface of the housing, which is intensively cooled with air [3, 4, 9].

Both air cooling of screw vacuum pumps (cooler, ribs, fan, air guidance, etc.), and water cooling (cooling water guidance, water jacket, regulation, protection against corrosion, etc.) are costly and decisive for the reliability of the pump. A correspondingly wide variety of technical approaches can be found in the market. The choice of the cooling principle depends on the market needs and on the size of the pump. For pumps with high capacity water cooling is typically preferred, for smaller pumps both principles are used.

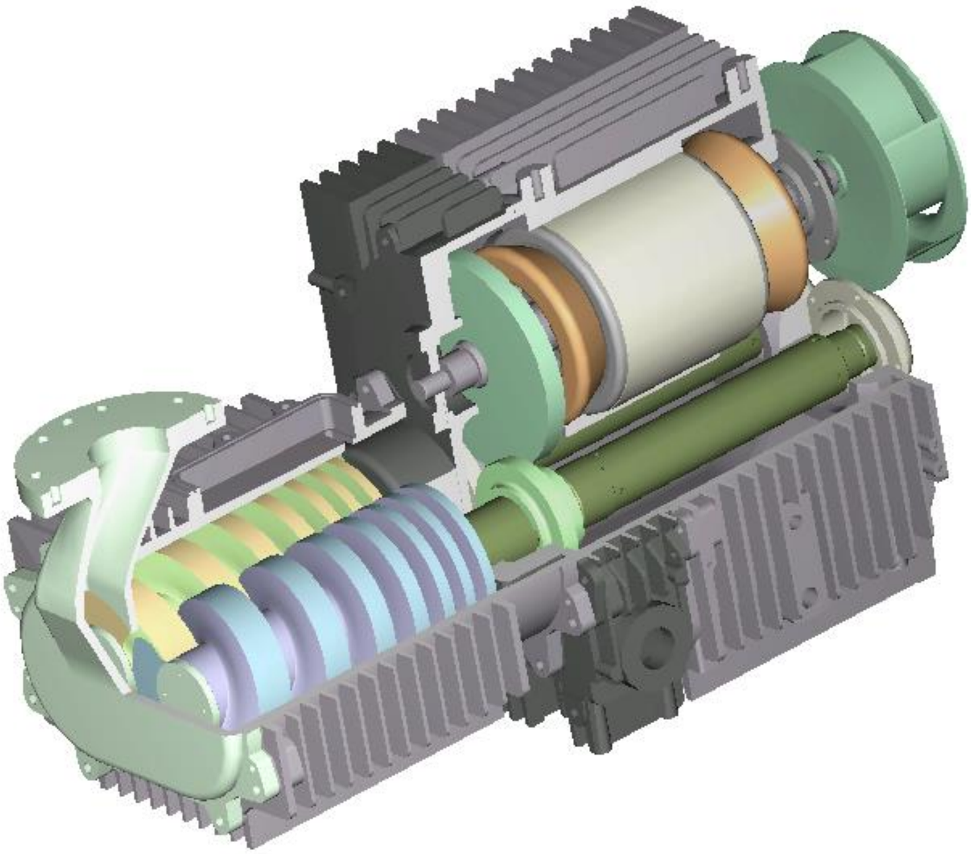

Fig. 8: Internal structure of a screw pump with cantilevered rotors, built-in motor and air cooling. The rotor shafts run at twice the speed of the motor shaft due to the gearing. The motor shaft holds at its two ends the oil pump (front) and the fan (rear).

The materials used are aluminium or steel or cast iron for the main components (rotors and pump housing). Aluminium offers the advantage of being easier to machine and better heat conduction but is not suitable for all processes (especially those involving corrosive process media).

Development trends in screw vacuum pumps

In view of the advantages of dry-compressing screw vacuum pumps a replacement of oil-sealed rotary vane pumps can be observed in an increasing number of processes. It can be expected that this trend will intensify due to continuing development of this still relatively young technology.

Further development work aims at the one hand of further reducing the acquisition and operating costs. This includes the achieving of higher internal compression ratios to reduce the amount of compression power. In addition, efficient drive units are required in order to achieve the desired savings. Furthermore, the working life of the parts that are subject to wear and of the lubricants are being continuously increased so that longer maintenance intervals are possible.

The manufacturing costs of the pumps can be reduced by employing modular strategies. Both screw pumps and Roots pumps can be built on the basis of platforms (drive unit, bearings / seals) so that a large number of identical parts can be used for both types of pumps. Fig. 7 and Fig. 9 show a Roots pump and a screw pump from a module. Parts such as bearings, seals, gears, motor and frequency converter are common with all pumps, while the rotors and rotor housings are specific to each pump.

On the other hand, there is also an increasing tendency to equip the pumps with drive electronics, sensors and controllers. These make optimised operation possible and monitor all important functions of the pump or system at the same time (see Fig. 9).

At the moment there is no standard pump design being used across all manufacturers. The above-mentioned technical characteristics have led to various optimised concepts that are competing with one another in the market. No new manufacturers have appeared in recent years. This is an indication that the entry threshold for mastering the technology, production and application of screw vacuum pumps is still high. The established manufacturers are expanding their ranges of models and continue to improve their products and production processes. The technology of the screw vacuum pump is still in the growth phase of its life cycle. There is no sign in sight of it being replaced by other technologies.

Fig. 9: Pump system consisting of a Roots pump (top) and a screw pump (bottom). The pump stand has a monitoring system for cooling water and purge gas, outlet pressure monitoring and speed regulation for both pumps. It is operated from a touch panel on the top.

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