Modern vacuum and overpressure generation for pneumatic conveying

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1. General

The operating costs of a pneumatic conveying system mainly depend on the correct selection of the vacuum or pressure generator.
By choosing modern pressure generation equipment an economic and environmentally-friendly operation of conveying systems is possible.
To select the most effective compressor it is necessary to know the actual operating conditions of the conveying system.
These parameters are of vital importance when selecting the most appropriate type of compressor.
Important factors influencing the selection are the type of material being conveyed and its characteristics, e.g. its length and diameter and the kind of conveyance (for example dense and lean phase pneumatic conveying).
By means of these parameters the differential pressure (Δp) can be determined. Both in pressure and vacuum conveying the differential pressure is the main influencing factor in selecting the compressor.
For economic analysis the following factors must be considered: primary costs, energy consumption, costs depending on the compressor (e.g. throttle control, valves, control), operating time (e.g. continuous operation, batch operation) and maintenance costs.

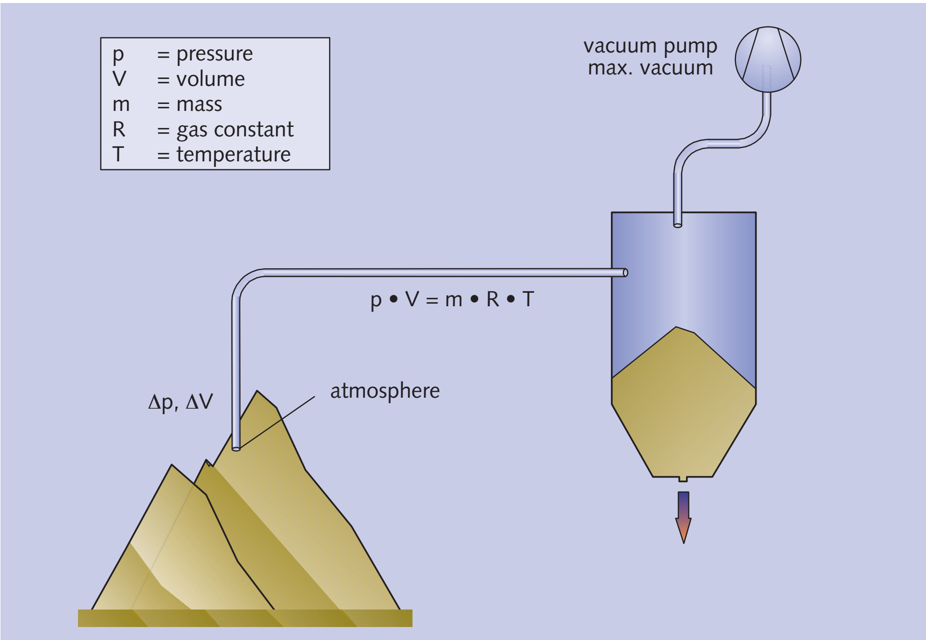

Figure 1: Principal design vacuum conveying

2. Fields of application

The following figure shows the vacuum pumps and compressors mainly used in vacuum and overpressure conveying. Nowadays side channel blowers, conventional Roots blowers and Mink rotary claw vacuum pumps/compressors can be used for both vacuum and overpressure conveying, with Mink rotary claw vacuum pumps/compressors being used in nearly all applications in pneumatic conveying.

Side channel blowers can be used best for short conveying and for vacuum conveying because only small differential pressures are required.
Rotary vane vacuum pumps and Mink rotary claw vacuum pumps in vacuum operation respectively screw compressors in pressure operation offer high pressure reserves and therefore can be used best for long or dense phase conveying.

Mink rotary claw vacuum pumps and compressors compress absolutely oil-free thus making them ideal for gas circulation conveying.

Additionally there are further types of vacuum generators such as liquid ring vacuum pumps, multi-stage side channel blowers, ejectors etc. which were not successful in pneumatic conveying because of their characteristics or inefficiency.

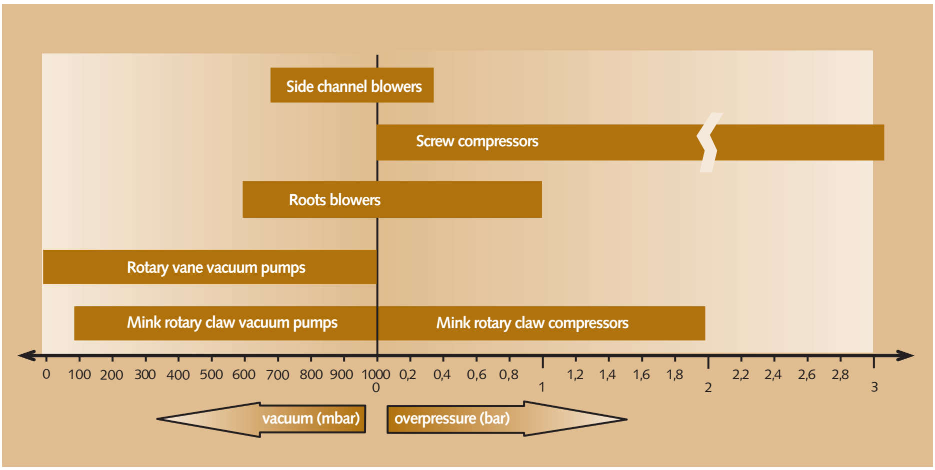

Figure 2: Application areas of various vacuum and overpressure generators

3. Description of the vacuum and overpressure generators

3.1 Side channel blowers

There are two different types of side channel blowers: single- and two-stage side channel blowers.
Conventionally driven side channel blowers can achieve differential pressures of up to ±300 mbar.
In frequency controlled operation side channel blowers can be used for vacuum conveying up to -400 mbar for overpressure and up to +500 mbar for overpressure conveying.

In contrast to vacuum pumps/compressors side channel blowers work according to the impulse principle: impeller and side channel form an annular working chamber.

In the side channel the gas forms a whirl shaped like an eight. The unidirectional wheel together with the aluminium housing forms the side channel, in which the gas is compressed and then discharged through the pressure-side silencer.
By the rotation of the impeller the gas is transported through the side channel.
Depending on the back pressure the gas gets impulse energy by the impeller vanes.
Compression takes place if gas penetrates into the impeller.
The side channel between suction and pressure connection is separated by the so-called interruptor which is a narrowing of the side channel to the width of the impeller. Part of the circulating gas stream is transported to the pressure connection.

