Mechanical Vacuum Pumps

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Contents

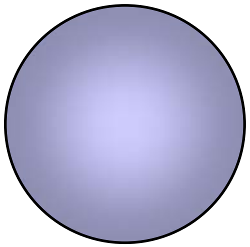
- Vacuum basics: reminder

- Primary and secondary mechanical pump technology

Gas Quantity

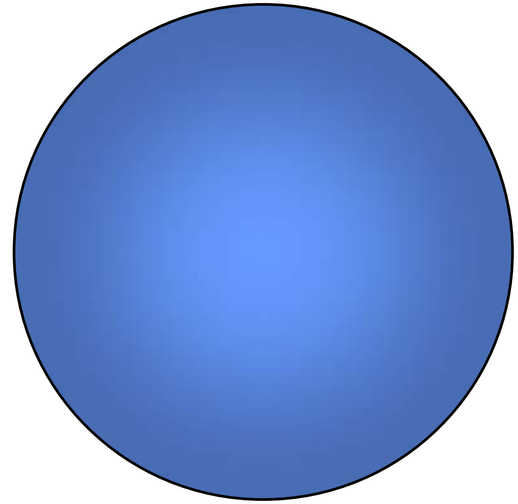
- Mass
- Number of molecules
- Moles
- Pressure/Volume units
  - q = PV
  - e.g. mbar liter/sec
  - Could be expressed in joules

Quantity q



$$q = PV$$

q = 100 mbar liter



1000 mbar

100 mbar

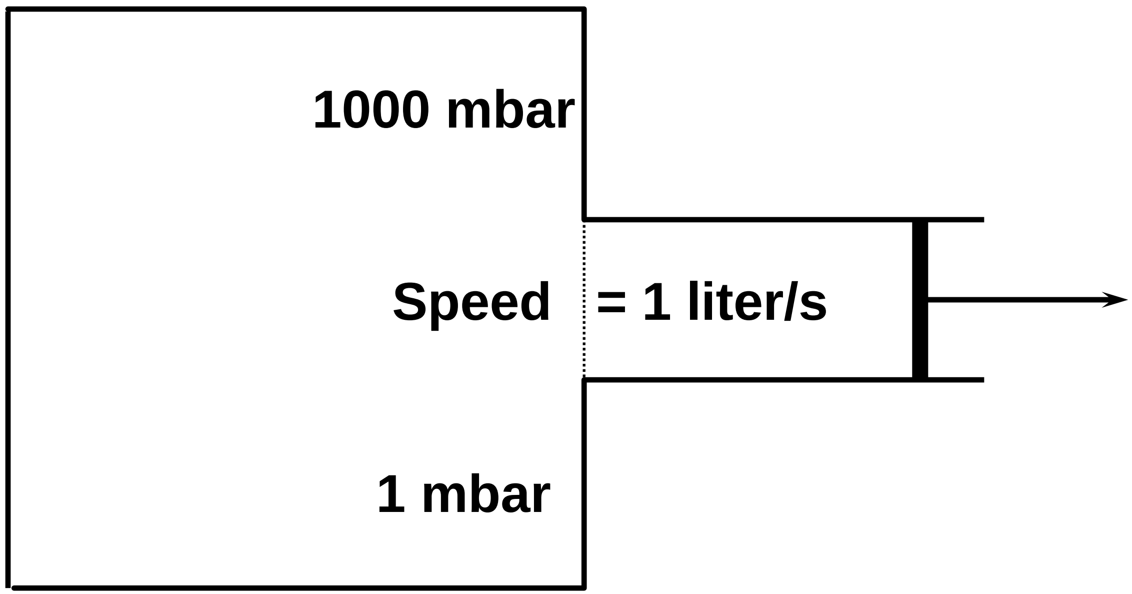
$$PV = n_m R_o T = \frac{w}{M} R_o T$$

Given PV	**mass can be found**
Given w	**q can be found**

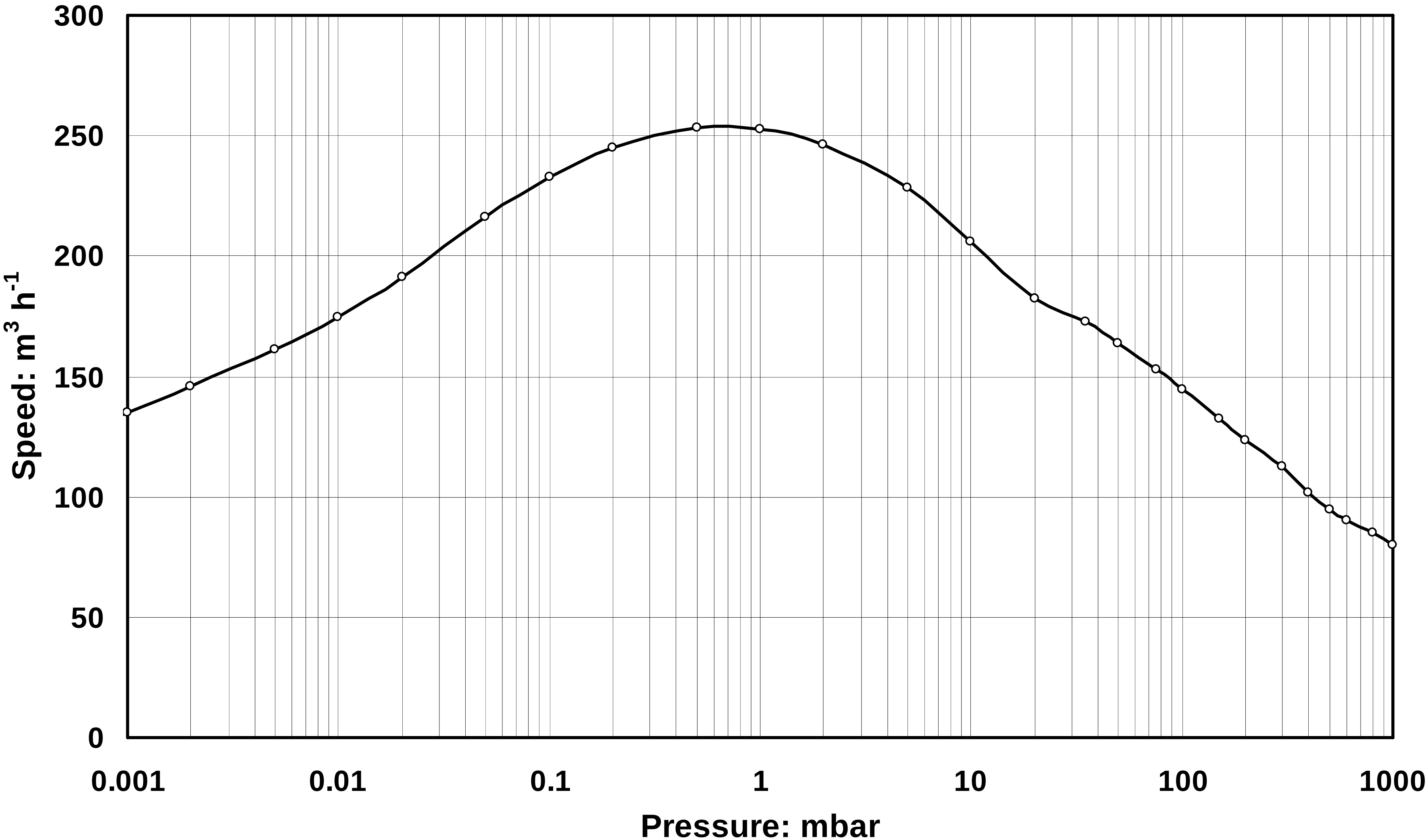
Only if we know M and T

Speed

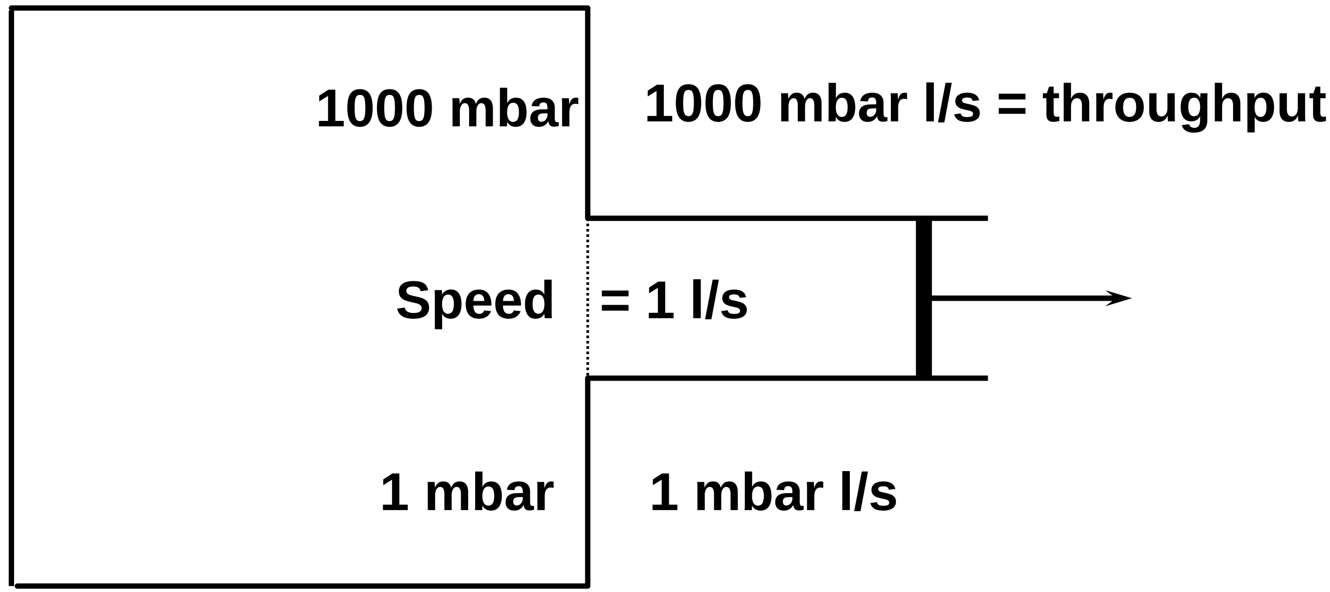
- Speed ≡ Volume rate $S \equiv \dot{V}$



Speed curve example



Throughput



- **Throughput = Pressure x Volume rate (where pressure is constant)**

$$Q = P\dot{V} = PS$$

Throughput and Mass Flow

Quantity

$$q = PV = w\frac{R_oT}{M}$$

Quantity/unit time (Throughput)

$$Q = P\dot{V} = \dot{w}\frac{R_oT}{M}$$

Q **tells us nothing about Pressure and Volume rate separately - only the product**

What do we mean by Speed?

- Manufacturers generally mean

  - Volume flow rate measured under standard conditions
  - Generally units are:

m3/h, l/m or cfm for primary

and l/s for secondary

………….(many other units used)

  - Gas inlet from a source at 20^{o}C (standards specify between 15^{o}C and 25^{o}C)

Displacement?

- Manufacturers generally mean:

  – This is the swept volume rate D

  i.e. the trapped or isolated inlet volume/unit time

  – Maximum possible flow rate of the pump

  – $S < D$

Rarefied gas and ranges of vacuum

Vacuum range	mbar	Pa
Rough	1013 - 1	10^5 - 10
Fine/medium	1 - 10^{-3}	10^2 - 10^{-1}
High	10^{-3} - 10^{-7}	10^{-1} - 10^{-5}
Ultra high (UHV)	$< 10^{-7}$	$<10^{-5}$
Extreme high (XHV)	$<10^{-10}/10^{-11}$	$<10^{-8}/ 10^{-9}$

Flow Regimes

Knudsen number: $$\mathrm{Kn} = \frac{\lambda}{d}$$

Mean free path (λ)

Characteristic dimension (d)

Regime

Molecular | **Transitional** | **Continuum**

Increasing Pressure →

Typically < 10^{-3} mbar | **Typically > 1 mbar**

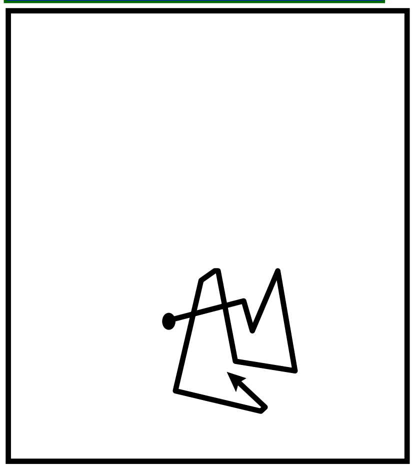
n, λ, and J at various P for N_2 at 293 K

P (mbar)	n (m^{-3})	λ	J ($cm^{-2}\ s^{-1}$)
10^3 = 1 atm	2.5×10^{25}	6.6×10^{-6} cm	2.9×10^{23}
1	2.5×10^{22}	6.6×10^{-3} cm	2.9×10^{20}
10^{-3}	2.5×10^{19}	6.6 cm	2.9×10^{17}
10^{-6} HV	2.5×10^{16}	66 m	2.9×10^{14}
10^{-10} UHV	2.5×10^{12}	660 km	2.9×10^{10}

