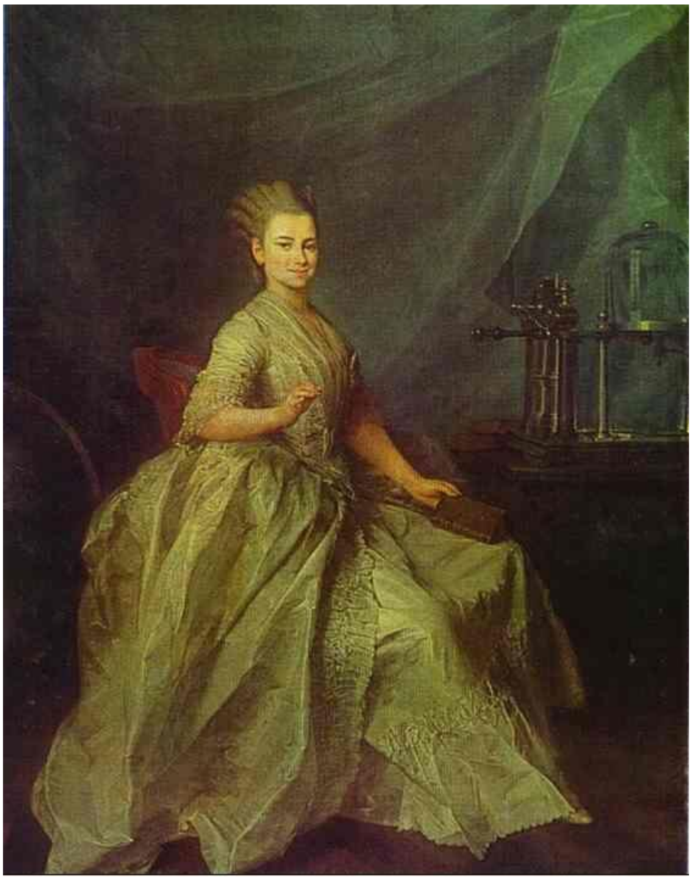
Introduction to Vacuum Technology with Reference to Vacuum Treatment of Liquid Steel



Student of Smolny Institute, Sankt Peterburg, Catherine Molchanova
with Vacuum Pump, by Dmitry Levitzky, 1776

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1 General

A vacuum is defined as a diluted gas or the corresponding state at which its pressure or density is lower than that of the ambient surrounding atmosphere. The atmospheric pressure fluctuates locally over the Earth's surface and lessens with altitude above sea level. It reaches a minimum of about 300 mbar at the highest mountain peaks (Mount Everest). By this definition, vacuum is therefore less than 300 mbar.

1.1 Fundamentals

1.1.1 Pressure

Any gas isolated within a volume is always uniformly distributed. The individual gas molecules are constantly moving back and forth at high-speed within the volume; upon striking the vessel wall they exert a force **F** on surface **A** due to impulse transmission. The pressure **P** that is exerted on the wall is defined as

$$P = \frac{F}{A}$$

1-1: Definition of pressure

If the gas is made up of different types of gases, each of these gases will exert a pressure that corresponds to its concentration; this is called partial pressure. The sum of all partial pressures equals the total pressure. Air is a good example of this. In addition to its main constituents of nitrogen, oxygen and water vapor, air also contains many trace gases.

Gas	Partial Pressure, mbar	%
Nitrogen	781.8	77.16
Oxygen	209.7	20.70
Water vapour	12	1.18
Argon	9.34	0.92
Carbon Dioxide	3.30E-01	0.033
Neon	1.82E-02	0.00180
Helium	5.23E-03	0.00052
Krypton	1.15E-03	0.00011
Hydrogen	4.94E-03	0.00049
Xenon	8.70E-05	0.00001
TOTAL	**1013.25**	**100.00**

Table 1-1: Partial and total pressures and composition of air at 20 °C and 50 % relative humidity

As a consequence of the definition of pressure, the force keeping two parts of an evacuated, split vessel together is

$$\boldsymbol{F = P * A}.$$

In a famous experiment in 1657 Otto von Guericke, Mayor of Magdeburg, Germany, demonstrated that not even 30 horses could pull apart two bronze half-spheres of 1.2 feet diameter, held together by vacuum inside.

Figure 1-1: Otto von Guericke’s experiment with two bronze half-spheres in 1657

A distinction is made between the following pressure ranges:

Vacuum Range	**Pressure Range, mbar**
Rough vacuum	10^{3} - 10^{0}
Medium vacuum	10^{0} – 10^{-3}
High vacuum	10^{-3}– 10^{-7}
Ultra-high vacuum	10^{-7} – 10^{-14}

Table 1-2: Vacuum and pressure ranges

For pressure definition the SI unit **Pa = N/m²** will be used. Also customary in actual practice are the units of pressure shown in the conversion table below. It is still common to use **mbar** as a unit of pressure. By definition, it is exactly equal to **hPa**.

Unit	Pascal (Pa)	bar (bar)	atmosphere	torr (torr)	pound-force per
1 Pa	= 1 N/m^2	10^{-5}	$9.8692*10^{-6}$	$7.5006*10^{-3}$	$145.5006*10^{-6}$
1 bar	100'000	= 1 bar	0.98692	750.06	14.504
1 atm	101'325	1.01325	= 1 atm	760	14.696
1 torr	133.322	$1.3332*10^{-3}$	$1.3158*10^{-3}$	= 1 torr	$19.337*10^{-3}$
1 psi	6'894.76	$68.948*10^{-3}$	$68.948*10^{-3}$	51.715	= 1 lbf/in^2
1 kgf/cm^2	98'066.50	0.980665	0.967838	735.5576	14.22357

1 torr ≈ 1 mmHg = 1'000 microns

Table 1-3: Conversion table for pressure units

1.1.1.1 Standard Pressure

The standard atmospheric pressure is defined as 1013.25 mbar.

1.1.1.2 Ultimate Pressure

Ultimate pressure p_e is the lowest pressure that is asymptotically approached by the pressure of a blank-flanged vacuum pump under defined conditions and without gas inlet. If a pump is operated at ultimate pressure, the usable pumping speed will be zero, as only its own backflow losses will be displaced.