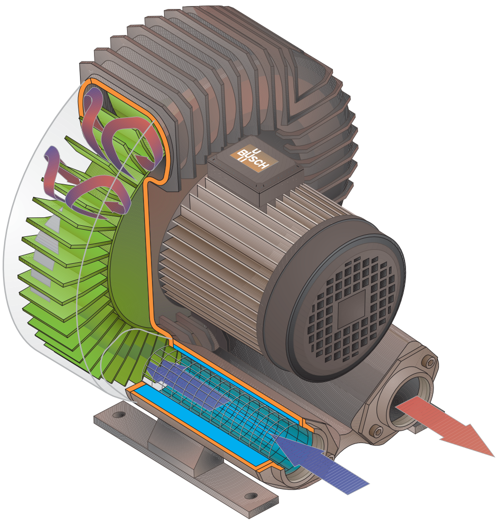

Figure 3: Sectional drawing of a side channel blower

The other part of the circulating gas is tranported to the suction side in the spaces between the impeller vanes side. This residual volume causes a flow within the side channel even if the inlet or outlet is closed converting motor power into potential and kinetic energy of the gas. Therefore a closed inlet or outlet of the blower can cause overheating of the blower. For protection against too high temperatures (especially of the bearings) it is necessary to fit a vacuum or pressure relief valve.

Due to these effects the efficiency of side channel blowers does not exceed 50%. Low primary costs and almost no maintenance costs make side channel blowers ideal for short and vacuum conveying because only small differential pressures are required.
Side channel blowers have no stable characteristic curves. Therefore they do not compress isochorously, e.g. not at equal volume. For multi-stage operation more power is required than for other compression principles.

3.2 Rotary vane vacuum pumps

Currently oil lubricated rotary vane vacuum pumps and side channel blowers are the most important resp. most frequently used vacuum generators in pneumatic conveying.
These pumps distinguish themselves by the high differential pressure (almost 1,0 bar) and an almost constant characteristic curve concerning the relevant working area (in suction conveying).
These outstanding qualities offer a high power reserve in critical conveying processes or with critical conveying materials resulting in a high planning reliability.
Also in continuous operation rotary vane vacuum pumps guarantee a stable volume flow for the entire pressure range from atmospheric pressure to ultimate pressure, e.g. these pumps do not need to be protected by a pressure relieve valve (for example, by an infiltrated air valve).
The principle of operation of a rotary vane vacuum pump is shown in figure 4.

In an excentrically installed rotor driven by an electric motor so called vanes slide in slots in the rotor and are pushed towards the wall of the cylinder by the centrifugal force of the rotation.
The gas to be sucked of enters through the suction flange in the sickel-shaped space between rotor and cylinder.
The pumping effect results from the increasing sickel-shaped space between rotor and cylinder when the pump rotates. If this space is as large as possible the following vane covers the suction slot forming a space in which the sucked gas is trapped.
At the same time new gas is sucked in by the following chamber while the closed chamber decreasing with further rotation compresses the trapped gas until the exhaust valve is opened at a pressure of about 1200 mbar and the gas is discharged through the separator.
The exhaust valve is covered with oil for better sealing.

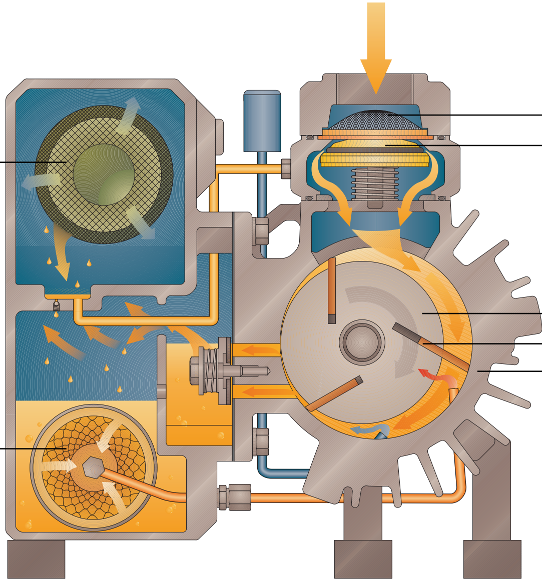

Figure 4: Sectional drawing of an oil lubricated rotary vane vacuum pump

The oil and the air are then discharged into the bottom part of the oil mist separator and then separated from rough oil drips by gravity and the demister.
The gas now only contaminated by oil mist is conveyed through oil mist separators for fine separation; the filter is covered with permeable fibres collecting the residual oil that drains off.

The gas, if it is air, is discharged directly into the atmosphere or can be transported through a pipeline away from the pump.
Oil lubricated rotary vane vacuum pumps operate nearly free of wear since the vanes always slide on an oil film and are of robust design.

The circulating oil also serves as a cooling, sealing and lubricating medium.
The automatic oil circulation is based on the differential pressure between the oil mist separator, where considerable overpressure exists caused by the filter resistance, and the inlet flange of the pump.
No separate oil pump is required.
The pump is equipped with a suction-side valve that prevents the flow of air or conveyed gas back into the vacuum chamber when the pump is switched off to avoid pump oil being drawn into the suction line by the differential pressure.
The inlet of the valve is equipped with a screen to prevent the pump from being polluted.

No separate oil pump is required.
The pump is equipped with a suction-side valve that prevents the flow of air or conveyed gas back into the vacuum chamber when the pump is switched off to avoid pump oil being drawn into the suction line by the differential pressure.
The inlet of the valve is equipped with a screen to prevent the pump from being polluted.

Additionally conventional rotary vane vacuum pumps used for pneumatic conveying are equipped with a fine filter (filtration efficiency 5 μ) at the suction side which is to protect the pump against admittance of solid particles (e.g. product abrasion).

Oil lubrication of rotary vane vacuum pumps requires maintenance work, like for example:

- check oil level at the oil sight glass at regular intervals
- change oil every 2000 to 5000 operating hours depending on application; at least change oil once a year
- change oil and replace oil filter
- replace exhaust filter once a year depending on saturation or contamination.

A so-called filter pressure gauge is used to check the condition of the exhaust filters; the filter pressure gauge is installed in the drilling through which oil is filled in. The exhaust filters need to be replaced if the filter pressure is ≥0,6 bar.

Dry running rotary vane vacuum pumps

Basically there are two types of rotary vane vacuum pumps:
- oil lubricated vacuum pumps
- dry running vacuum pumps

The vanes of dry running vacuum pumps are made of special carbon. These vanes are self-lubricating. These vacuum pumps need no oil as operating medium.
The more the sealing gaps increase due to permanent abrasion of the vanes the more the suction capacity decreases.
This effect is aggravated more or less drastically if particles are conveyed.
To avoid a total vacuum pump failure caused by broken vanes it is necessary to check them for wearout regularly and replace them as required.
Therefore it is not recommended to use dry running rotary vane vacuum pumps in pneumatic conveying.

3.3 Liquid ring vacuum pumps

Liquid ring vacuum pumps normally operate with water as operating medium.
An excentrically installed impeller rotates in the cylindrical pump casing partly filled with liquid (usually water).
By the rotational movement of the impeller and the resulting centrifugal force the liquid within the cylinder forms the so-called liquid ring.
Gas is conveyed in the spaces between the single blades and the liquid ring.
As a result of the excentrical installation of the impeller the spaces enlarge and the process gas is sucked in through the suction slot.
Further rotation reduces the spaces, the gas is compressed and discharged through the pressure slot.