Flow Regime

Regime

Continuum

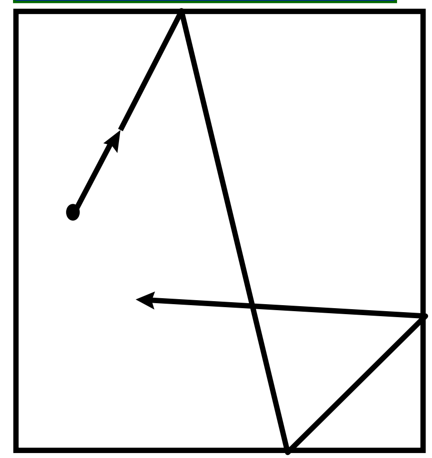


Kn<<1, λ <<d

molecule-molecule

collisions dominate

Molecular



Kn>>1, λ>>d

molecule-surface

collisions dominate

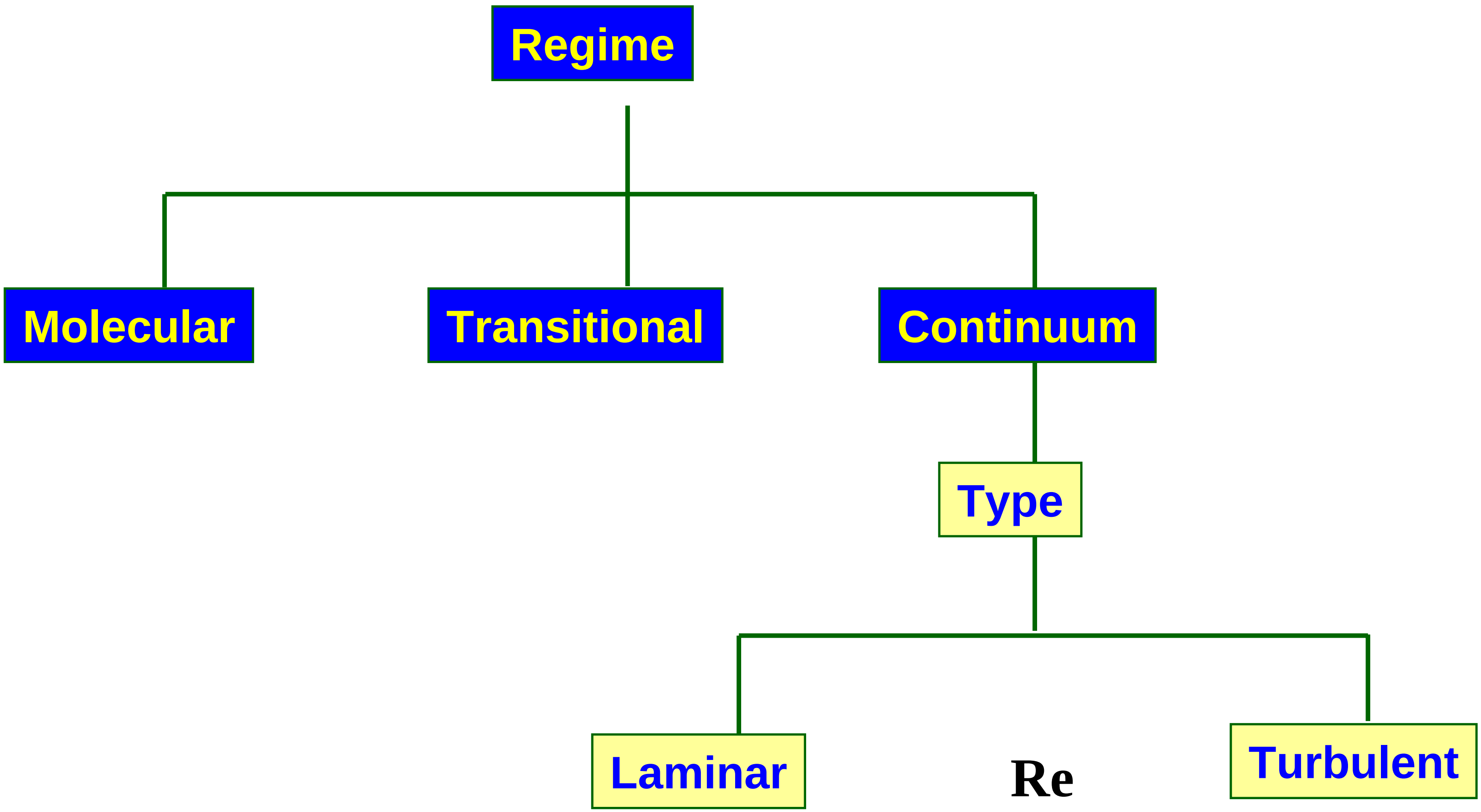
Continuum and molecular states

Knudsen number $$\mathrm{Kn} = \frac{\lambda}{d}$$

d here is a typical dimension (NOT molecular diameter)

Kn < 0.01	Continuum state
0.01 < Kn < 1	Transitional state
Kn > 1	Molecular state

Flow Regimes and Types

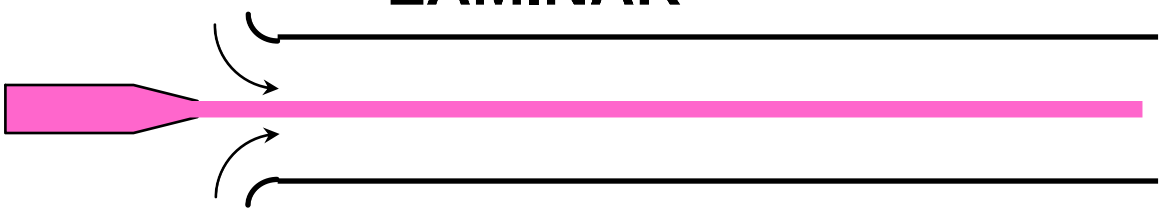


Reynolds Number

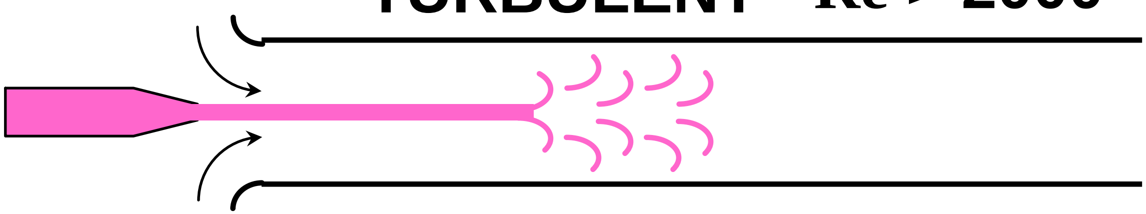
Primary controlling parameter in the viscous behaviour of Newtonian fluids

$$Re = \frac{\rho u D_h}{\eta}$$

LAMINAR $Re < 2000$



TURBULENT $Re > 2000$

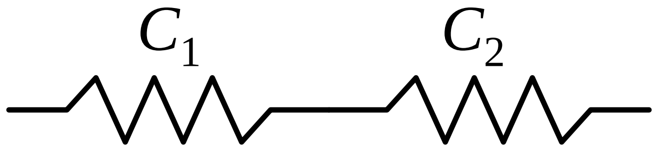


Conductance

Definition: $$C = \frac{Q}{P_u - P_d}$$

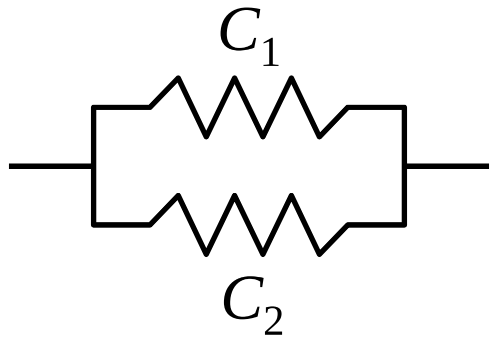
Conductance = 1/Resistance

Series



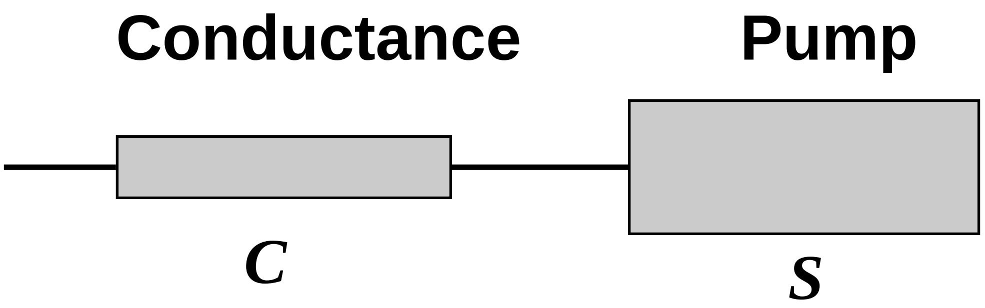
$$\frac{1}{C_n} = \frac{1}{C_1} + \frac{1}{C_2} + \cdots$$

Parallel



$$C_n = C_1 + C_1 + \cdots\cdot$$

Net Speed of a Pump



Pumping speed can be combined with a conductance in the same way as conductances in series

$$\frac{1}{S_{net}} = \frac{1}{S} + \frac{1}{C}$$

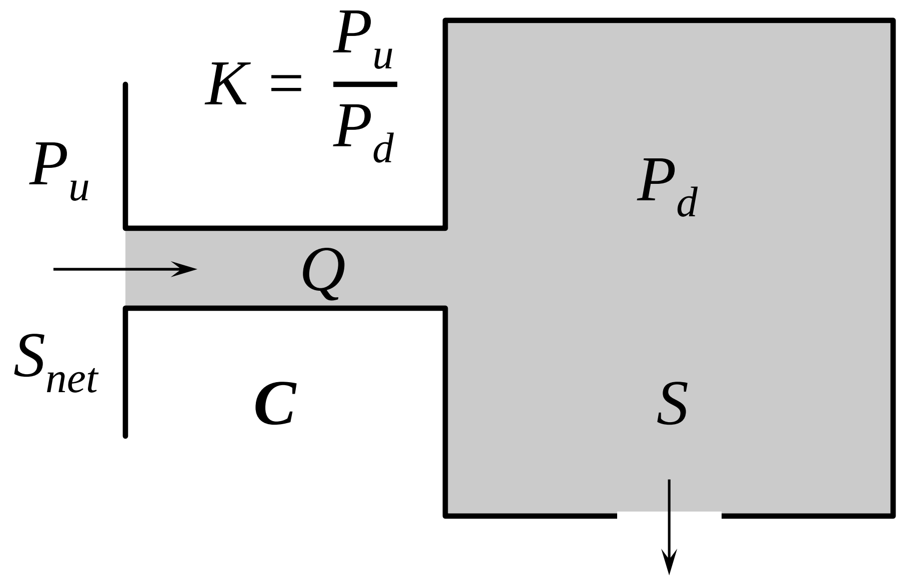
Note: In molecular flow
we need to introduce concept of transmission probability

Speed, Pressure Ratio, Conductance

$$\frac{1}{S_{net}} = \frac{1}{S} + \frac{1}{C}$$

$$P_u S_{net} = P_d S$$

$$S_{net} = \frac{S}{K}$$



From the definition of conductance

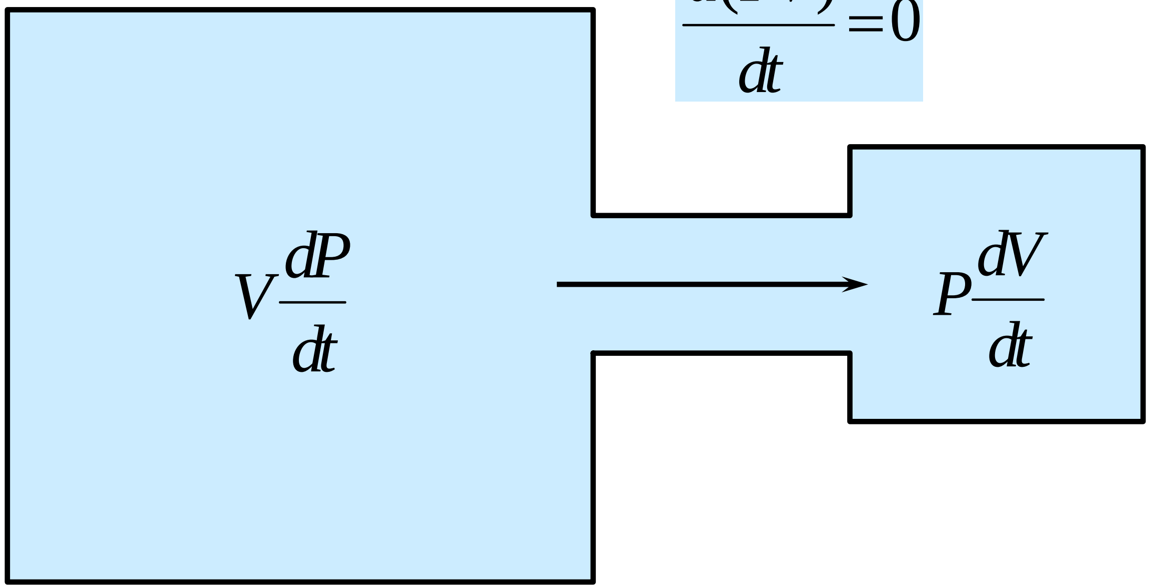
K is (zero flow) compression ratio

$$Q = P_d S = (P_u - P_d)C$$

$$\therefore \ C = \frac{S}{K-1} \quad \textbf{or} \quad K = 1 + \frac{S}{C}$$

Chamber Exhaust

$$\frac{d(PV)}{dt} = 0$$



$$P = P_0 e^{-\frac{S}{V}t}$$

$$t = \frac{V}{S}\ln\left(\frac{P_0}{P}\right)$$

Mechanical pump types (> 1 m^3/h)

Primary pumps – exhaust to atmosphere

Secondary pump – exhaust to a backing (primary pump)

Max speeds shown exponent of maximum pump speed 10^n (m^3/h or l/s)

- Wet pumps

– Oil sealed rotary vane:	Primary	n = 0 to 3 (m^3/h)
– Piston:	Primary	n = 0 to 2 (m^3/h)
– Liquid Ring:	Primary	n = 1 to 3 (m^3/h)

- Dry Pumps

– Northey-claw:	Primary	n = 1 to 3 (m^3/h)
– Roots:	Primary or Secondary	n = 2 to 5 (m^3/h)
– Scroll	Primary	n = 1 to 3 (m^3/h)
– Screw	Primary	n = 1 to 3 (m^3/h)
– Regenerative	Primary	n = 1 to 3 (m^3/h)
– Piston	Primary	n = 1 to 2 (m^3/h)
– Diaphragm	Primary	n = 0 to 2 (m^3/h)
– Drag	Primary or Secondary	n = 0 to 2 (l/s)
– Turbomolecular	Secondary	n= 1 to 4 (l/s)

Operating principle

- All rely on principle of positive displacement of gas (or vapour)

……..Except

  – **Drag pumps:** which utilise molecular drag
  – **Turbomolecular pumps:** capture technique (exploits molecular flow phenomena)

Globally >> 500 000 made per annum

Choice of mechanical pump type….