1.1.1.3 Compression Ratio K_0

The maximum pressure ratio between discharge pressure p_2 and intake pressure p_1 is referred to as the compression ratio:

$$K_0 = \frac{p_2}{p_1}$$

1-2: Definition of compression ratio

At maximum compression ratio the gas flow is zero.

1.1.2 Gas Laws

Commonly used gas laws are based on the continuum theory, meaning that a gas behaves like a fluid and completely fills any volume.

$$\boldsymbol{p * V = constant}$$ ***1-3: Boyle-Mariotte's Law for isothermal conditions***

$$\boldsymbol{\frac{V}{T} = constant}$$ ***1-4: Charles' Law for isobar conditions***

$$\boldsymbol{p * V^{\kappa} = constant}$$ ***1-5: Poisson's Law for adiabatic conditions***

$$\boldsymbol{\Sigma p_i = p_{total}}$$ ***1-6: Dalton's Law***

A gas volume of 22.414 liters (molar volume) at a temperature of 273.15 K (standard temperature = 0 °C) and a pressure of 101,325 Pa (standard pressure) contains $6.02*10^{23}$ particles (Avogadro's number). The mass of the gas thus enclosed is its molecular weight in grams. The Ideal Gas Law describes the state of a gas as a function of pressure, temperature and volume.

$$\boldsymbol{p * V = \frac{m}{M} * R * T}$$ ***1-7: Ideal Gas Law***

where

p = pressure [Pa; N/m²]
V = volume [m³]
m = gas weight [grams]
M = molar mass [g /mol]
R = general gas constant = 8.314510 [J/mol K]
T = thermodynamic temperature [K].

Although the Ideal Gas Law strictly applies to ideal gases only, it is sufficiently accurate for calculations in steel degassing technology.

1.1.3 Flow Types

Three types of flow are mainly encountered in vacuum technology:

- viscous or continuous flow
- molecular flow
- Knudsen flow at the transition between these two.

Flow type and calculations for steel degassing largely refer to the **viscous flow** range. Transitional and molecular flows will not be dealt with here.

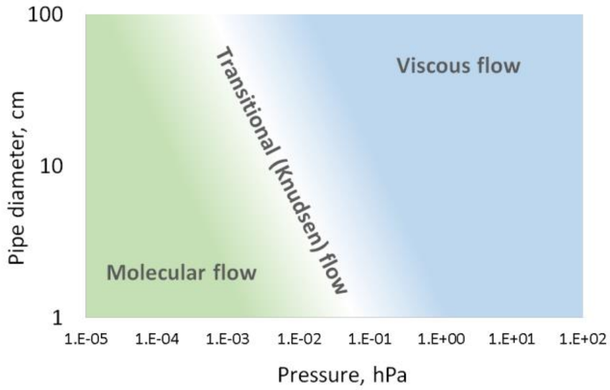


Figure 1-2: Flow type as function of pressure and pipe diameter

1.1.3.1 Volumetric Flow

Volumetric flow designates the gas volume which flows through a piping element within a unit of time at the prevailing pressure and temperature. Although two volumetric flows may be identical, the number of molecules moved may differ, depending on the pressure and temperature. Commonly used unit is m^3/h.

1.1.3.2 Mass Flow

Mass flow designates the gas mass which flows through a piping element within a unit of time. This gas mass is in fact a number of molecules, regardless of pressure and temperature. Commonly used unit is kg/h.

1.1.3.3 pV Flow (Throughput)

pV flow appears in the viscous flow range. This is the flow type of interest in steel degassing.

Dividing the Ideal Gas Law equation with time ***t*** yields the gas flow:

$$\boldsymbol{qpV = p * \frac{V}{t} = \frac{m * R * T}{t * M}}$$

1-8: pV Flow

1.1.3.6 Choked Flow

Choked flow appears upon venting of a vacuum vessel. When the venting valve is opened, ambient air flows into the vessel at the ambient pressure $\mathbf{p_1}$. The maximum velocity the flow can reach is equal to sonic velocity (343 m/s for dry air at 20 °C). Therefore, the volume flow, $\mathbf{q_{pV}}$, through the valve is not a function of the vessel's interior pressure $\mathbf{p_2}$. This condition is called *choked flow*.

When the successively increasing pressure ratio $\mathbf{p_2/p_1}$ exceeds the *critical pressure ratio*, the velocity will successively fall. When the pressures are equal, the gas velocity into the vessel obviously goes down to zero.

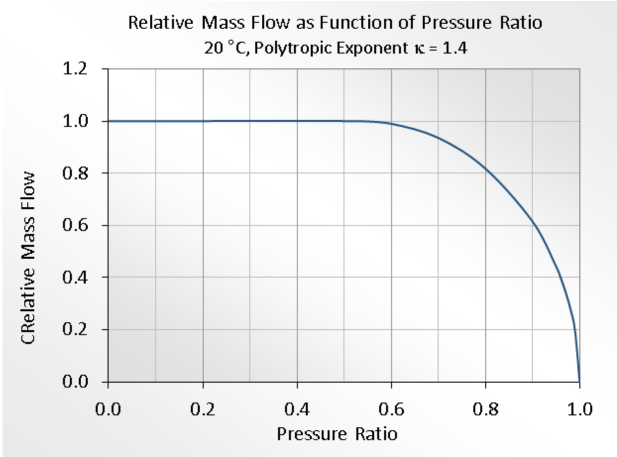


Figure 1-3: Choked flow for air at 20 °C

The **critical pressure ratio** is a thermodynamic constant, which can easily be calculated on basis of the polytropic exponent κ for any gas or gas mixture. For air with $\kappa = 1.40$ the critical pressure ratio is 0.528 at 20 °C.