The vacuum pump can be operated with water recirculation cooling, semi-open or closed loop cooling circuit.
Depending on the efficiency and design the fluid used as operating medium has the following functions:

- energy transmission from the impeller to the medium to be compressed
- sealing of the cells in radial direction
- sealing of the space between impeller and casing parts
- cooling and lubrication of the shaft seals

Depending on the application the ring liquid has the following functions:

- absorption of heat caused by compression and friction
- absorption of heat caused by condensation and reaction
- absorption of gaseous contaminants
- absorption of particles

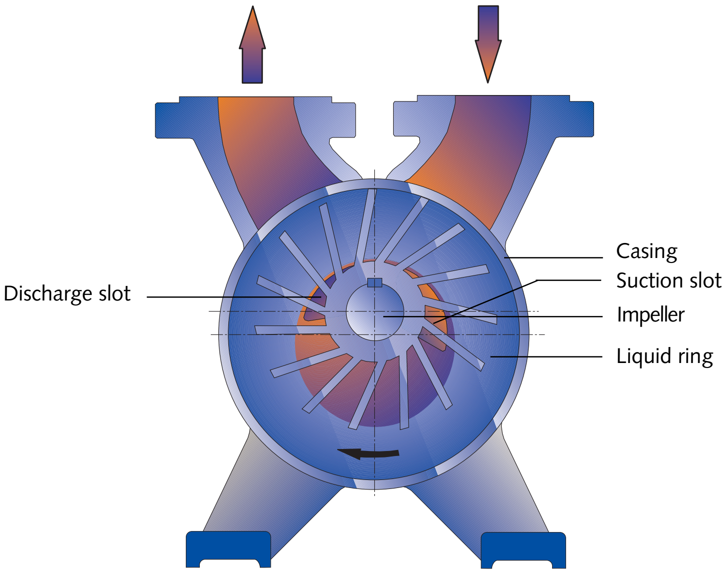

Figure 5: Sectional drawing of a liquid ring vacuum pump

Advantages of liquid ring vacuum pumps:
- simple and cost-effective design
- 100% oil free
- condensation of vapours is possible
- good material resistance (alternative materials possible)

Disadvantages:
- **Operation strongly depends on**
  - temperature of the operating liquid
  - density of the operating liquid
  - solubility of gases in the operating liquid
  - temperature of the gases to be sucked off
  - condensation effect

- **Danger of cavitation**
  Damage or even destruction the surfaces by implosions caused by the condensation of vapour bubbles.
- **Danger of calcifying**
  Should water evaporate from the ring liquid, the dissolved salts settle on the casing surface.
  The deposits reduce the suction capacity of the vacuum pump which can result in a failure of the unit depending on the thickness of the deposit.
- high supply or disposal costs in continuous operation
  These costs possibly will be increased dramatically by environmental process gas in the operating fluid.
- „possible "danger of silting up" in circulation operation with solid particles.

3.4 Roots blowers

Conventional two- and three-lobe Roots blowers work according to the well tried Roots principle.
Two parallel rotors with identical profiles rotate in opposite directions within a casing.
As they rotate gas is drawn into the space between each rotor and the casing where it is trapped, transported and discharged by the rotation. The gas is compressed isochorously, e.g. at equal volume. If a chamber containing gas under suction pressure reaches the pressure inlet the chamber is filled with returning gas from the pressure side and therefore compresses to atmospheric pressure.

There is no actual internal compression and no mechanical contact between rotors and cylinder.
These blowers are contact-free (and no oil is needed as sealing fluid) and can be used for differential pressures of up to 0,6 bar in vacuum operation and up to 1,0 bar(g) in pressure operation.
In pneumatic conveying Roots blowers can only be used in applications in which high volume flows at low differential pressures are required. In this small range of applications Roots blowers are distinguished by their small power consumption.

Disadvantages are their high acquisition costs and costs for noise reduction.
In pneumatic conveying Roots blowers are normally equipped with the following accessories:

- inlet filter
- vacuum or pressure relief valve as protection against overload
- suction-side non-return valve
- inlet/outlet silencer

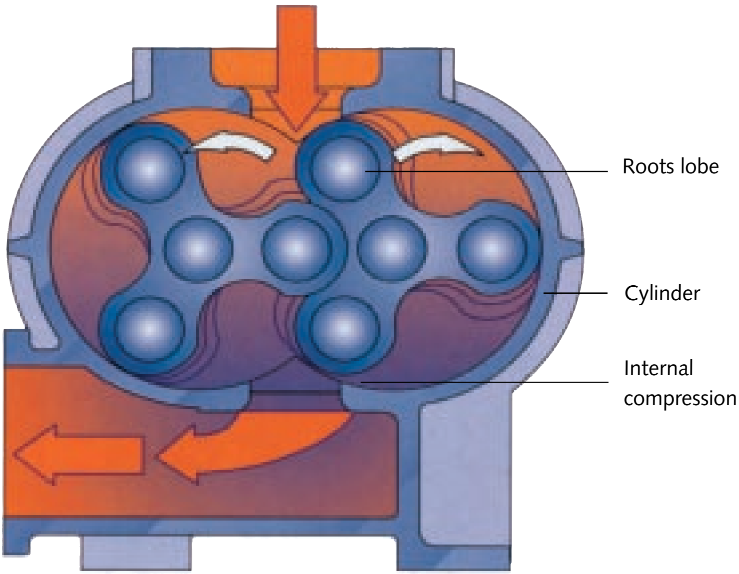

Figure 6: Sectional drawing of a Roots blower

3.5 Mink rotary claw vacuum pumps/compressors

Mink rotary claw vacuum pumps are available with suction capacities from 60 m^3/h to 500 m^3/h for vacuum conveying up to -750 mbar (continuous working pressure). Mink rotary claw compressors can be operated in overpressure conveying up to 2 bar.
By connecting several single Mink vacuum pumps or compressors in parallel bigger volume flows can be generated.
Mink vacuum pumps or compressors operate according to the well tried rotary claw principle. They compress absolutely oil and contact free and hence free of wear.

Further savings are achieved by minimum maintenance work and considerably lower energy consumption thus making Mink compressors the most economical alternative in pressure conveying up to 2 bar(g).

Two rotary claws rotate in opposite directions within a cylinder. There is neither contact between claws and casing nor between the two claws.