	Wet Pumps	Dry Pumps
Capital Cost	Low	High
Oil Loss	Can be high at > 1 mbar	Very Low
System Contamination	Backstream at < 0.1 mbar (1 part in 15 at ult)	Very Low (1 part in 10000 at
Add on Costs	Oil return/filtration	Not necessary
Aggressive Process	Not suitable	Resistant
Purge	Sometimes	Almost always

Excellent detailed and in-depth of coverage in General Literature and Manufacturers' websites etc.

Choice of pump type

Roughing time ?
Throughput ?
For process?
Ultimate ?
Leakage/outgassing?
Cleanliness?

Up-time?

Service interval?

Running Costs?

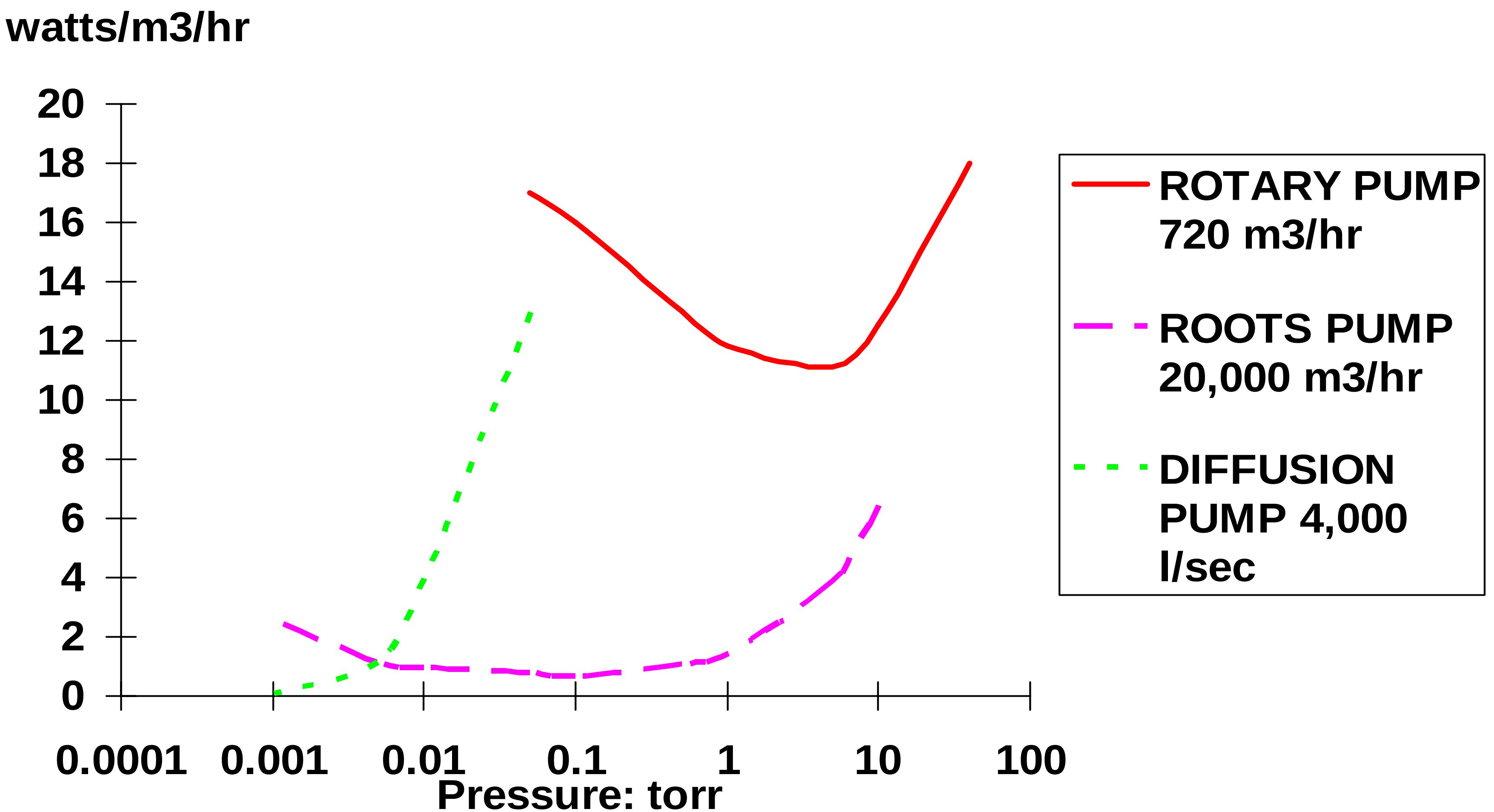
£ $ €?

Choose pump size > requirements

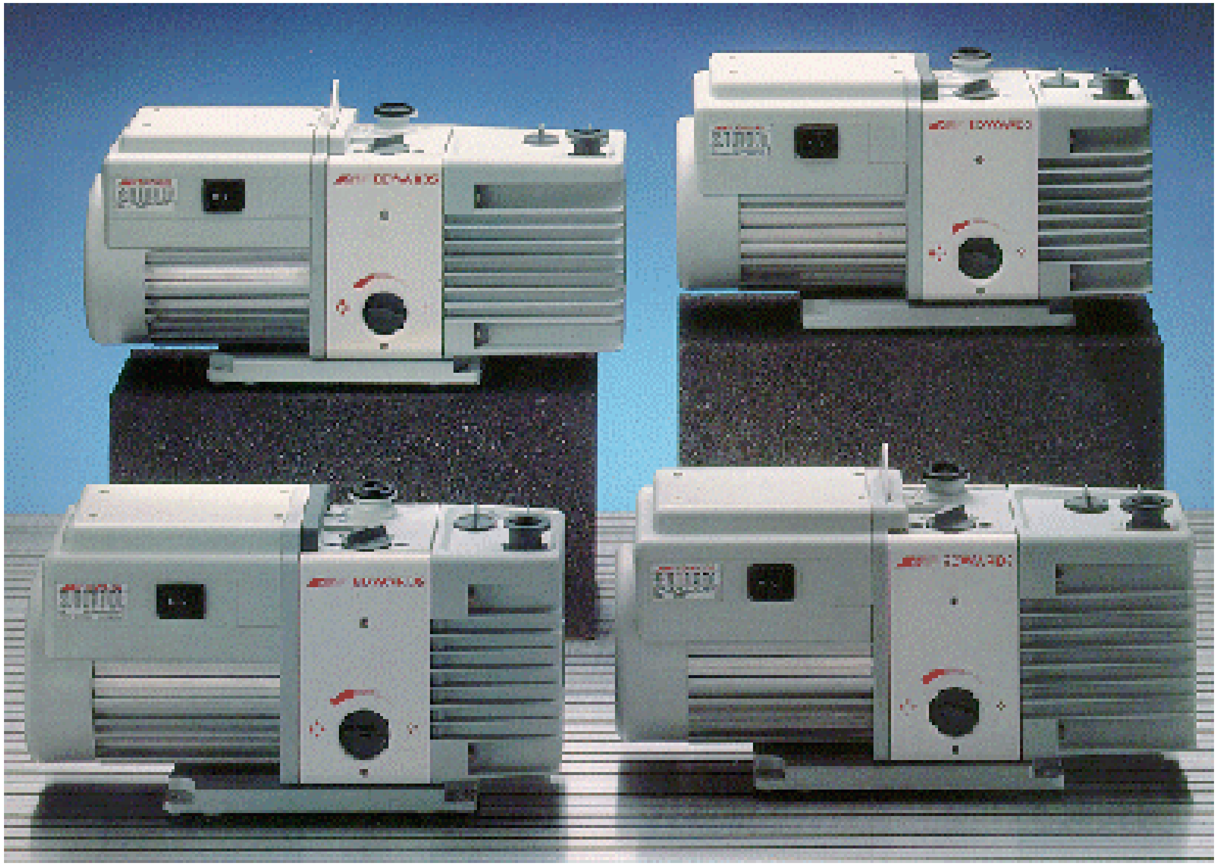
Check: acceptable cost
Pump + foreline still meet requirement

Or re-define requirements/foreline

Pump type comparison



Oil Sealed Rotary Vane Pumps

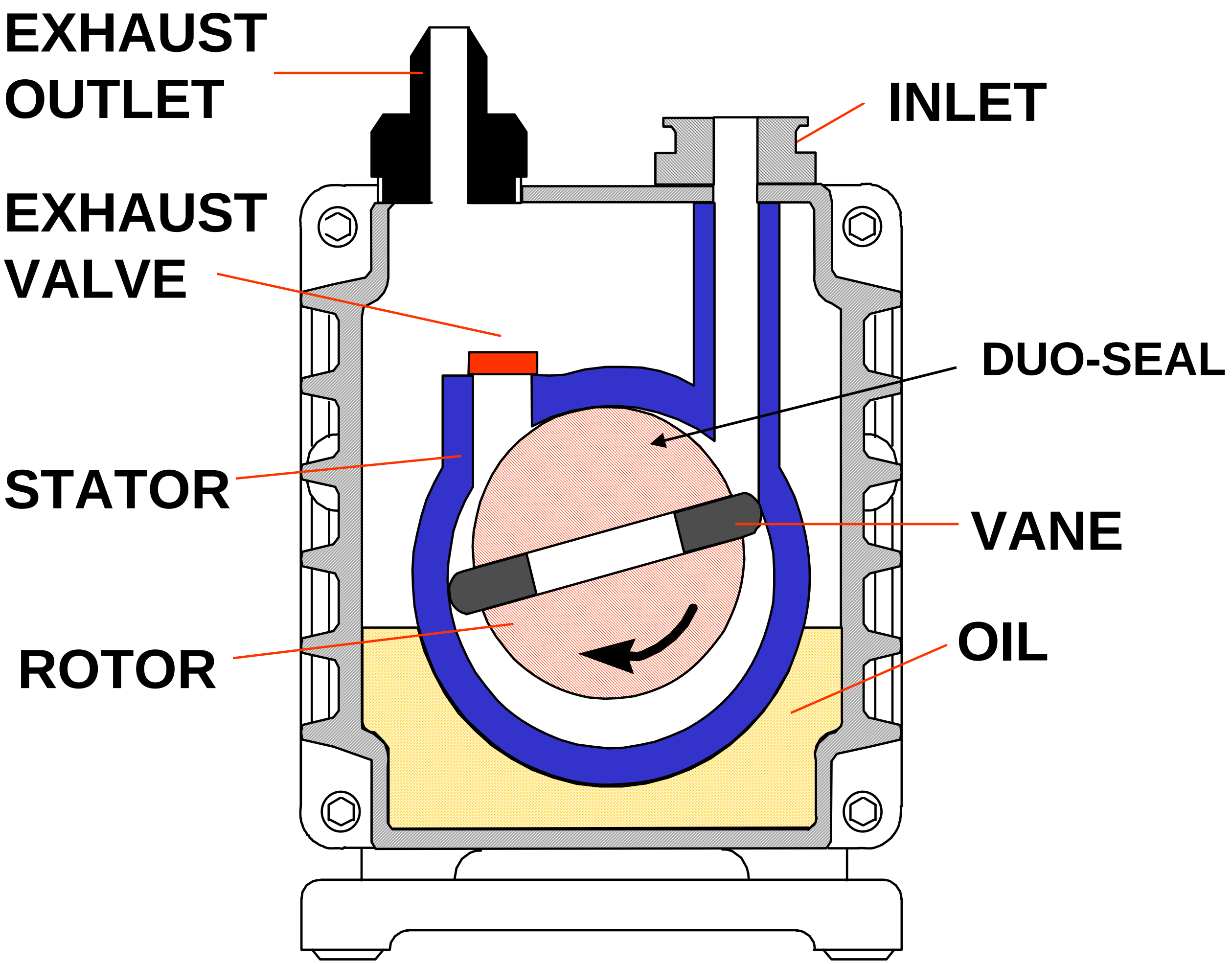


Oil Sealed Rotary Vane Pumps

- Oil sealed rotary vane pumps were first developed in the early 1900s

- Today, the two commonly used oil sealed pumps are rotary vane and rotary piston pumps
  - Oil sealed rotary vane often used for low inlet pressures and light gas loads
  - Oil sealed rotary piston pumps are often large and are most often found in high gas load, high inlet pressure industrial applications