1.1.4 Pumping Speed S_0

The pumping speed is the mean volumetric flow through the vacuum pump's inlet port. In the volume flow diagram, the volumetric flow is shown as a function of the pump inlet pressure. The pump's maximum achievable pumping speed is always referred to as its rated pumping speed. Pumping speed is indicated in m^3/s. The units of m^3/h, l/s and l/min are also customary.

$$S_0 = \frac{dV}{dt}$$

1-9: Pumping speed

1.1.5 Effective Pumping Speed S_{eff}

The effective pumping speed of a Roots pump can be calculated on basis of intake and outlet pressures as well as of its maximum compression ratio. In the viscous flow range, the effective pumping speed can be expressed as

$$S_{eff} = S_o * [1 - \frac{1}{K_0} * \left(\frac{p_v}{p_a} - 1\right)]$$

1-10: Effective pumping speed

where $\mathbf{S_0}$ is the nominal pumping speed and $\mathbf{p_v}$ and $\mathbf{p_a}$ are actual outlet and inlet pressures.

The narrower the Roots pump manufacturing tolerances, the higher the maximum achievable compression ratio $\mathbf{K_0}$ because the inevitable, internal back-flow is reduced. High $\mathbf{K_0}$ and limited actual compression ratio $\mathbf{p_v/p_a}$ favor effective pumping speed and therefore high mechanical efficiency $\mathbf{S_{eff}/S_0}$.

1.1.6 Pump Throughput q

The throughput for a pump is equal either to the mass flow through the pump's inlet port

$$q_m = \frac{m}{t}$$ ***1-11: Mass flow***

or

to the **pV** flow through the pump's inlet port

$$q_{pV} = p * \frac{V}{t}$$ ***1-12: pV flow***

It is normally specified in mbar*l/s. Here **p** is the pressure on the inlet side of the pump.

If **p** and **V** are constant at the inlet side of the pump, the throughput can simply be expressed

$$q_{pV} = p * S$$ ***1-13: Throughput***

where **S** is the pumping speed.

The pump throughput should not be confused with the pumping speed. The pump throughput is the quantity of gas moved by the pump per time unit, expressed in hPa *l/s. The pumping speed is the "transportation capacity" available per time unit, measured in m^3/h or l/s. The calculated throughput of the high vacuum pump is important to determine the size of the backing pump in order to ensure that the backing pump will be able to "swallow" the gas moved by the high-vacuum pump.

In the case of pumping stations that consist of gas-displacement pumps, the throughput of all pumps will be the same.

1.1.7 Leak Rate q_L

The leak rate $\mathbf{q_L}$ reduces the effective throughput of a pumping system. It therefore has the same unit as throughput, namely Pa*l/s or mbar*l/s.

A leak rate is often measured with atmospheric pressure prevailing upstream the leak and vacuum pressure in the system.

For steel degassing installations, the leak rate is traditionally expressed as kg of air per h, which relates back to steam ejector pumps, the suction capacity of which traditionally was expressed in kg/h of **D**ry **A**ir **E**quivalent.

1.1.8 Pump-Down Time

The pump-down time of any vessel can be calculated as

$$t = \frac{V}{S} * ln\left(\frac{p_1}{p_2}\right)$$

1-14: Pump-down time

where

t = pump-down time [h]
V = vacuum system volume [m^3]
S = available pumping speed at (1st stage) pump inlet [m^3/h]
p_1 = is start pressure
p_2 = is end pressure.

Due consideration must additionally be given to any leak, which reduces available suction speed.

2 Vacuum Generation for Steel Degassing

2.1 Classification of Vacuum Pumps

A vacuum pump is a device for creating, improving and/or maintaining a vacuum (an environment in which the pressure is below atmospheric pressure).

Two basically distinct categories of vacuum pump may be considered: *Gas Transfer Pumps* and *Entrapment Pumps*.

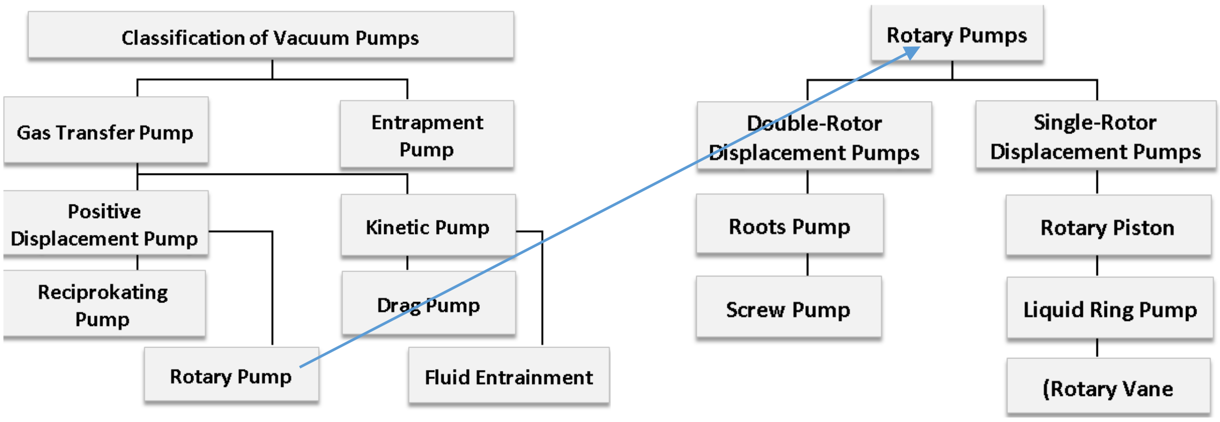


Figure 2-1: General classification of vacuum pumps and

Figure 2-2: Mechanical vacuum pumps commonly used in steel degassing

Gas transfer pumps are classified either as positive displacement pumps or kinetic vacuum pumps.

Positive displacement pumps displace gas from sealed areas to the atmosphere or to a downstream pump stage. They are divided in reciprocating pumps and rotating, positive displacement pumps.

Kinetic pumps displace gas by accelerating it through a mechanical drive system or through a vapor stream that is condensed at the end of the pumping section.

Only rotary vacuum pumps are used in liquid steel degassing. Roots pumps and screw compressors are the most common ones. From an investment point of view also liquid ring pumps find application as an economical alternative to screw compressors, although the electric energy consumption increases slightly.

Rotary vane pumps have relatively low investment cost but are sensitive to dust and are therefore not preferred in liquid steel degassing.