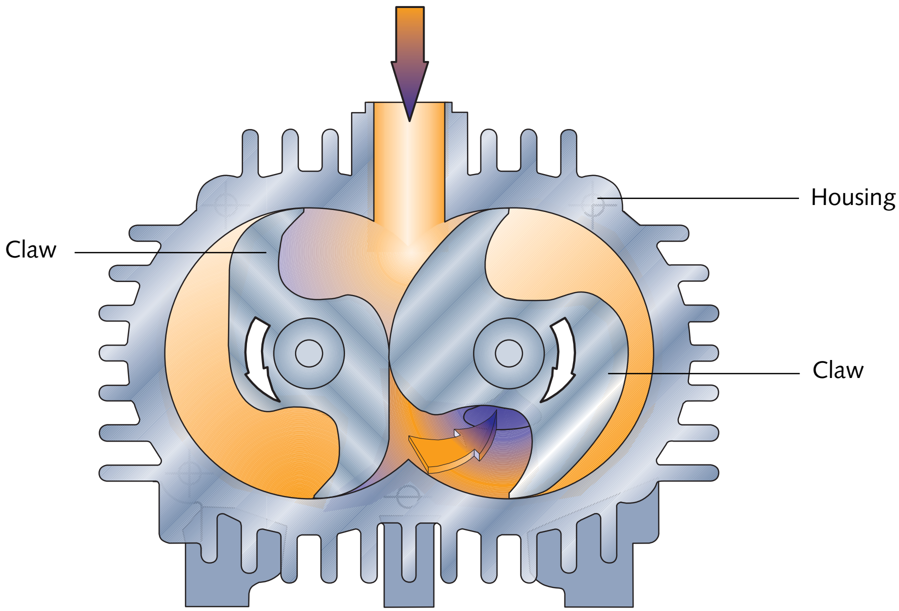

Figure 7: Sectional drawing of a Mink rotary claw vacuum pump

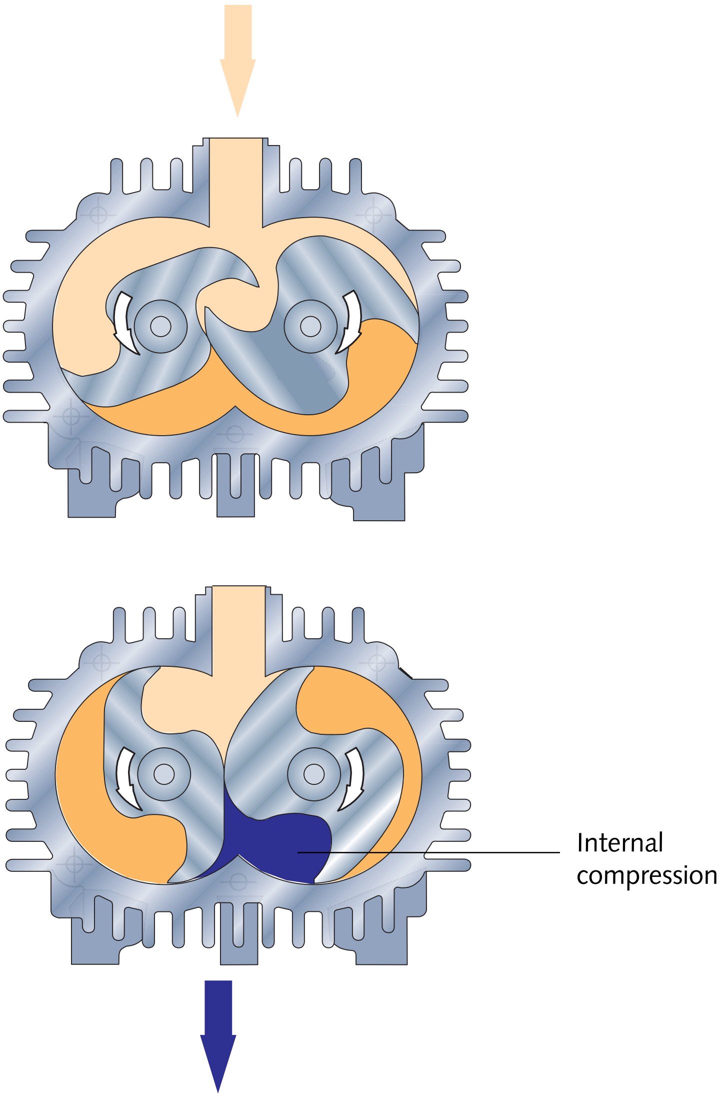

Figure 8: Compression process of a Mink rotary claw vacuum pump

The remaining gaps at the virtual point of contact are manfactured so precisely that they serve as sealing (labyrinth) because of air turbulence within the gap.
Therefore the compression chamber is divided into two parts:

- an enlarging chamber on the suction side drawing in air
- a decreasing chamber on the discharge side compressing and discharging air at the same time.

The exact rotation of both claws is controlled by a synchronized drive. However, in contrast to Roots blowers, Mink rotary claw vacuum pumps work with internal compression.
As a result of the special profile of the claws the conveying medium is pre-compressed internally in rotational direction in front of the claws before reaching the pressure side. At the same time gas is drawn in behind the claws in rotational direction for the next cycle.
Mink rotary claw vacuum pumps and compressors are driven by three-phase motors that are conventionally used for frequency controlled operation and are equipped with PTC thermistors.
In frequency controlled operation the pump adapts optimally to the process by speed control. This results in a further saving in energy or increase of conveying power by about 20%.
Mink vacuum pumps and compressors are air cooled. A separate additional electric fan guarantees a constant cooling, also with variable pump speeds.

Bearing/Sealing

There is an atmospherically ventilated inter-space between compression chamber and gear side.
This inter-space:

- causes thermal separation between the compression chamber and bearings. The bearings are not affected by the compression heat resulting in long service life.
- prevents pressure fluctuations on the shaft seal rings by atmospheric ventilation and therefore excessive or premature wearout.
- prevents both the penetration of product gas into the bearing or storage chamber respectively and the conveying of oil particles into the compression chamber. Compared to conventional Roots blowers the compression is guaranteed to be actually oil free.

The bearings are robust roller bearings:

- the fixed side (gear side) has angular ball bearings
- the free bearing side has cylindrical roller bearings

The shaft sealing between the compression chamber and the atmospheric inter-space is affected by labyrinth seals.
Towards gear and storage chamber radial shaft seal rings are used.

Standard equipment for pneumatic conveying:

In pneumatic conveying Mink vacuum pumps/compressors are equipped with the following accessories:

a) Suction conveying:
- suction air filter
- vacuum relief valve as protection against overload
- Suction-side non-return valve
- exhaust gas silencer

b) Pressure conveying:
- inlet silencer, in combination with suction air filter
- pressure relief valve as protection against overload
- pressure-side vessel for pulsation reduction
- pressure-side non-return valve

With the appropriate combination (parallel operation) of several individual units every conveying capacity can be realized.

Such modular solutions have the following advantages:
- simple power adaptation by series switch-on or switch-off
- in case of power control by frequency converter only a smaller converter (adapted to an individual unit) is required
- availability of a stand-by machine guaranteed at any time
- cost-effective due to standardized modular design
- cost-effective silencing measures possible

Figure 9: System solutions for higher conveying capacities

3.6 Screw compressors

Single-stage air cooled screw compressors are used for volume flows from approx. 200 to 15000 m^3/h. These compressors achieve pressures of more than 10 bar. They should only be used where pressures of >2 bar (abs.) are actually required.
Screw compressors are expensive and their power consumption is very high. Furthermore the oil required for compression must be extracted from the compressed air.

Compared to Mink rotary claw pumps the synchronism of both screw rotors is guaranteed by a synchronisation drive. Furthermore, integrated transmission gears allow variable power levels.
Roller bearings are used. Drive shaft and main rotor are equipped with multiple bearings.