Basic OSRV Schematic



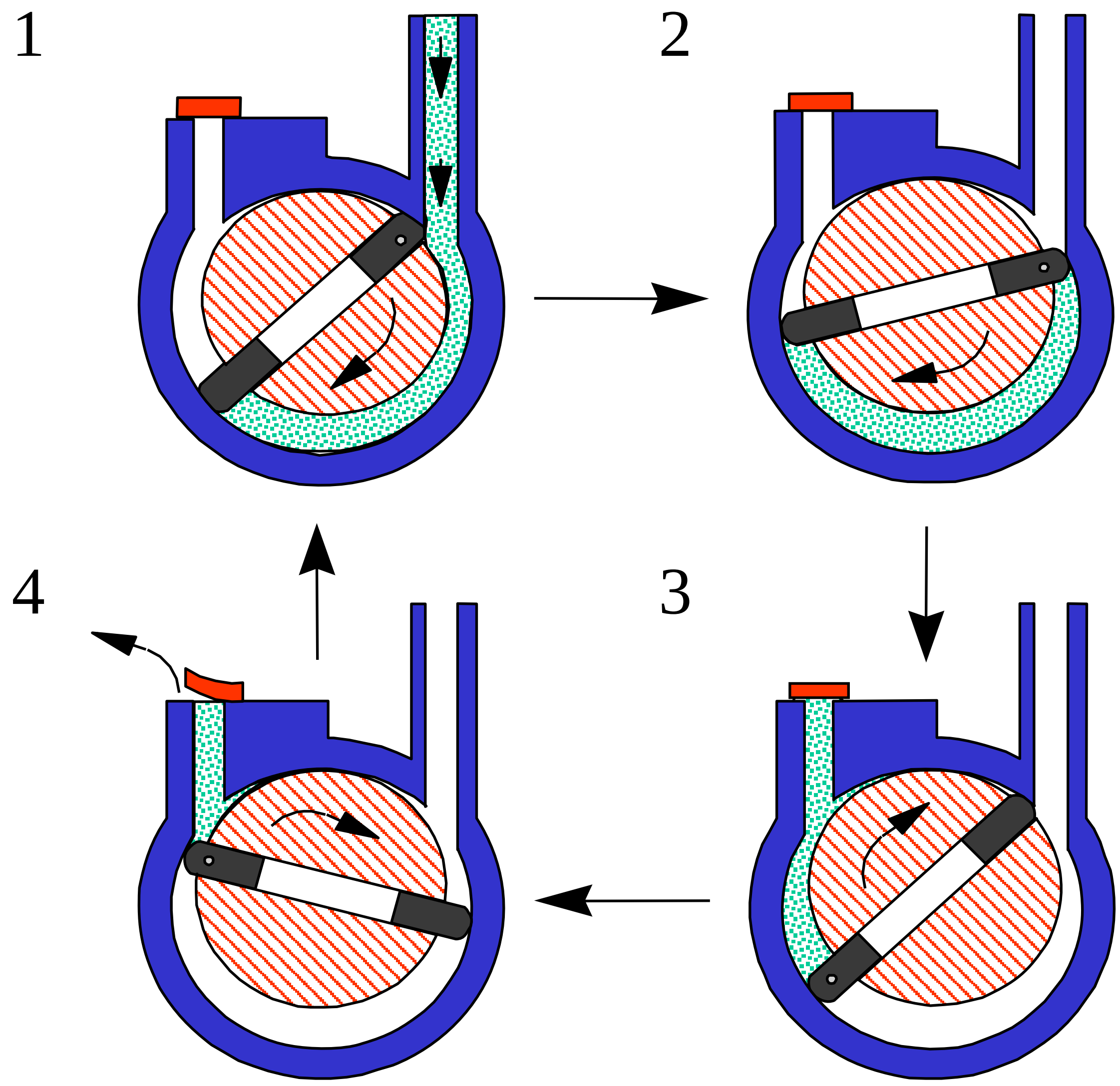
The Pumping Cycle

1 Inlet exposed

2 Trapped volume

3 Compression

4 Exhaust



Rotary vane animation.swf

Functions of Oil

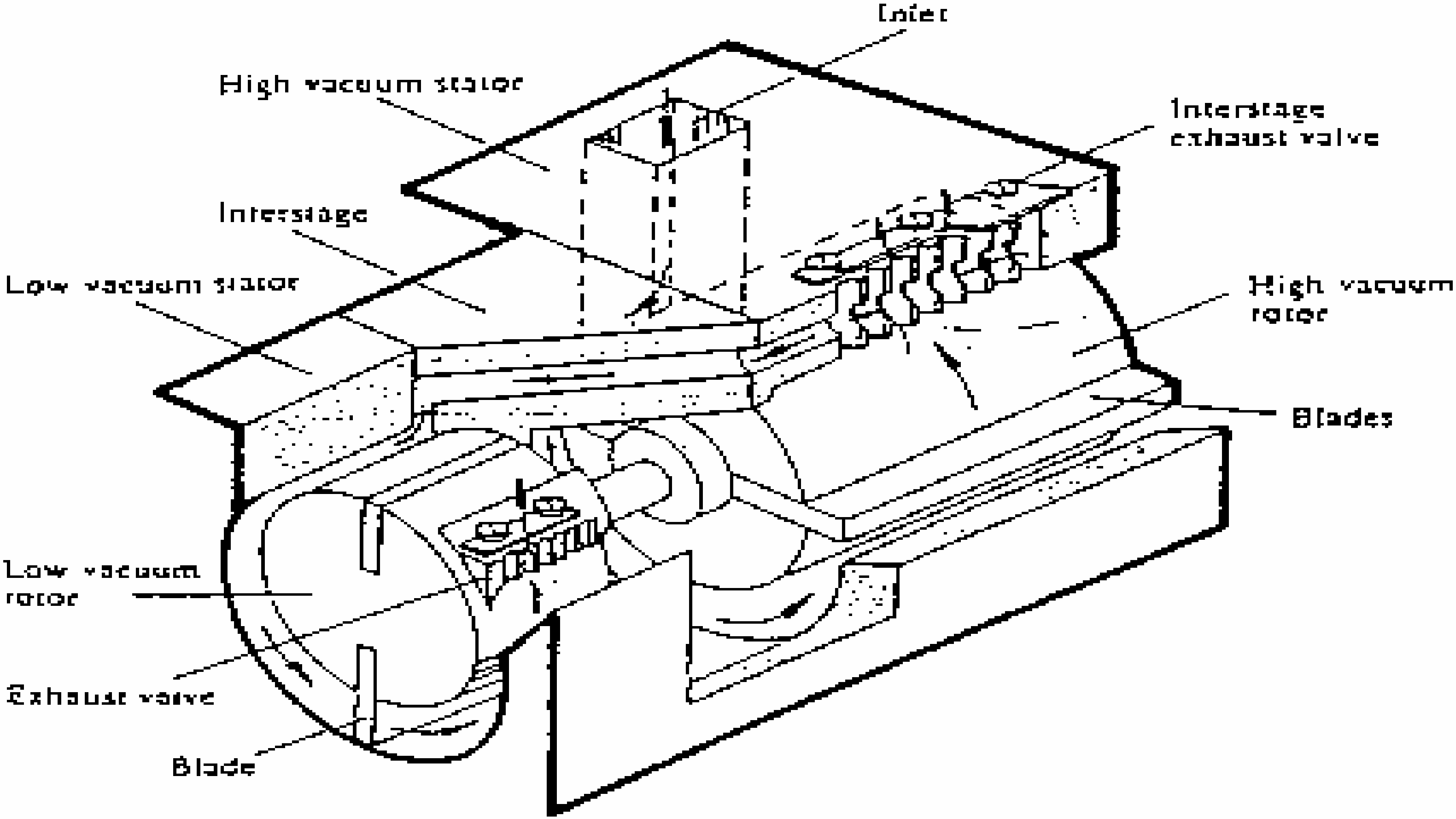
- Seals
  - Oil surface tension seals the duo-seal
  - Fills gaps between the vanes, rotors & stators
- Lubricates
  - Bearing areas and blade contact surfaces
- Cools
  - Moves heat from rotors & stators to the oil box
- Protects parts from rust and corrosion
  - Coats surfaces to protect from aggressive gas

Single versus Dual Stage Pumps

- A single stage pump has one rotor and one set of vanes (approx. 10^{-2} mbar)
  - Lower cost where strong ultimate vacuum is not required
  - Used for higher inlet pressures or high gas loads due to lower compression

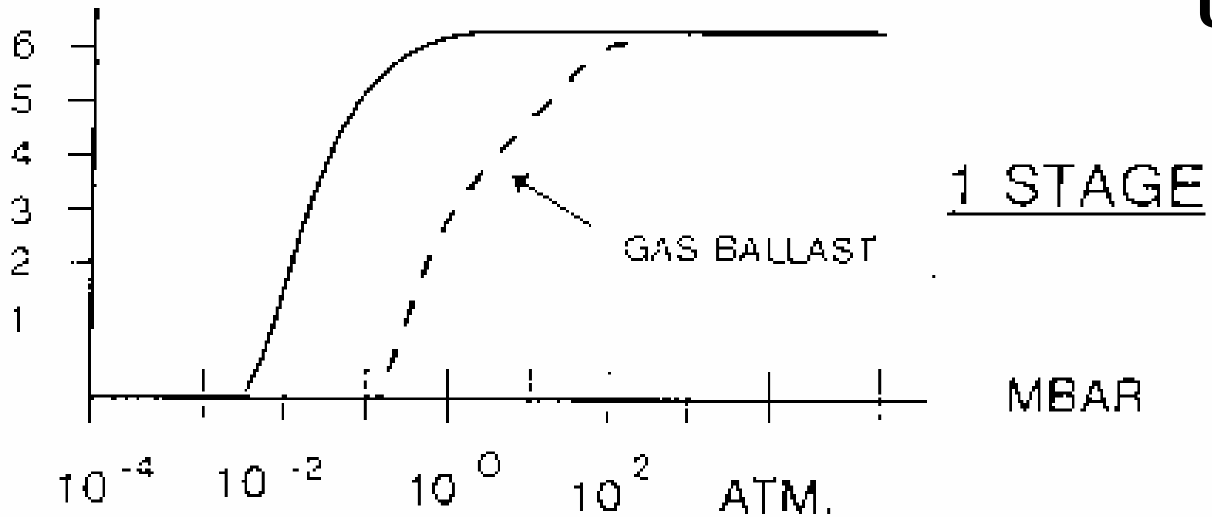
- A dual stage pump is simply two single stage pumps in series (approx. 10^{-3} mbar)
  - Higher compression ratio gives better ultimate vacuum