2.2 Roots Vacuum Pumps

2.2.1 Operating Principle

Also known as Roots blowers and rotary-lobe blowers, Roots vacuum pumps are positive displacement compressors. They are termed Roots pumps or Roots blowers after the inventor's name. Roots vacuum pumps contain two intermeshing rotors that rotate in opposite directions within the pump housing to move the gas.

The rotors have a figure "8" shape and run separated from one another and from the housing by narrow gaps. Their operating principle is analogous to that of a gear pump that displaces the gas from the inlet port to the outlet port without compressing it.

Figure 2-3: Roots blower

Compression takes place only when the gas moved inside the pump meets with the gas present in the exit port. One shaft is driven by a motor. The other shaft is synchronized by means of timing gears in the gear chamber. Lubrication is limited to the two bearings and gear chambers, which are sealed off from the suction chamber.

The absence of reciprocating masses also affords trouble-free dynamic balancing, which means that Roots vacuum pumps operate with extremely little vibrations.

Mechanical efficiency of Roots pumps is in the order of 0.85 at optimum rotational speed and compression ratio.

2.2.2 Design

Rotor shaft bearings are arranged in the two side pieces. They are designed as fixed bearings on one side and as sliding internal rings on the other in order to enable unequal thermal expansion between housing and piston.

Rotors run dry within the pump housing. Gears and rotor bearings are oil-lubricated, but they are external to the pump, as shown in the schematic. A slight back-flow of gas will occur in the gaps between rotors and between rotors and housing and reduce mechanical efficiency. Water-cooling is applied on the gear oil.

For detailed data please refer to ***ELIVAC*** Roots pump data sheet.

2.2.3 Limiting Risk of Over-Heating

Since Roots pumps do not have internal compression, compression takes place only when the gas being moved through the pump meets with the gas in the outlet port. As a result of this external compression and particularly in the presence of a high pressure differential between inlet and outlet, a significant heat-up of the pump may occur at the outlet port. As compared with the housing, the rotating Roots pistons can only be provided with relatively weak cooling. Consequently, they expand more than the housing.

To prevent contact or seizing, the maximum possible pressure differential for a given pump type can be limited by a by-pass valve. It is connected to the inlet side and the pressure side of the pump-through channels.

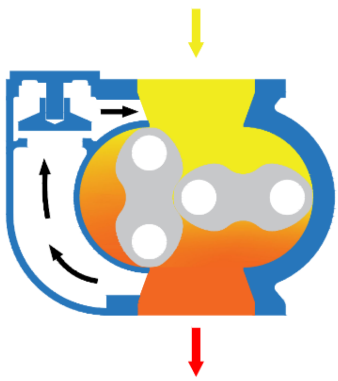


Figure 2-4: Roots pump with by-pass valve

A weight-loaded valve plate opens when the maximum pressure differential is exceeded and allows a variable portion of the intake gas to flow back from the pressure side to the inlet side. Another common method of limiting the pressure differential is to feed the Roots pump through a frequency converter. The pressure differential is proportional to the pump torque, which is approximately proportional to the electric motor current. Proper set-up of the frequency converter will limit maximum current and maximum motor frequency to safe values so that the pump will not overheat or run too fast. Water-cooling will be applied in the outlet port if undue heating-up is expected. Due to the limited allowable pressure differential, ordinary Roots pump boosters cannot discharge against atmosphere and require a backing pump.

2.2.4 Backing Pumps

Ordinary Roots blowers can typically tolerate a pressure differential of 30-70 hPa without particular precautions for cooling. If the required vacuum pressure is, say, < 1 hPa, Roots pumps creating the required volume flow at low pressure must be backed by one or several stages of backing pumps to reach up the atmospheric pressure 1013 hPa.

It is customary in steel degassing to use two or three, sometimes even four, stages of Roots blowers for successive compression up to 25-30 hPa total pressure followed by primary pumps raising the pressure from this level up to atmospheric pressure. The primary pump must therefore be able to provide a very high differential pressure although at a modest volume flow.

In case the process gas is clean, rotary vane pumps can be used. If there is risk of contamination with dust, like in steel degassing, screw compressors or liquid ring pumps are a better choice.

2.2.5 Gas-cooled Roots Pumps

To allow Roots vacuum pumps to work with very high differential pressure against atmospheric pressure, some models are designed with gas cooling. In this case, a partial gas flow from the outlet port is cooled and re-admitted into the middle of the suction chamber through a cooler.

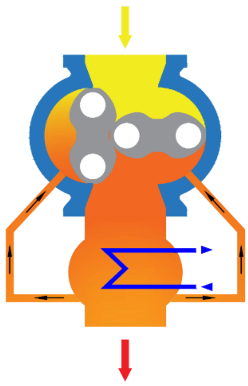


Figure 2-4: Operating principle of a gas-cooled Roots pump

This recirculated gas flow cools the pump by expansion, enabling it to compress against atmospheric pressure. Gas entry is controlled by position of the Roots pistons, thus eliminating the need for any additional valves. There is no possibility of thermal overload, even when operating at maximum pressure difference.

Gas-cooled Roots pumps can be used in the inlet pressure range of 130 to 1013 hPa. The gas being pumped is not contaminated by lubricant or water. Although gas-cooling enables Roots pumps to

A cross section of a Roots vacuum pump is shown. The direction of gas flow is from top to bottom, enabling any liquid or solid particles entrained in the gas flow to exit downward.

At first, the chamber is opened by the rotation of the pistons. Gas flows into the chamber through the inlet flange at pressure $\mathbf{p_1}$. After that, the chamber is sealed off against both the inlet flange and the pressure flange. Until the inlet opening for the cooling gas is exposed by rotation of the pistons, the pressure in the chamber remains at $\mathbf{p_1}$.

Finally, the chamber is filled at the outlet pressure $\mathbf{p_2}$, and the mixture of incoming process gas and re-circulated, cooled gas is advanced by the Roots pistons toward the exit port at constant volume. Since the pressure $\mathbf{p_2}$ is higher than $\mathbf{p_1}$, the recirculating gas entering the chamber cools by expansion. The piston continues to rotate and this movement pushes the compressed gas across the cooler to the discharge side at pressure $\mathbf{p_2}$.

operate with very high differential pressure, this advantage comes at a considerable cost:

- The high compression makes the gas-cooled Roots pumps very noisy so that silencers are a must.
- The mechanical efficiency drops rapidly with the compression ratio and goes down to about 50 % at highest compression ratio. In other words, up to 50 % of the supplied electric energy is lost by using gas cooled pumps.
- High-powered electric motors must be installed to cover such additional energy losses.
- Very large heat exchangers are also needed for dissipating not only the heat of compression but also the energy lost in the gas-cooled Roots pumps.
- Heat exchangers may be exposed to corrosion and clogging if dust enters the vacuum generation system.