Oil lubricated screw compressors are additionally equipped with an oil pump, oil cooler and an oil mist separator.

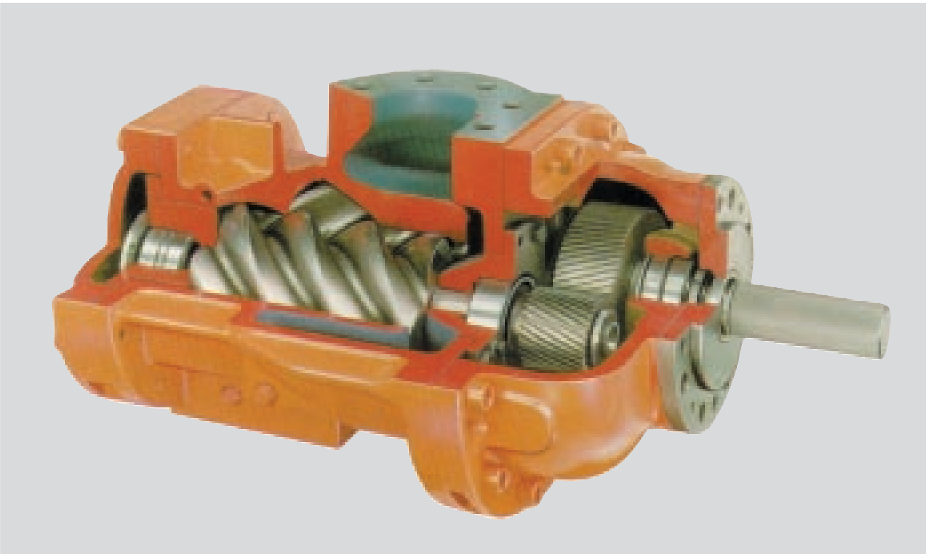

Figure 10: Screw compressor with integrated gear stage

In pneumatic conveying screw compressors are equipped with the following accessories:

- Inlet air filter
- Safety valve
- Non-return valve
- Pressure silencer
- Silencing hood

4. Comparison of the characteristic curves

The following diagrams show the suction or pressure characteristics of the individual types of vacuum generator depending on the corresponding differential pressure.

The volume flows are stated in % of the nominal suction or conveying capacity of the individual types.

Vacuum generator

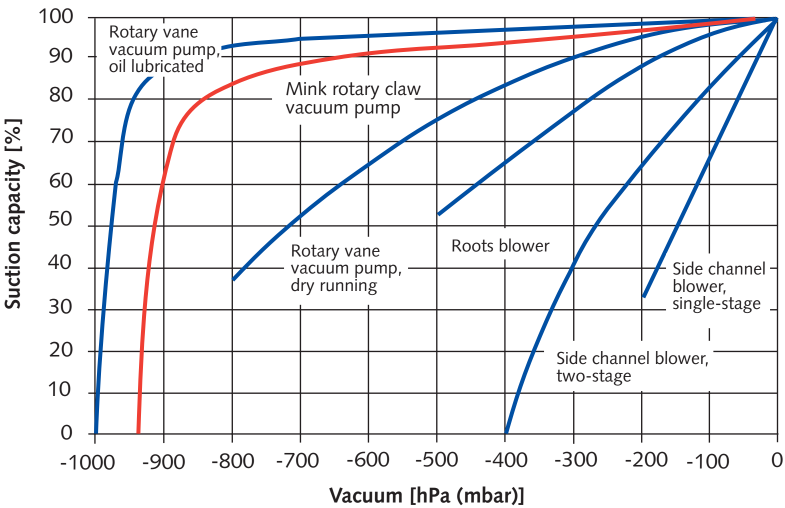

Figure 11a: Comparison of characteristic curves stability of various vacuum generators

Compressor

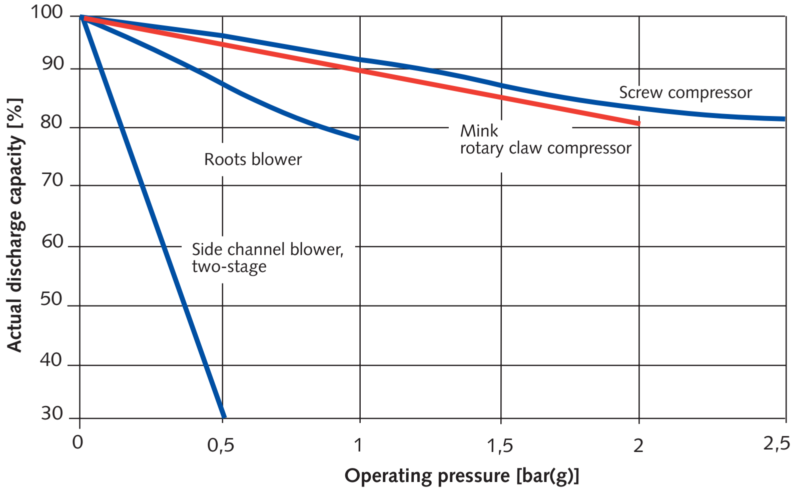

Figure 11b: Comparison of characteristic curves stability of various pressure generators

5. Technological differences

There are technological differences between the various vacuum and overpressure generators presented that influence power characteristic and efficiency of the corresponding unit. "Internal compression" is the decisive advantage of the design principle Mink rotary claw compressor over the conventional Roots blower working according to the Roots principle. This is described in the following pV-diagram:

The region between point 1 and point 2 in the pV-diagram shows the filling of the respective pumping chamber at suction pressure. In case of the Roots blower (left diagram, next page) the pressure remains constant until there is an opening towards this chamber between point 2 and point 3. The gas increases in pressure at the same volume. Between point 3 and four it reaches discharge pressure and is ejected.
The region between points 1, 2, 3 and 4 in the pV-diagram (on the next page) describes the compression work to be done.

The functional principle of the Mink rotary claw vacuum pumps and compressors on the other hand result in the following process:
Between points 1 and 2 in the pV-diagram the chamber within the compressor is filled with gas at suction pressure.