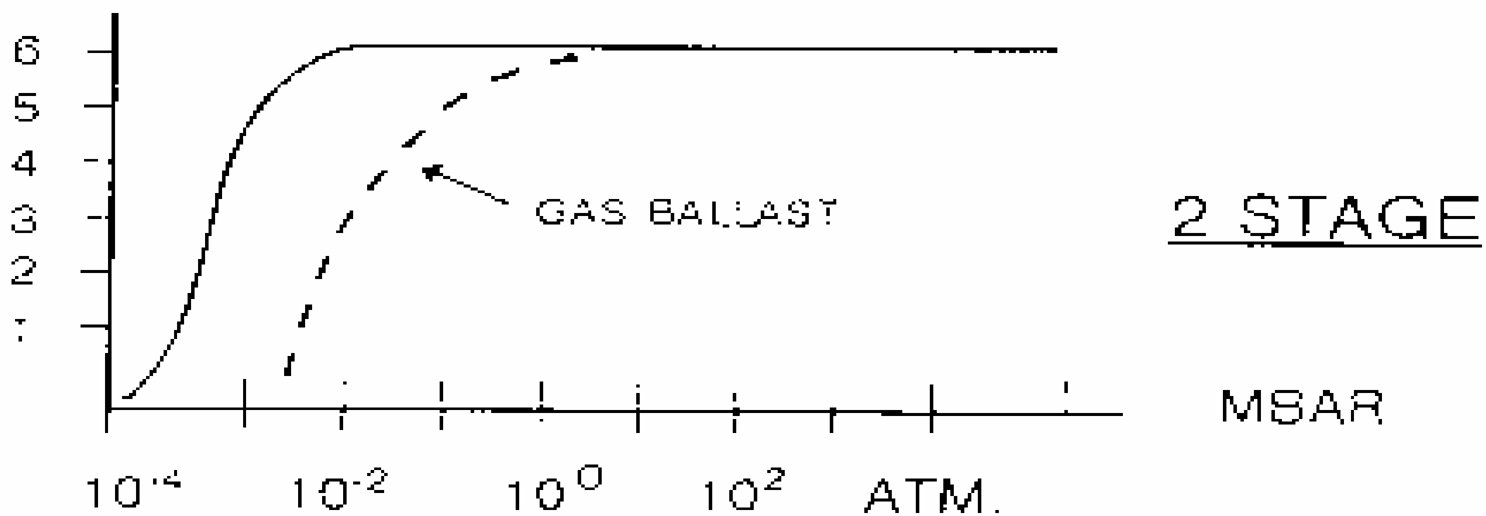
Dual Stage Pump Cutaway



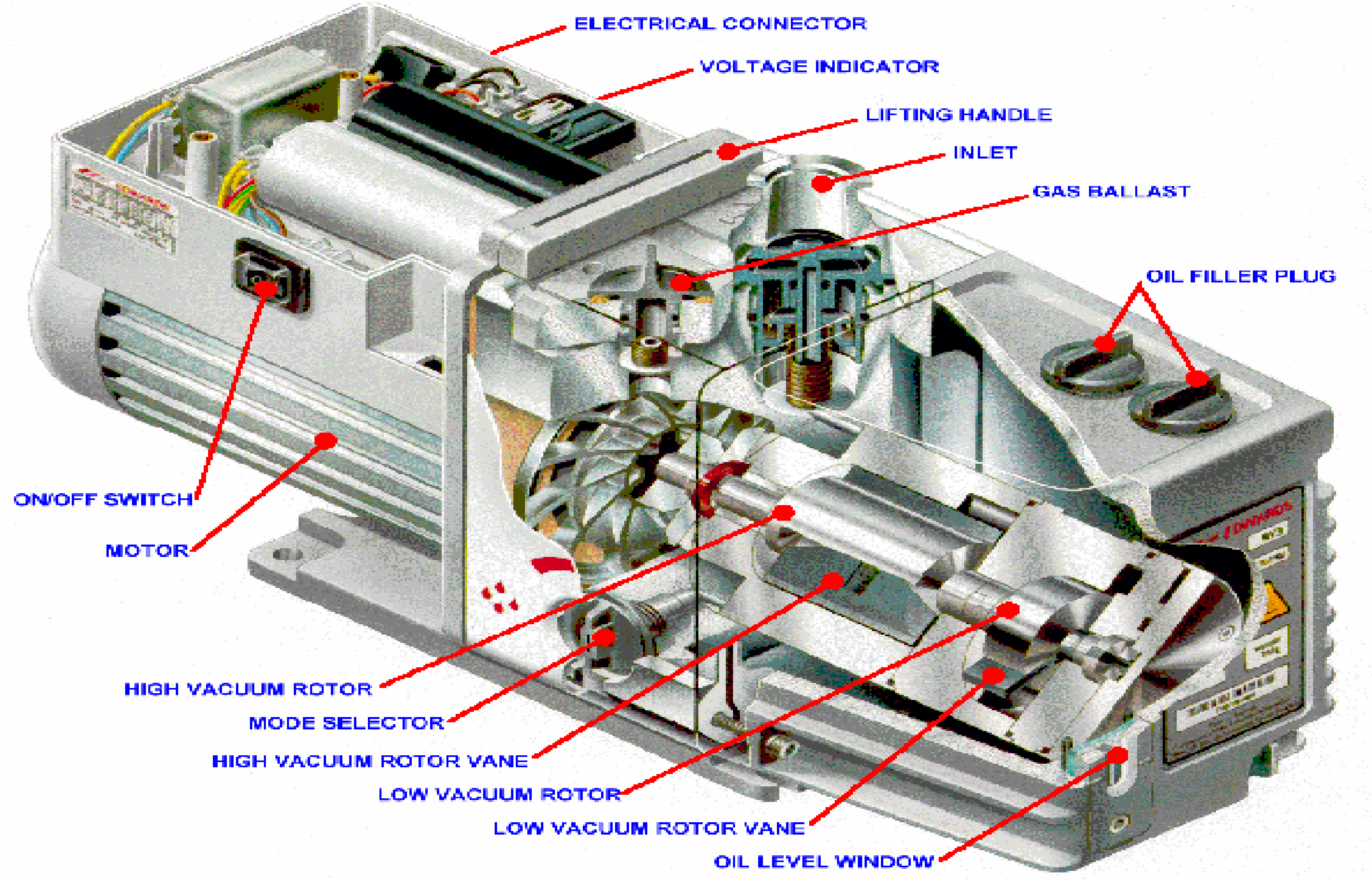
Rotary Pump Speed Curves

Units => cfm, l/m, m^3/hr

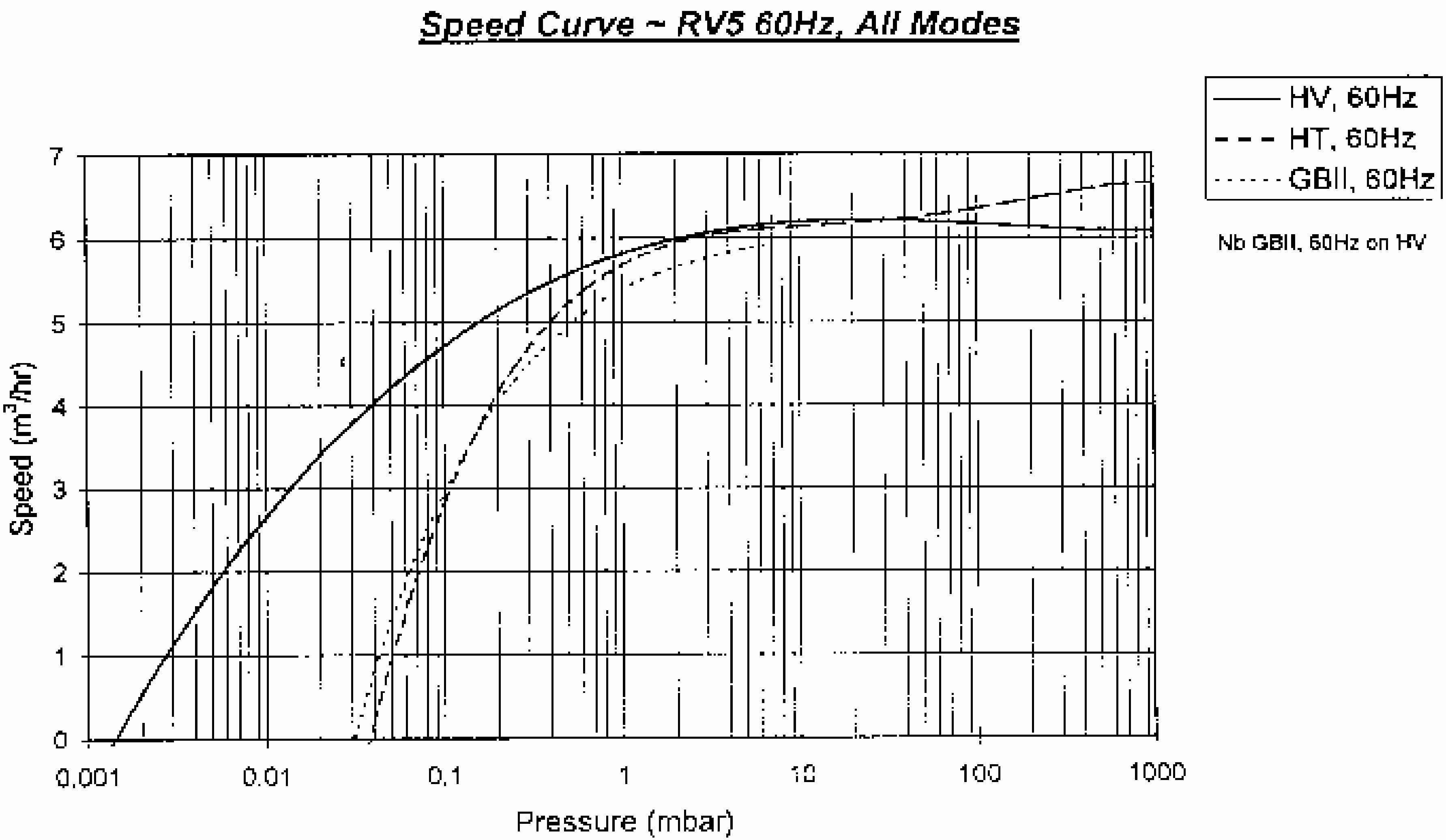




OSRV Pump Cutaway View



OSRV 2 stage 5 m^3/h Speed Curves

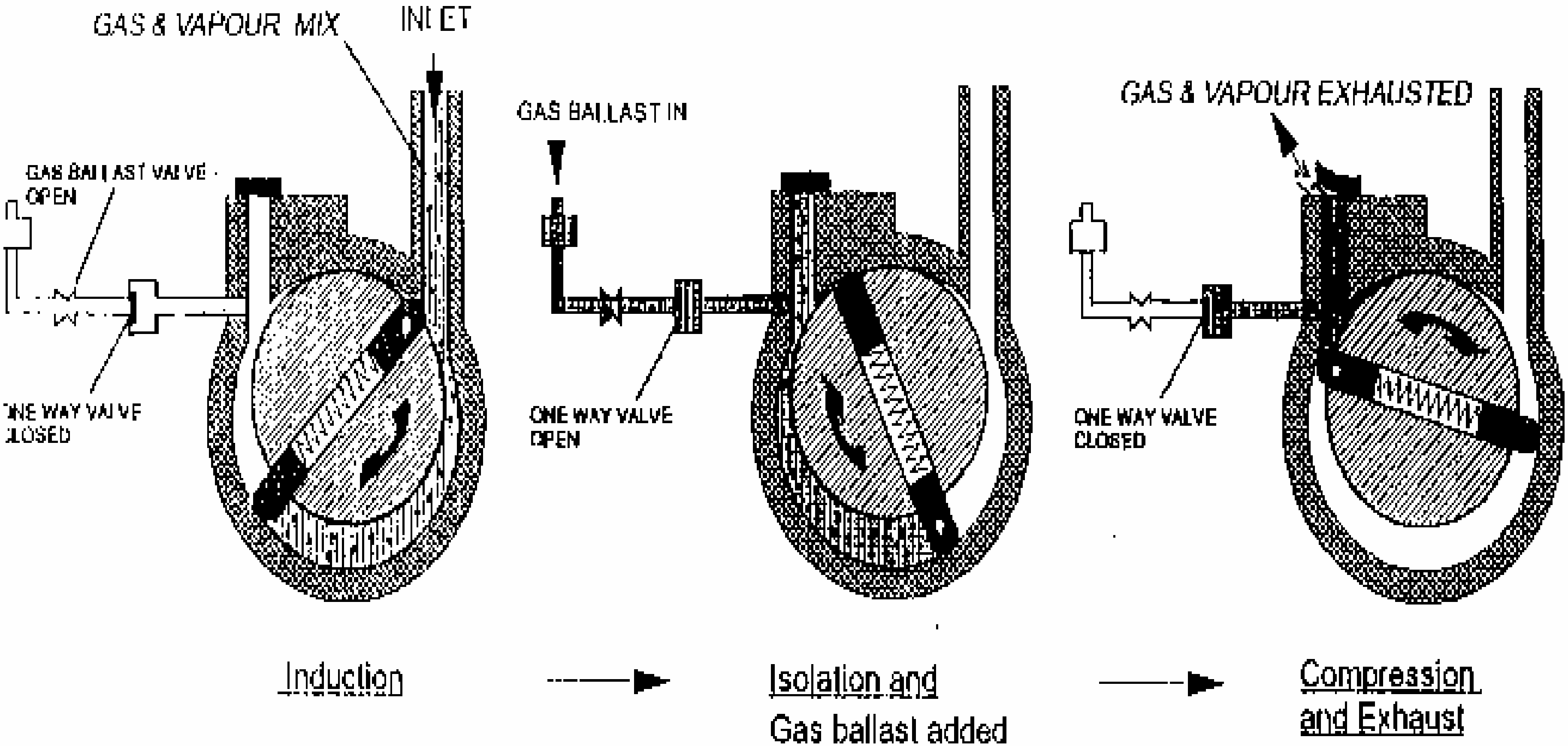


Rotary Pump Gas Loads

- Pumped gas may contain both permanent gases and vapors
  - Vapors can condense when compressed
  - Condensed vapors may include liquid H_2O and solvents which can mix with pump oil to form an emulsion

- Condensed vapors can reduce the ultimate vacuum, cause corrosion, and possibly lead to pump seizure