In view of clearly inferior mechanical efficiency, additional investment and operation costs and technical risks with gas-cooled Roots pumps, ***ELIVAC*** prefers the use of conventional Roots pumps with very high mechanical efficiency in combination with screw compressors or liquid ring pumps.

In the near future, ***ELIVAC*** multi-stage Roots pumps for high differential pressures will become available as a very economical, energy-efficient and non-complicated alternative to screw compressors and liquid ring pumps.

Figure 2-5: High-quality Roots casings queuing up for machining

Figure 2-6: 3-D view of Roots pump

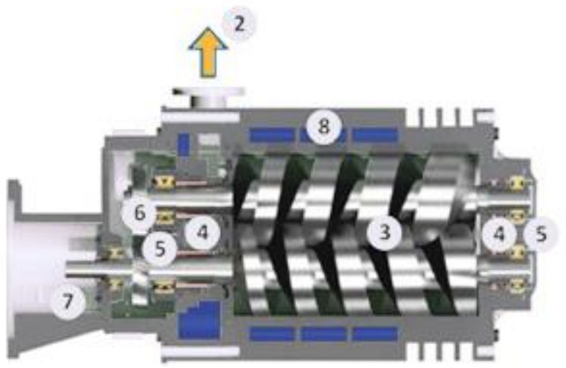
2.3 Screw Vacuum Pumps

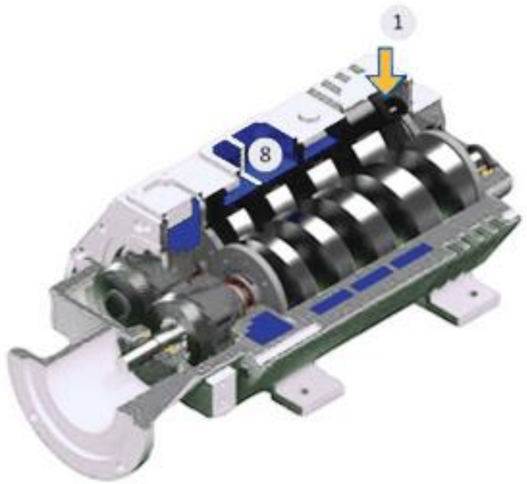
2.3.1 Operating Principle

Two parallel screws (3) with opposite threads rotate synchronously but in opposite directions and without contact in a housing with overlapping cylindrical bores that tightly encloses the screws and together form a multi-stage pump, where the hypothetical number of stages is equal to the number of convolutions on the rotors. Timing gears (6) ensure synchronization of rotors.

Because of the intermeshing of the two rotors, pockets of gas are trapped between the convolutions of rotors and the housing and successively advanced along the rotors to the outlet (2). When a pocket of gas reaches the outlet port, its pressure is equalized with that in the exhaust duct.

Mechanical efficiency of screw compressors is high and in the order of 0.92-0.98.





1. Suction
2. Discharge
3. Screws
4. Seals
5. Bearings
6. Timing Gears
7. Shaft/Coupling
8. Cooling Jacket

Figure 2-6: Operating principle of a screw pump with continuously variable pitch rotors

2.3.2 Design

If screws have a *constant pitch*, then *no internal compression* will take place but the pockets of gas will simply be moved at constant pressure from inlet to outlet port. Compression will then take place in a pulsating manner each time a pocket of gas comes into contact with gas in the exhaust duct, similar to what happens in a Roots pump.

Heat of compression is then concentrated to the outlet port and to that end of the screws. In contrast to this, modern, dry screw compressors do *have internal compression* to successively approach the pressure in the exhaust duct.

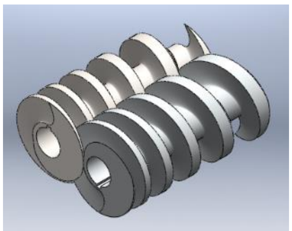


Figure 2-7 Screws with continuously variable pitch

The screws are identical and with *continuously variable pitch* so that compression and heating by compression takes place over the entire screw length. In this manner, the *heat of compression* is no longer concentrated to the outlet area but *distributed over the entire screw length*, thereby *minimizing the risk of local overheating*. Screws with continuously variable pitch offer clear advantages over screws with constant pitch what regards overall efficiency, energy consumption and noise level.

The housing is cooled by water channels. Air-cooling flanges over the screw length to dissipate the heat of compression. Screw pumps usually rotate at fixed rpms because below a certain rotational speed, the volume flow falls off drastically.

The gaps between housing and screws, as well as that between the screws, determine achievable ultimate pressure of a screw pump. Highest efficiency is reached with housing and screws at operating temperature. For detailed data please refer ***ELIVAC*** screw compressor data sheet.

2.4 Liquid Ring Pump

2.4.1 Operating Principle

Liquid ring vacuum pumps represent a very wide-spread vacuum pump design. They are non-pulsating, rotary vacuum pumps that compress gas internally using a rotating liquid, hence the name *liquid ring pump*.

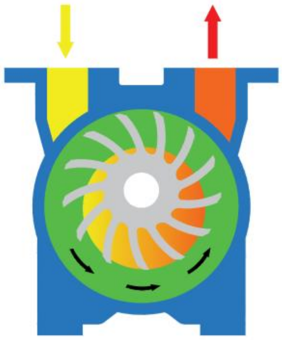


Figure 2-8: Liquid ring pump

The housing of the liquid ring pump contains a sealant fluid, which forms a rotating ring along the inside. The ring is formed by a rotating, multi-bladed, off-center impeller.