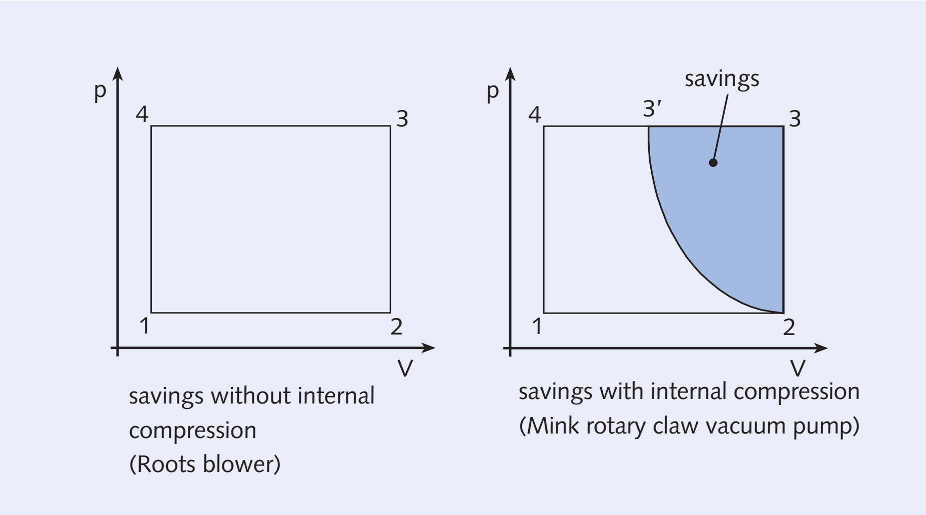

Figure 12: Advantage due to internal compression shown in the pV-diagram

However, before the gas volume reaches the pressure side, there is internal compression of the gas in front of the claws. The pressure simultaneously increases to the decrease of the volume.
No gas flows back into the compression chamber from the pressure side. During the rotation the pressure mouth in the compression chamber is opened as a result of the specific design of the claw and the gas is discharged on the pressure side.
The region between points 2 and 3‘ describes the compression process, the region between points 3‘ and 4 describes the discharge process.

The pV-diagram shows that the region and therefore the compression work to be done is considerably smaller for compressors with internal compression than for blowers without internal compression. Therefore the same compression work can be done more economically.

When compressing gas the temperature is increased both in the case of the Roots blower and the Mink rotary claw vacuum blower. The temperature increase is proportional to the energy added.
If a compressor with internal compression requires lower energy for compressing this results in lower temperature increase. This lower temperature increase can be used to realize higher discharge pressures at constant power consumption.
The claw principle achieves a discharge pressure of 2 bar(g) and a vacuum of 80%.

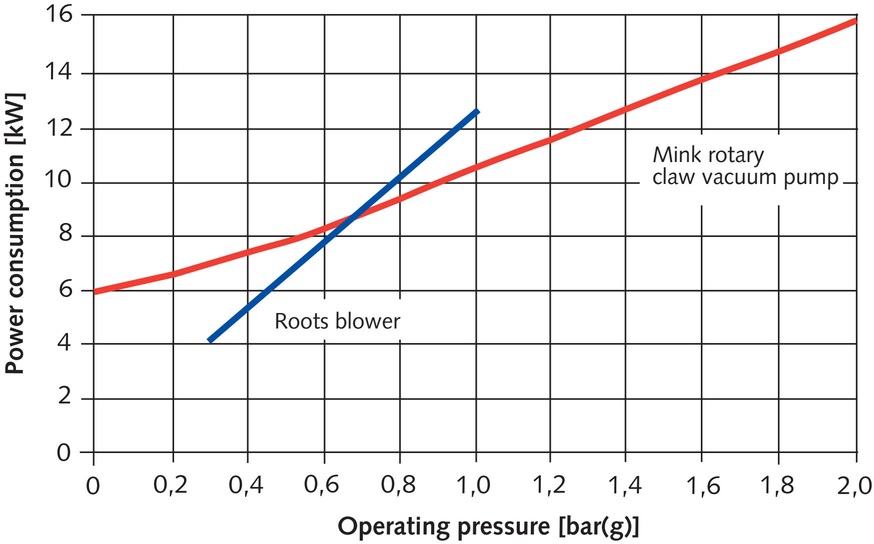

Figure 13: Comparison power requirement Roots blower/Mink rotary claw vacuum pump

This diagram shows the power consumption of a Roots blower compared with a Mink vacuum pump.
The effect of the internal compression to power data is obvious.
At small overpressures the Roots blower is better than the Mink vacuum pump with internal compression.
The reason is the fact that internal compression creates internal overpressure that is blown out at the pressure gap.
At small overpressures Roots pumps are more economical. The point of intersection is about 0,8 bar(g). It is obvious that the power consumption of the Roots pump increases up to about 1 bar since Roots blower have no internal compression.
Mink compressors with economical internal compression can compress up to 2 bar(g).

6. Economic efficiency analysis of various vacuum generators by analysis of overall expenses

The efficiency of a pneumatic conveying system also depends on the operating costs of the respective vacuum/pressure generator.
The correct selection of vacuum or pressure generators is of vital importance. This especially applies to complex systems since they cause a considerable part of the operating costs of the system.
These operating costs, for example, depend on:

- Reliability
- Process compatible suction or pressure characteristics
- Good coefficient of efficiency
- Low maintenance work
- Price
- Potentially good controlability of volume
- Smaller pipeline diameters

In this chapter only vacuum generators already successfully used in pneumatic conveying for many years are compared with each other.
The pumps are compared with respected dense phase pneumatic conveying.
This type of conveying is characterized by higher differential pressure, compared to lean phase conveying, for example.
Mink rotary claw vacuum pumps, liquid ring vacuum pumps with integrated sealing fluid circulation, four-stage side channel blowers and the already successfully used oil lubricated rotary vane vacuum pumps are compared with each other.
The following comparison shows the power requirement of these vacuum generators (with equal suction capacities) in relation to the corresponding working pressure.

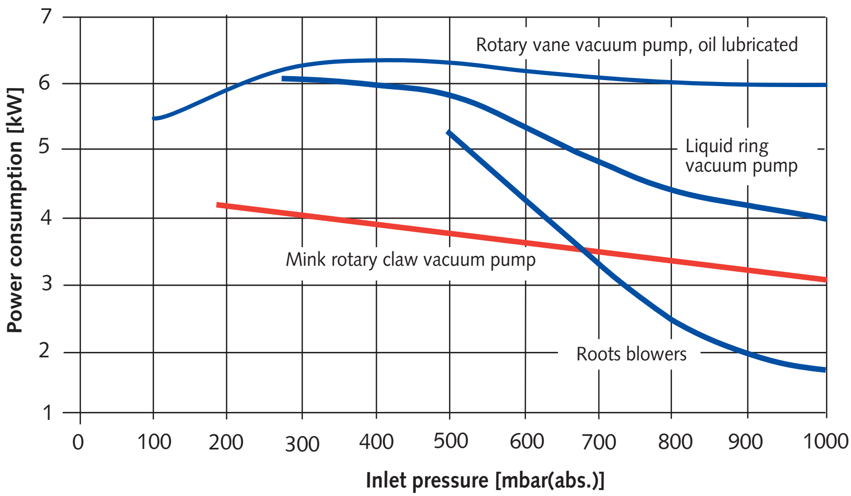

Figure 14: Power requirement of various vacuum generators

The comparison of the power requirement of various vacuum generators at a fixed operating point shows that Mink rotary claw vacuum pumps have the lowest energy consumption due to "internal compression"and oil and contact free operation.

This is illustrated in the following figure as "specific suction capacity" to determine the suction capacity per kW.