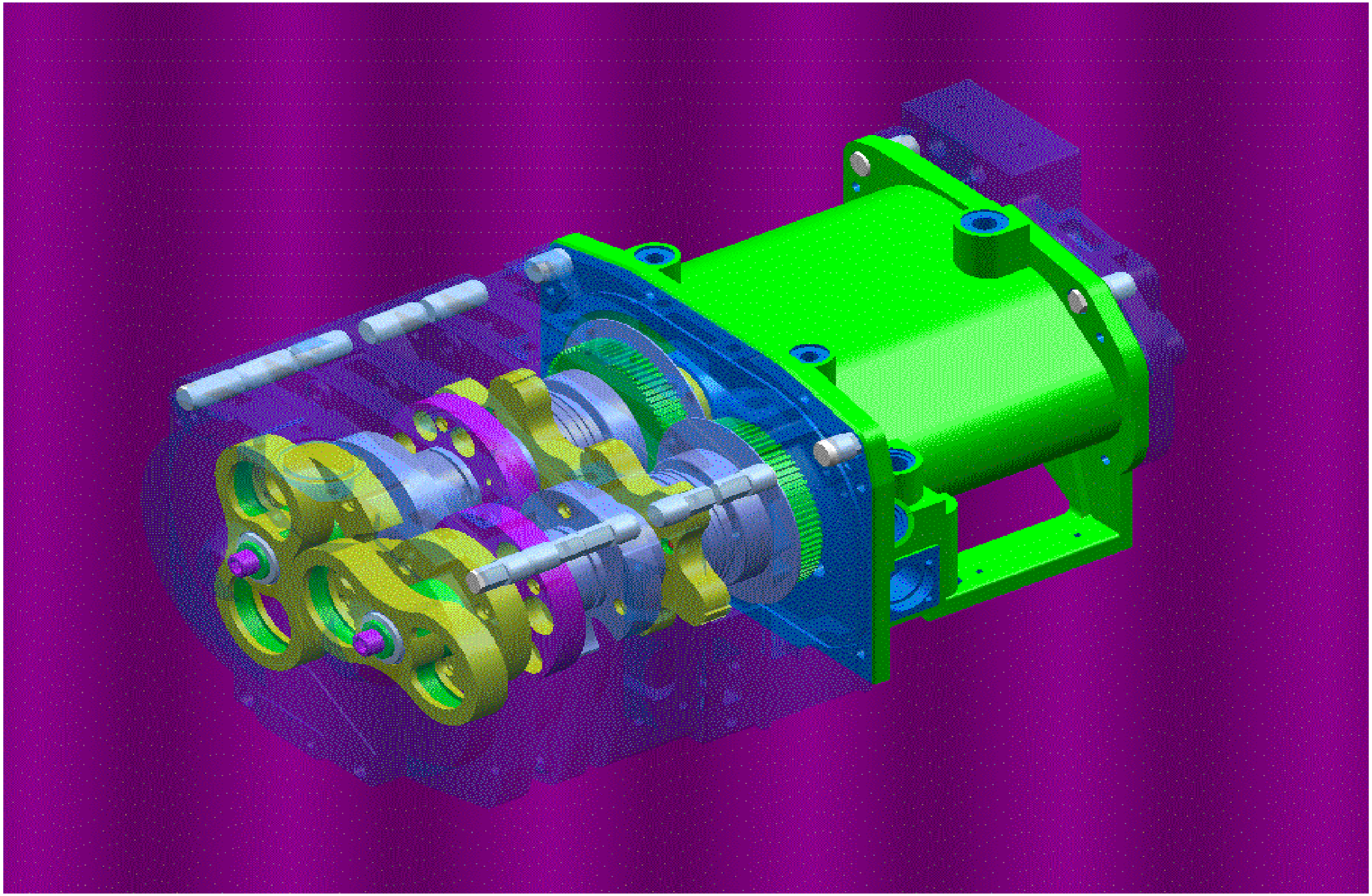
Gas Ballast – allows vapour pumping without condensation



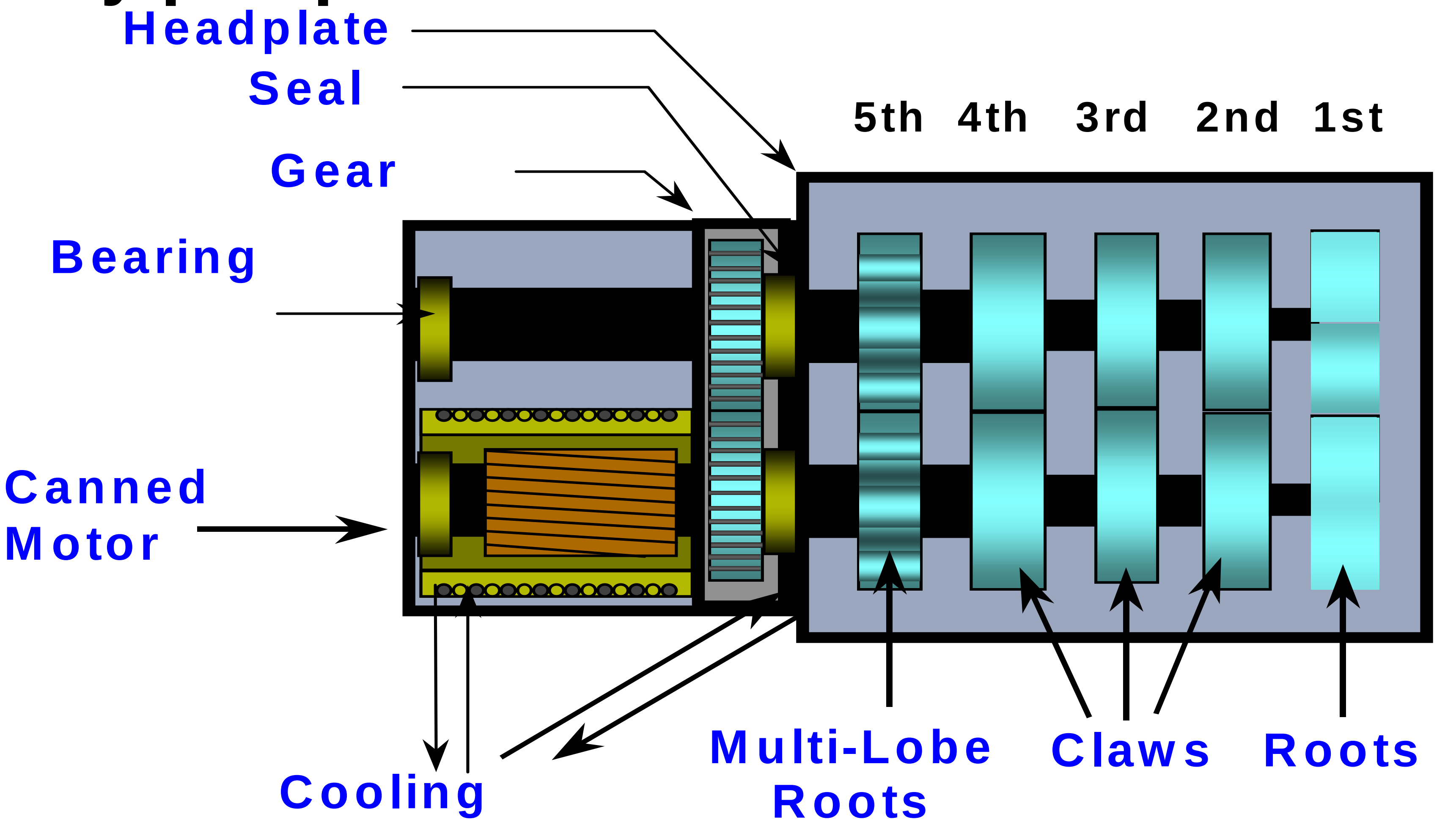
With gas ballast, no condensation of vapours occurs during compression

Ballast gas opens exhaust before compression pressure allows vapours to condense

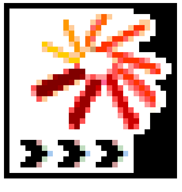
Dry Pumps – Clearance mechanisms
Ult. 0.001 mbar