Gas enters through the suction port and is trapped by the liquid ring in the *expanding* pockets between the blades. The gas is then moved in a series of *shrinking* pockets. The compressed gas exits through the discharge port. Liquid ring vacuum pumps do not require any internal lubrication because the rotors do not contact the housing. The primary function of the liquid ring is to act as a seal. In addition, it absorbs heat of compression, friction and condensation. The liquid ring can also cool by evaporation of the sealing liquid (if dry process gas and water as sealing liquid).

2.4.2 Design

The gas entering the pump will become saturated with vapor from the sealant fluid (often water) at its actual temperature. As a consequence, the effective suction capacity, expressed as mass flow, for a given liquid ring pump decreases with increasing operating temperature and falling inlet pressure because sealant vapor will take up an increasing part of the expelled gas volume. The achievable, ultimate inlet pressure is therefore in principle equal to the sealant liquid vapor pressure at prevailing liquid temperature. At this stage, effective suction becomes zero and the liquid ring pump may become mechanically severely damaged by cavitation (formation of gas bubbles by boiling sealant liquid).

Achievable volume flow depends on displacement and rotational speed. The latter must at least be such as to maintain a liquid ring.

Liquid ring vacuum pumps can be designed with one or two stages. Two-stage pumps have got two impellers in parallel housings but on the same shaft for successive compression of the process gas; single-stage pump one impeller in one housing only. Two stages offer a significantly better performance at low pressure.

Influence of sealing water temperature on effective suction capacity is shown here below. The reference water temperature is usually, but not always, 15 °C. Actual water temperatures above or below the reference temperature will increase or decrease effective suction capacity as expressed in the **CAPACITY FACTOR**. It will also limit the achievable operating pressure. The user is advised to accurately clarify this matter when determining actual pump suction speed.

If sealing liquid temperature is so high that the vapor pressure of the sealing liquid is equal to the suction pressure, the liquid boils and the pump will cavitate, causing severe, internal erosion. Capacity correction curves are calculated with such a safety margin that cavitation will not occur.

Example: 32 °C water temperature will result in a capacity factor of 0.47 with a recommended minimum pressure of 72 hPa on a single-stage pump. On a two-stage pump it will result in a capacity factor of 0.53 with a recommended minimum pressure of 62 hPa.

For detailed data please refer to ***ELIVAC*** liquid ring pump data sheet.

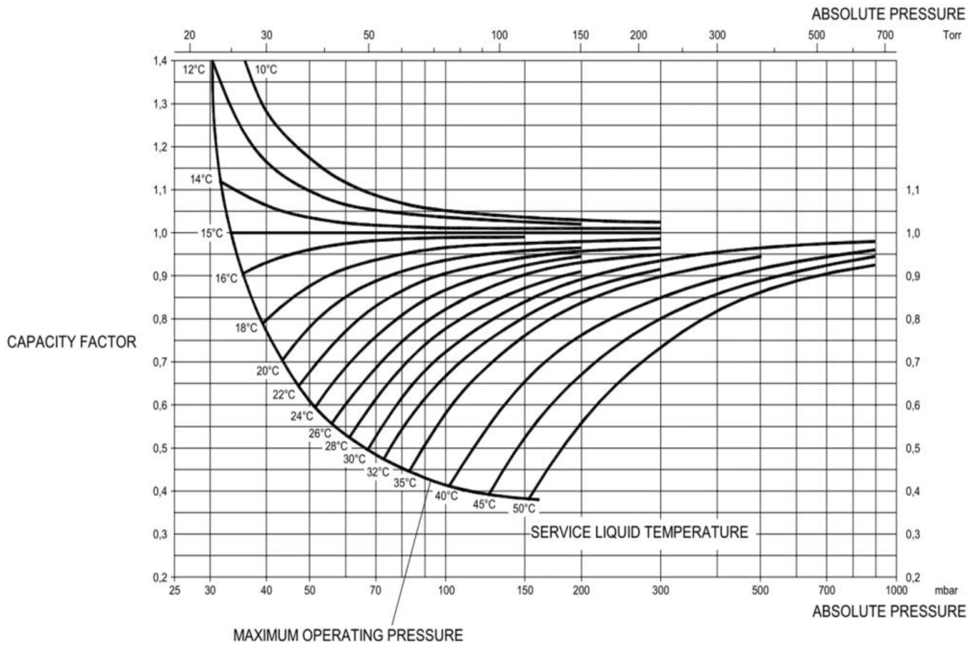


Figure 2-9: Capacity correction factor for single-stage pump and 15 °C reference temperature

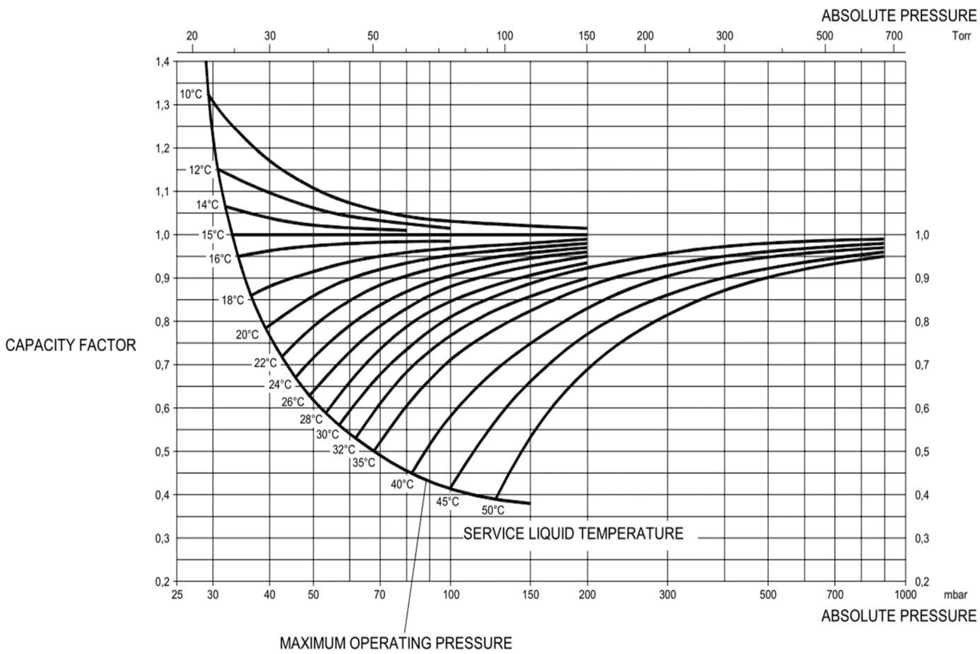


Figure 2-10: Capacity correction factor for two-stage pump and 15 °C reference temperature

2.5 Rotary Piston Pump

2.5.1 Operating Principle

Also known as plunger pumps, rotary piston vacuum pumps are positive-displacement compressors.