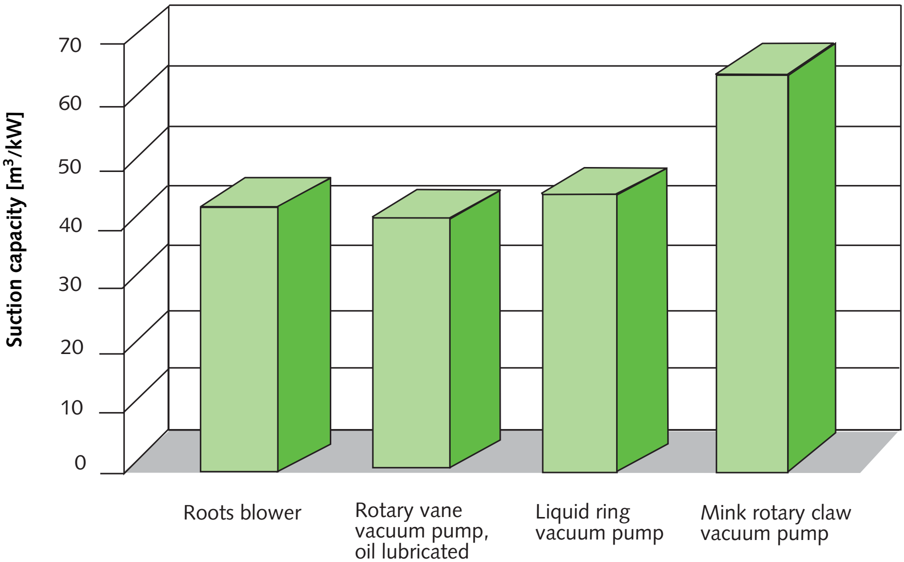

Figure 15: Comparison specific suction capacity of diffrent vacuum generators

The annual energy costs or savings using Mink rotary claw vacuum pumps and compressors are shown in the following figure.

The calculation of these costs is based on 7000 operating hours and 0,08 Euro per kW/h.

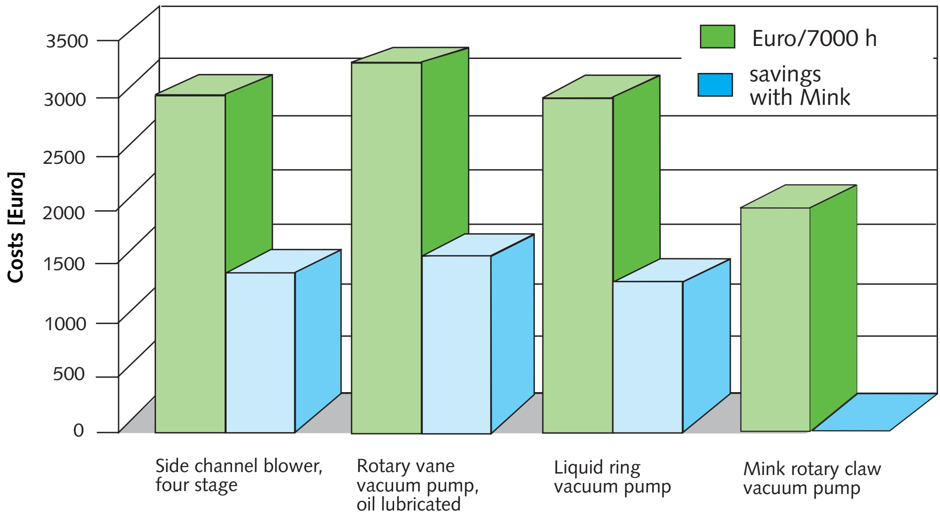

Figure 16: Comparison of energy costs per year

The following diagram shows the total costs in Euro refering to 8000 operating hours/year.
The acquisition costs have been determined on the basis of actually published list prices and refer to a linear depreciation over 5 years with an interest of 7%.
Energy costs were assumed to be Euro 0,08 per kW/h.
The maintenance costs only include material and work costs. Both additional costs for disposal of removed parts etc. and downtimes of the machines are not considered.

Energy costs are the biggest part of the total operating costs. Therefore energy costs are the most decisive factor in selecting the most effective vacuum generator.
However, experience shows that maintenance work to be planned and resulting downtimes of the machine will cause bigger problems.
The argument that machines are maintenance-free becomes more and more important for customers.

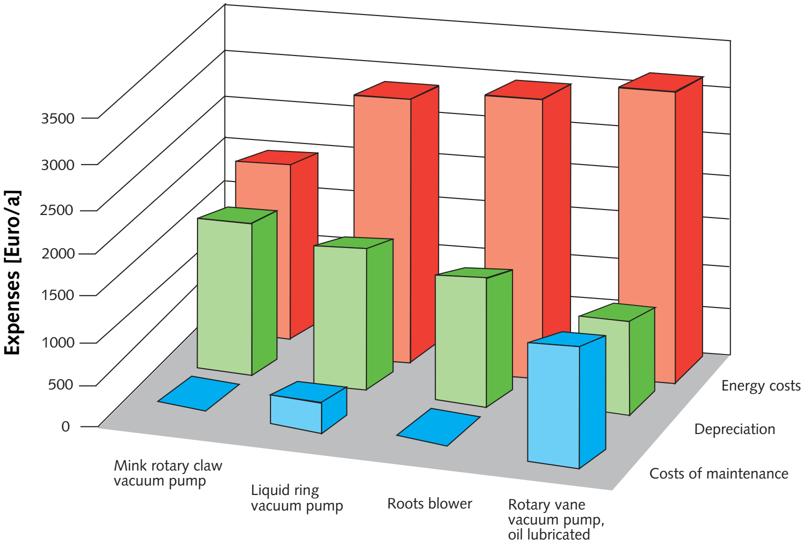

Figure 17: Costs distribution

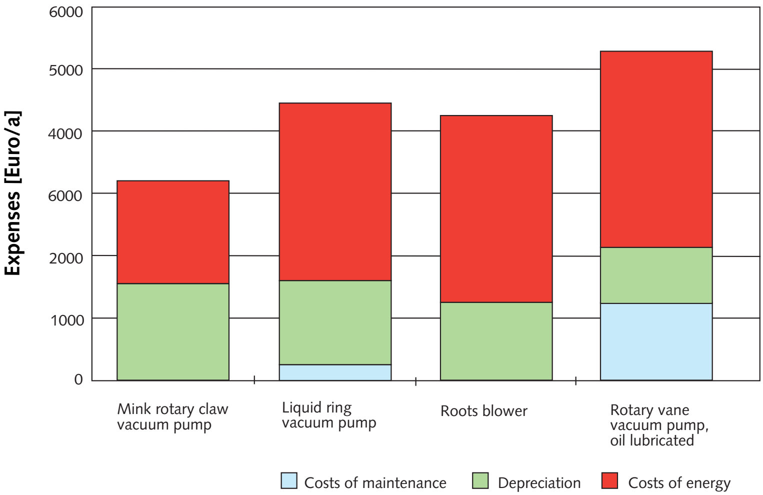

Figure 18: Total costs

7. Control: Larger customer benefit due to variable drives

Optimum operating costs mainly depend on energy costs; therefore it is interesting whether it is possible to optimize this important cost factor by speed control.
Basically the conveying speed at the material feed station is decisive for the design of pneumatic conveying systems. There is a pressure loss during conveying as the gas expands.
The pressure loss depends on the density of the material to be conveyed, the length of the pipes, the material (consistency of the materials) etc. The more the pressure decreases (during conveying) the more the suction volume for the vacuum generators increases.
Since many parameters collude an exact calculation of these processes is not possible. As a result the greater part of such systems is usually oversized which may cause excessive conveying speeds leading to pipeline or product wearout. However, "controls" with flaps or infiltrated air are used to avoid unnecessary wearout and for careful conveying.
Of course, this kind of control (by flaps or infiltrated air valves) is a waste of energy; adaptation to required power data by speed control is more economical.