Dry pump Ult. 0.001 mbar

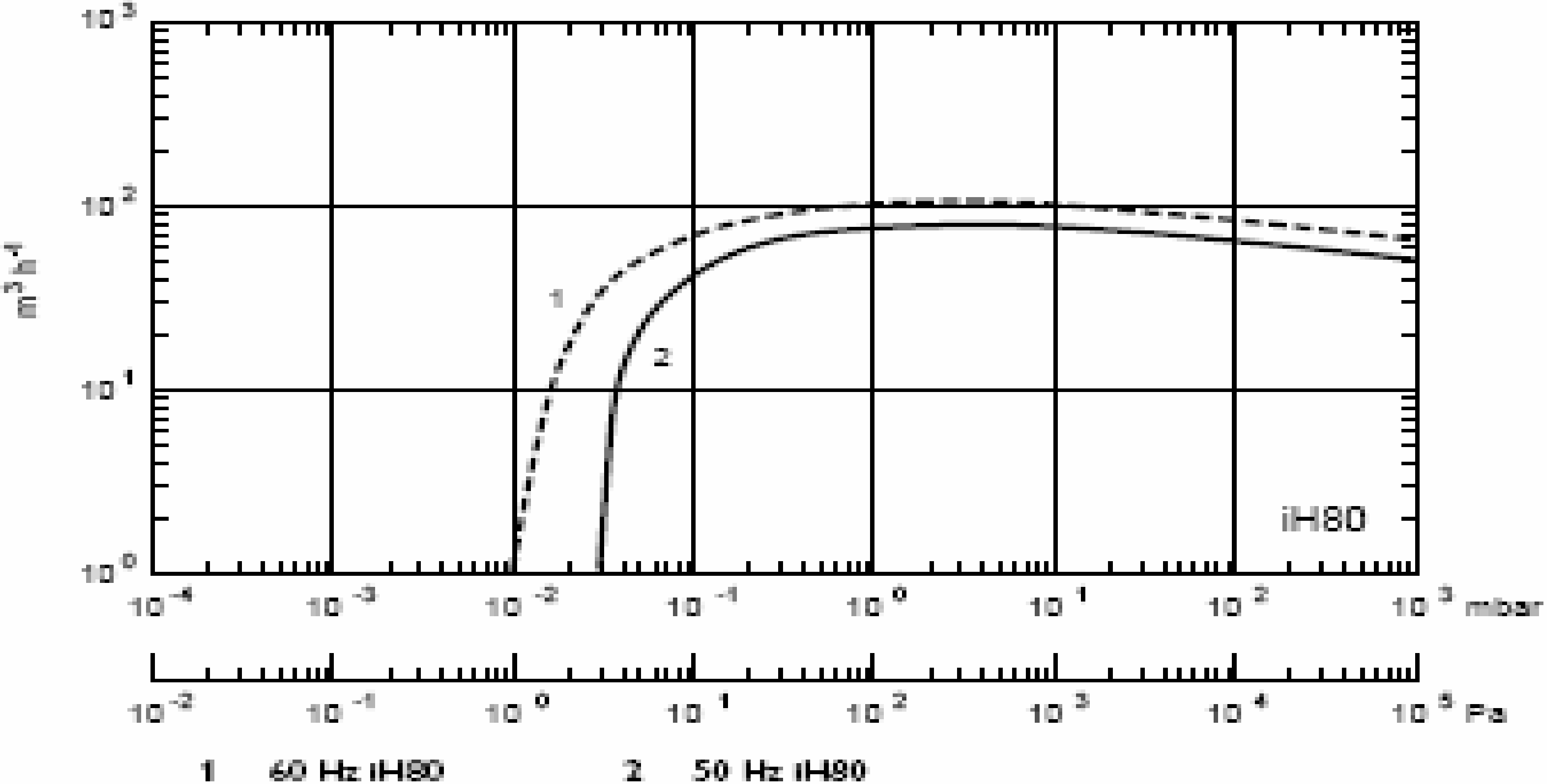


Clearance mechanism



Claw pump.swf

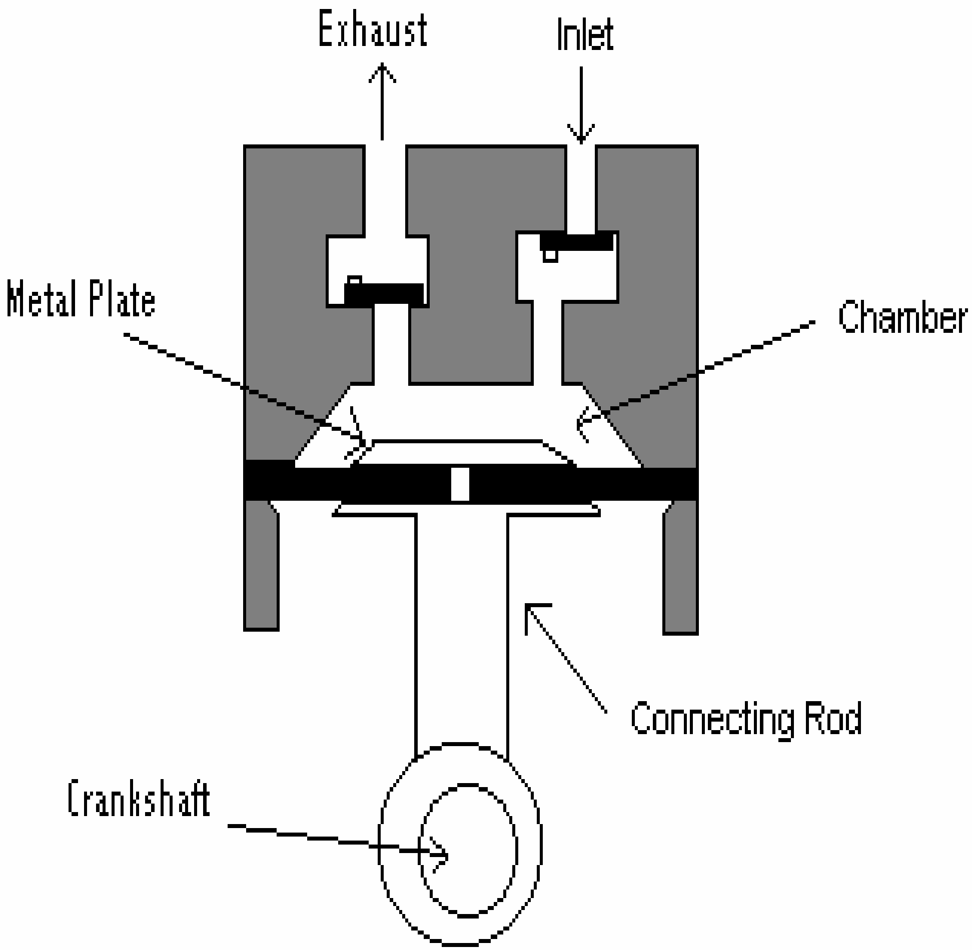
Dry pump speed curve



Clearance mechanism

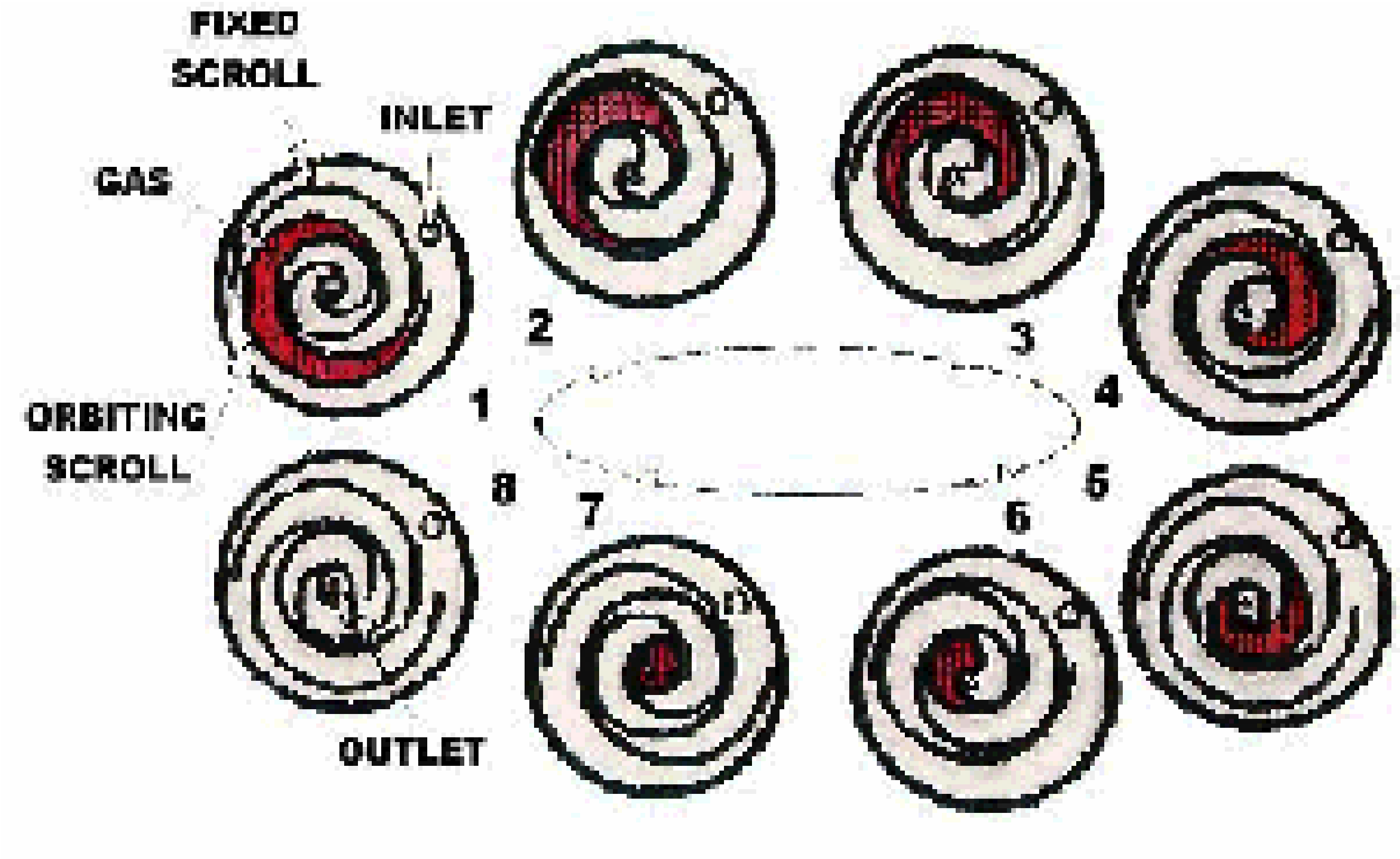
BOC Edwards iH80

Diaphragm Pumps ult. 0.1 mbar

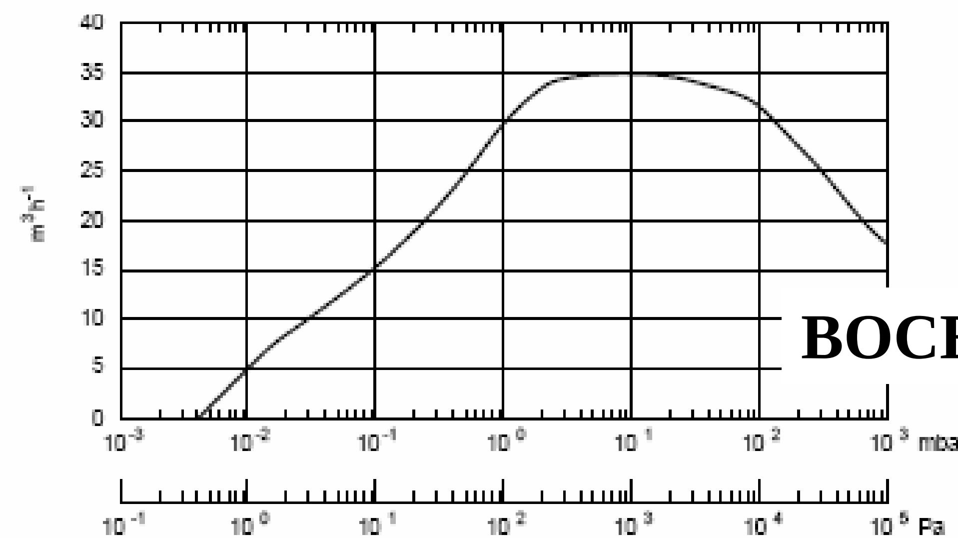


Crankshaft rotates and the connecting rod pulls diaphragm down, creating a vacuum in the chamber. This opens the inlet valve and closes the exhaust valve. The chamber fills with gas. As the crankshaft continues to rotate, the connecting rod forces the diaphragm to the top of the chamber. This compresses the gas, opens the outlet valve and closes the inlet valve. The valves on the inlet and outlet to the chamber are flapper types, which are operated by pressure.

Scroll pumps ult. 0.01 mbar

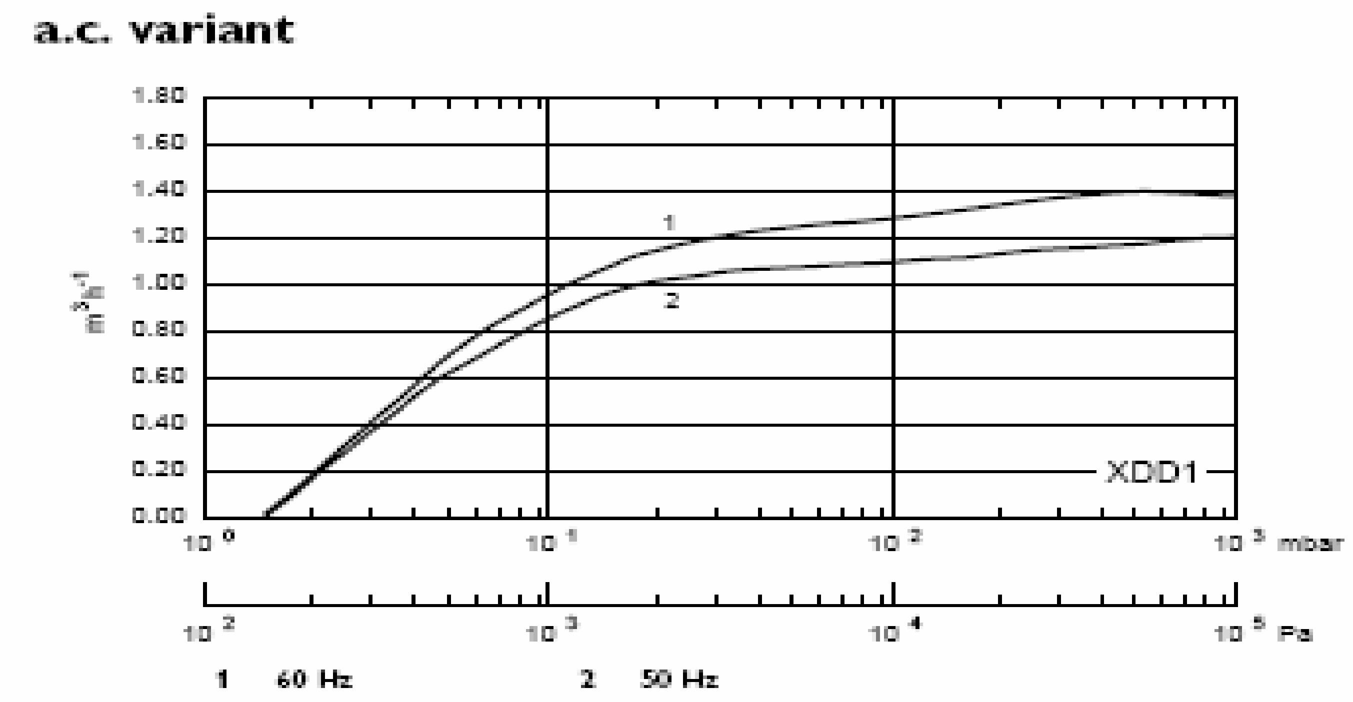


Scroll pumps ult. 0.01 mbar



BOCE XDS35i

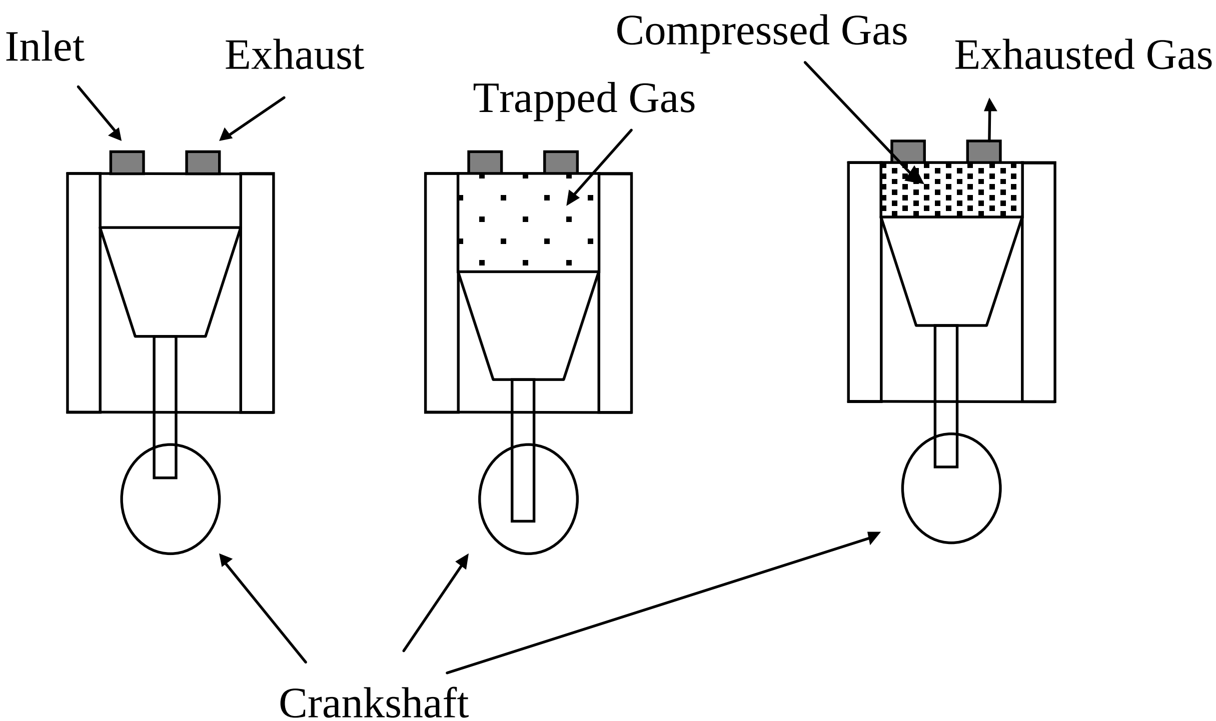
Diaphragm Pumps ult. 0.1 mbar



Vacuubrand MD series

Dry piston

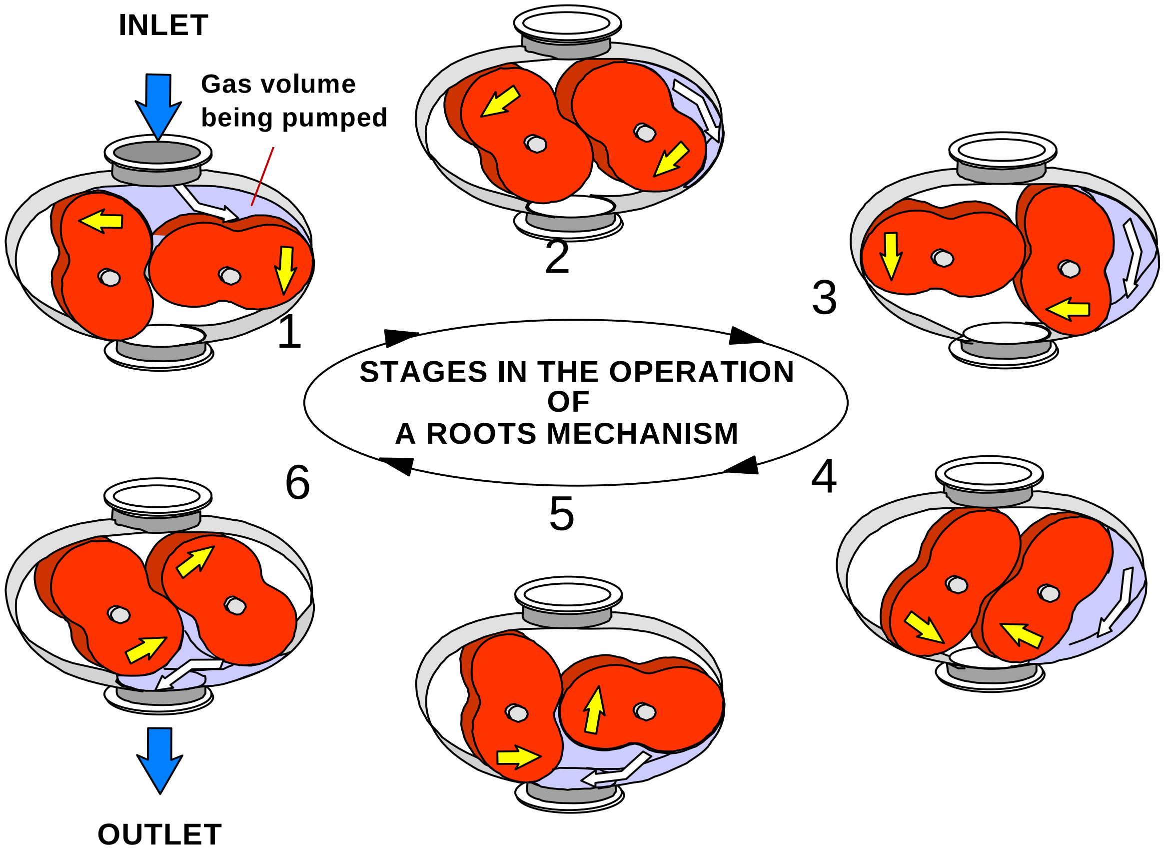
Dry Piston Pump Mechanism

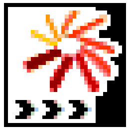


As the crankshaft rotates, it moves the piston vertically through the cylinder, which traps, compresses, and exhausts the gas from the pump.