In a rotary piston pump, the pumping action is created by the moving piston. The cam rotates inside the piston.

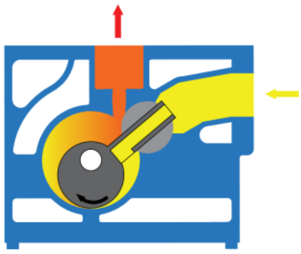


Figure 2-11: Rotary piston pump

The piston moves inside the stator, pumping the gas. The piston must complete two revolutions before the operating cycle is complete:

The gas fills the chamber in the first revolution and is discharged in the second.

The inlet and discharge volumes are always separated by the moving contact line between the piston and the stator. The small clearance at this contact line is lubricated with sealing oil.

2.5.2 Design

Rotary piston pumps use oil to seal internal components, transfer heat away from surfaces, flush moisture, and inhibit corrosion of internal components. Therefore the oil needs to be free of particulates and condensable vapors to avoid internal damage to the pump. If the gas being pumped can be expected to contain particulate matter, the oil will be exchanged at intervals or be continuously filtered. Gas ballasts can be applied to prevent condensation within the vacuum pump.

Rotary piston vacuum pumps are used in the semiconductor industry, in vacuum impregnations, drying, extrusion, degassing and small batch operations. They do not need any backing pump and can work reliably and silently down to 0.01 hPa.

For detailed data please refer to tables of ***ELIVAC*** rotary piston pump data sheet.

2.6 Purpose of Vacuum Treatment of Liquid Steel

Liquid steel for qualified purposes is typically exposed to vacuum treatment to improve its performance in the final application. The process aims at reducing the contents of H, N, S and O and sometimes also C.

The process takes place batch-wise with steel circulation provided by use of inert gas, usually 40-150 tonnes at a time, for a typical period of time of 15-25 minutes with a pressure at end of treatment of 0.5-1 hPa.

Special processes like VOD for stainless steel and RHO for low-carbon, automotive sheet steel are used for decarburization of liquid steel at a pressure of 35-130 hPa and for a period of time between 3 and 40 minutes.

The dust generated by vacuum treatment of liquid steel is extremely fine-grained. Although all process off-gas is always filtered in bag filters, some of the finest particles will inevitably pass through even a fully intact filter and pass through the vacuum pump. A certain tolerance against very fine-grained dust is therefore called for.

2.6.1 Vacuum Pump Configuration

A vacuum pump for steel degassing is configured with three to five stages, typically four. It can be built in a modular fashion, which considerably simplifies engineering and erection.

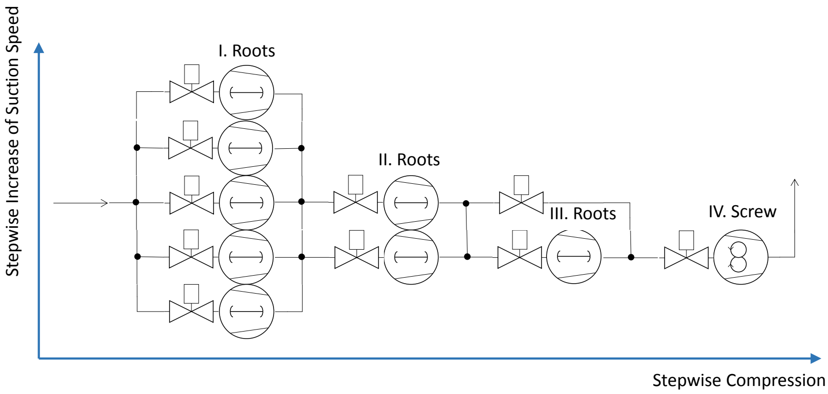


Figure 2-12: Example of vacuum pump configuration (one module)

Stage I always consists of Roots booster pumps, the number of which is determined so that the aim low pressure (0.5-0.8 hPa) with metallurgical load (H_2, N_2, Ar, air) can be reached.

Stages II and III always consist of Roots booster pumps and are configured so that the p*V flow from stage I remains approximately constant while respecting the maximum permissible differential pressures across Roots pumps.

Stage IV is a backing pump providing a considerable differential pressure so that atmospheric pressure is reached downstream stage IV. This stage must therefore be a screw compressor or a liquid ring pump.

Pump-down time is mainly determined by the pumping speed of stage IV and to a lesser extent by stages II and III. In case the system volume to evacuate is large, it may therefore be necessary to increase suction speed in stage IV by increasing number of pumps or their size.

Reduction of pump-down time can also be achieved by temporarily connecting a pre-evacuated volume to the vacuum system, for example opened only between atmospheric pressure and 450 hPa vacuum vessel pressure and then closed below that pressure. It is again pre-evacuated as the vacuum bag filter between degassing cycles so as not to cost process time. It offers reduction of pump-down time at very reasonable cost and with a very minimum of mechanical equipment. Essentially, it makes more intensive use of existing equipment instead of adding more pumps.

2.6.1.1 Pumping Speed Curve

The pumping speed curve is predicted on basis of data of all individual machines making up of the vacuum pump. As an example, the pumping speed curve as function of vacuum pump inlet pressure for the four-stage vacuum pump described in 2.6.1 is shown.