Not every type of vacuum pump or compressor can be used with a speed control, however.
There are restrictions like, for example, minimum speed (centrifugal force), maximum speed (heating/wear) and restrictions concerning efficiency.
Mink rotary claw vacuum pumps and compressors are ideal for speed control, since their power characteristic behaves linearly over the entire speed range as shown in the following diagram.

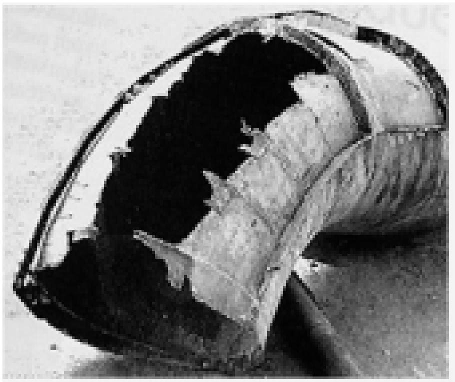

Figure 19: Wear caused by non-optimum conveying speed

As an option Mink rotary lobe vacuum pumps can be equipped with an integrated frequency drive.
This drive makes it possible to adjust the suction capacity almost linearly and thereby set the conveying speed to an optimal level.

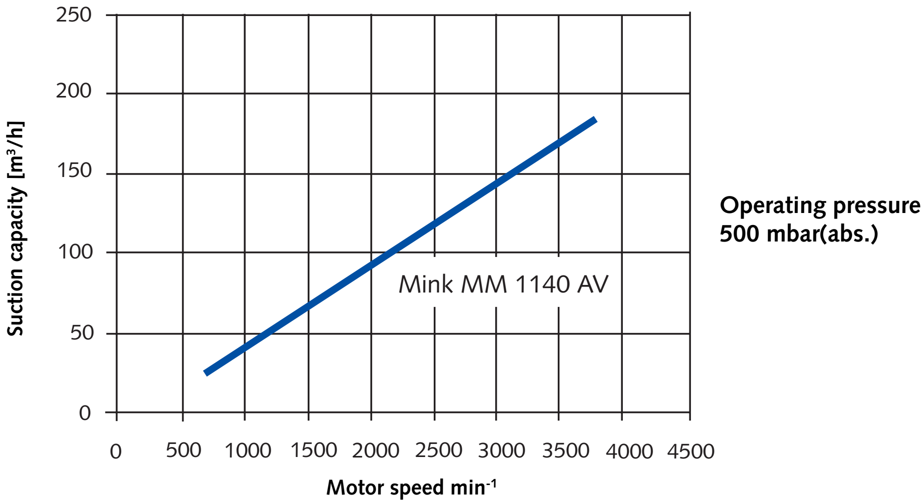

Figure 20: Suction capacity in case of frequency controlled Mink rotary claw vacuum pump

Due to the exact adjustment of the process, Mink vacuum pumps can be operated very economically. There is no need for throttle valves and furthermore substantial energy savings are possible as only the amount of energy is consumed which is actually needed for the required suction capacity.
In the most simple cases, the required air flow, i. e. the conveying speed in the pipe, is set manually with the integrated potentiometer. This leads to an improvement of process conditions during start-up. There is also the possibility of external control by SPS. Therefore, inputs with either 0-10 V or 4-20 mA are provided.

Some additional features:

- status output (motor on/off)
- speed output (with analogue output 0-10 V)
- start /stop of the drive by voltage signal from the SPS control
- selection of 3 fixed points of reference (preset references which are activated through the binary inputs)

Use of Mink rotary claw vacuum pumps with frequency controlled drive

Above picture clarifies the range of application of a Mink vacuum pump with frequency controlled drive.
When operated at a speed of up to 3800 min^{-1} the suction capacity can be increased significantly in comparison to machines with a conventional drive.

Due to the resulting capacity reserve the use of a smaller pump size is possible under certain circumstances which leads to substantial savings in costs.

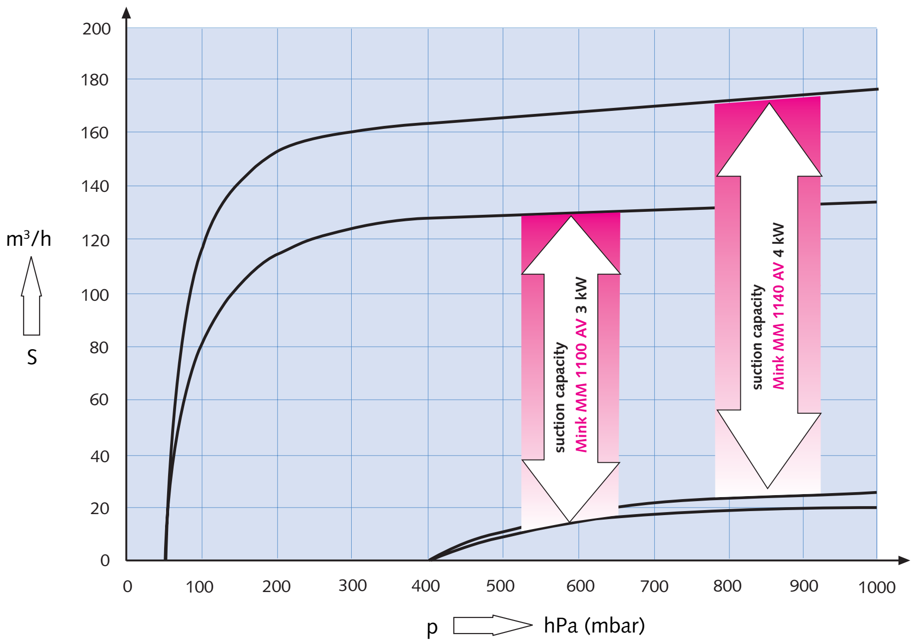

Figure 21: Mink rotary claw vacuum pump with frequency controlled drive

Figure 23: Mink rotary claw vacuum pump with frequency controlled drive

Above picture shows a claw vacuum pump of the Mink series with integrated frequency drive. The compact and integrated design of both motor and frequency inverter ensures full electromagnetic compatibility.

Compared to solutions with an external frequency inverter, there is no need for additional measures such as throttle valves or special shielding.