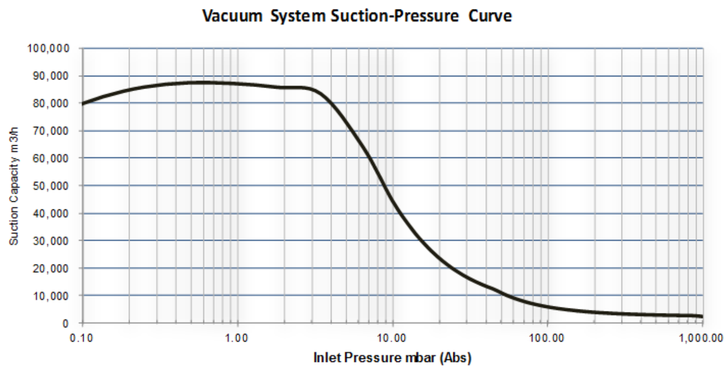


Figure 2-13: Pumping speed curve for a 4-stage vacuum pump

The pumping speed remains practically constant in the 0.3-3 hPa pressure range, simply because the rotational speed of first-stage pumps is constant and at its maximum in this pressure interval. If it instead were a 3-stage pump, the pumping speed would start to drop off already above 1.5 hPa. A 4-stage vacuum pump therefore always renders the vacuum system much more stable and insensitive to air leaks than does a 3-stage pump.

2.6.2 Performance Requirements on Vacuum Pumps

Vacuum pumps for vacuum treatment of liquid steel must be engineered to satisfy performance requirements regarding

- Pump-down time to low pressure, usually to < 1.33 hPa
- Ultimate pressure under operating conditions, typically 0.5-0.8 hPa
- Pumping speed to “swallow” process gas from forced decarburization in an intermediate pressure interval, such as in the VOD and RHO processes.

These requirements will be met by a careful choice of pumps for all stages in the vacuum pump.

In general, the *pump-down time* is mostly influenced by the number and suction capacity of backing pumps (screw compressors and/or liquid ring pumps).

The *ultimate pressure under operating conditions* will be mainly reached by optimizing the number and suction capacity of Roots blowers in the first stage. The suction speed at intermediate pressure requires that the number and suction capacity of all machines in all stages be optimized.

It is obvious that the intended vacuum treatment process must be carefully analyzed in its entirety so that the vacuum pump can be engineered to satisfy justified performance requirements.

2.6.2.1 Pump-Down Time

Regardless of what process and what degassing equipment is applied, the pump-down time from starting pressure to < 1.33 hPa is typically < 5 minutes. This time limit may result in particular emphasis on backing pump pumping speed.

The pump-down time is predicted by use of Equation 1-14. This equation refers to a certain pumping speed. However, a vacuum pump for steel degassing has got a very varying pumping speed depending on pressure interval as seen in Figure 2-13. The total pumping time must therefore be calculated as the sum of a times for passing through a number of pressure intervals, each with its own average pumping speed.

In batch-type, tank degassing processes like the VD process, the ladle slag will tend to foam when dissolved gases like H and N as well as volatile elements like Zn and Mg start to evaporate. This typically happens in the 100 → 5 hPa pressure interval. If the ladle slag foams, the suction speed must be reduced to contain the slag within the ladle. Mechanical vacuum pumps enable a very precise suction speed control by use of frequency converters and/or gas flow control.

Steam ejector pumps represent the opposite case with poor suction speed control so that ladle slag will frequently go overboard and accumulate on the bottom of the vacuum tank.

2.6.2.2 Ultimate Pressure under Operating Conditions

With low pressure is understood a pressure in the approximate range 0.3-3 hPa, in which the effective pumping speed is approximately constant in terms of volumetric flow. This means that the working vacuum pressure is approximately inversely proportional to the volumetric flow.

At low pressure mainly H and N escape from the liquid steel. Aim is to reach a pressure at vacuum vessel of 0.5-0.8 hPa towards end of degassing cycle.

When mass flows of H_2 and N_2 from steel, N_2 from any other source, like TV camera, as well as Ar from steel circulation and any other source, like O_2 lance, have been properly quantified, the requisite pumping speed to reach the desired pressure can easily be calculated.

The pumping speed at low pressure is primarily determined by boosters in the first stage. An approximate pumping speed at low pressure for a VD unit is calculated as (**x*M + y**) m^3/h, where **M** is the steel weight [tonnes], **x** a coefficient [$m^3/(h*tonne)$] representing gas escape (H_2 and N_2) from the steel and **y** a constant [m^3/h] representing air leak rate and other fixed gas flows like N_2 for TV camera.

2.6.2.3 Pumping Speed during Forced Decarburisation for VOD and RHO Processes

Forced decarburization is brought about by blowing oxygen gas onto the metal bath in the vacuum vessel. Carbon monoxide is generated at a pressure of 35-130 hPa. Some of it is post-combusted to carbon dioxide inside the vacuum vessel. The off-gas is composed of a mixture of CO, CO_2, O_2, Ar and air leaking into the vacuum vessel.

In the VOD process the decarburization reaction is physically limited by the violence of reactions in the ladle. The maximum applicable rate of decarburization is typically 100-200 ppm C per minute with lower values for large heat weights and vice versa. The pumping speed must therefore be dimensioned to primarily accommodate the CO and CO_2 flows resulting from decarburization plus minor flows of Ar, O_2 and air leaks.

In the RHO process the pumping speed is also primarily determined by the rate of decarburization. The Ar flow is usually much higher than in the VOD process for the same heat weight and must be particularly considered.

The decarburization rate in the VOD process is only indirectly related to the applied O_2 flow. On the average, only about 40 % of the supplied O_2 reacts with C to form CO. The rest reacts with CO to post-combustion to CO_2, with Al, Si, Cr, Mn and Fe. These reactions vary much over blowing time according to thermodynamic equilibria and kinetics.

Also in the RHO process, there is no linear relationship between O_2 flow and rate of decarburization but for different reasons.

Cr, Al and Si are practically absent in actual steel grades.

C is transported to the O_2 impingement zone by the Ar circulation gas in the up-snorkel. If a higher flow of O_2 is applied than what can be consumed by the C transported to the reaction zone, the excess O_2 will post-combust CO to CO_2, increase O_2 content in off-gas and oxidize liquid steel and solid skulls inside the RH vessel.

Dimensioning of vacuum pumps for the VOD and RHO processes must therefore always be based on actual rates of decarburization, not on O_2 flow.

Figure 2-14: Factory Acceptance Test of a steel degassing vacuum pump for a Swiss engineering company