A coating around the outside of the piston creates the seal between the piston and the cylinder wall.

Roots/Booster
Ult. < 0.0001 mbar




Dry pump.swf

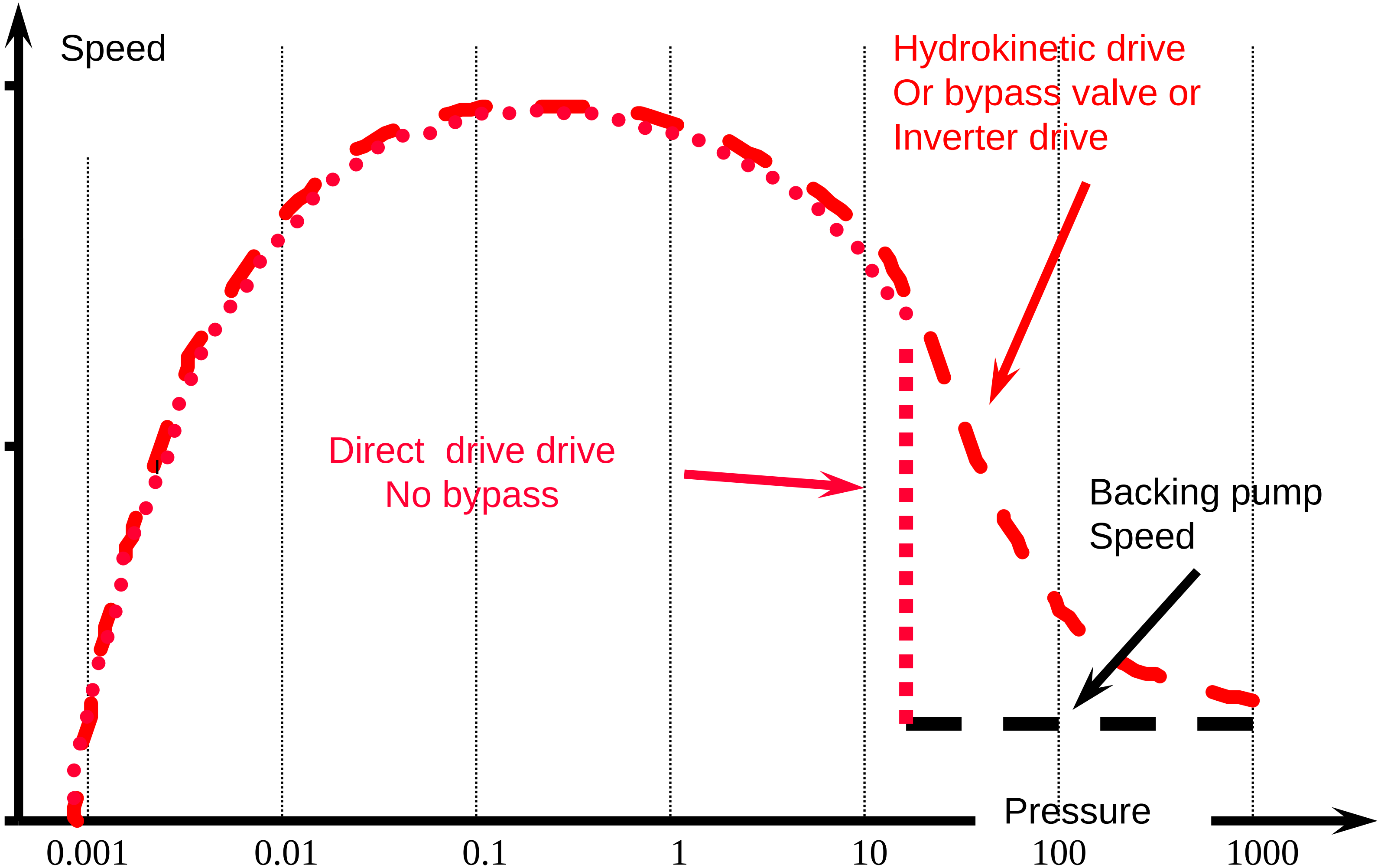
The lobed (2 or 3) rotors trap a volume of air against the stator body and sweep it around, exhausting the air 180° from the inlet.

Tight clearances between the rotors and the stator are critical to trap and moved through the pump body.

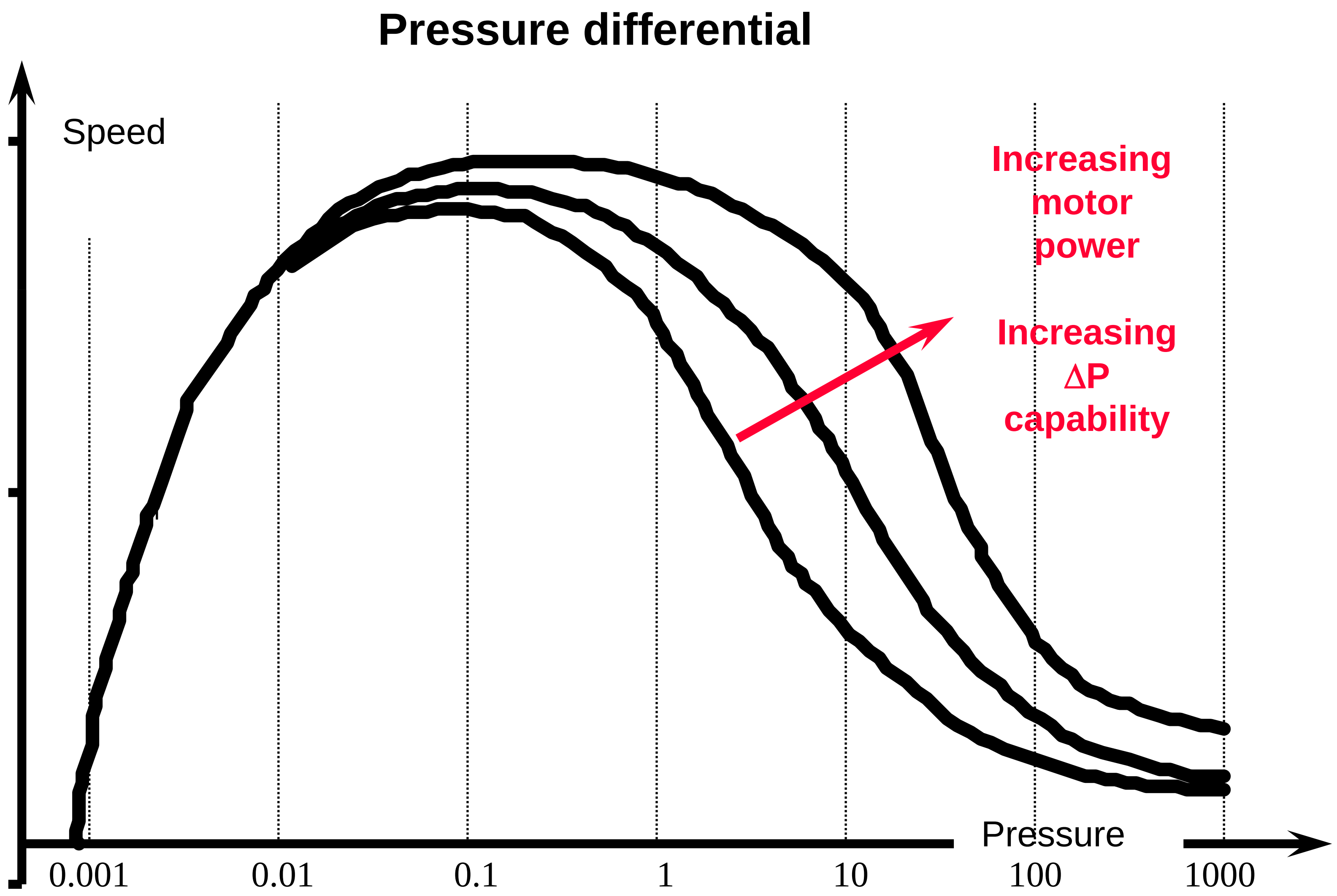
Booster ΔP (outlet/inlet) limitations

- Normally booster displacement is > backing pump speed therefore large ΔP's are generated at high inlet pressure.
- Unless the ΔP is limited, power demand increases rapidly
- Limiting methods include hydrokinetic drive, inverter motor control, pressure relief valves (outlet to inlet)

Mechanical boosters



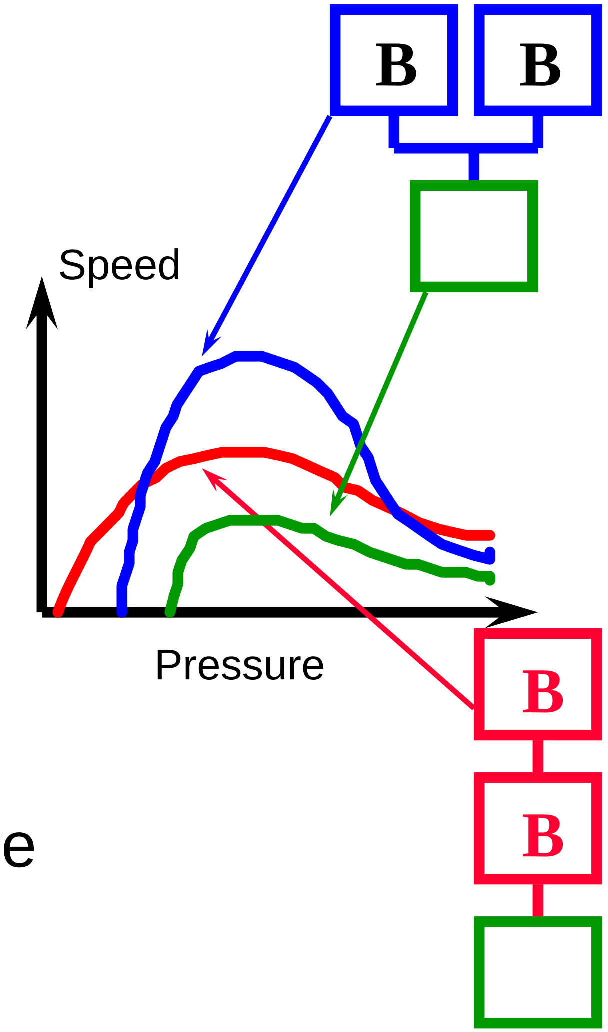
Mechanical boosters



Series/parallel boosters

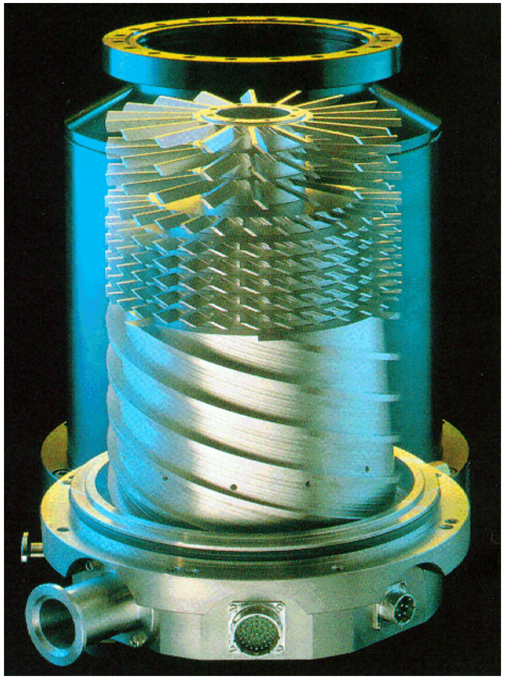
To achieve speed, ultimate or pump-down requirements, more than one booster may be used.

- In parallel
  - limited to approx one decade improvement in ultimate
  - modest improvement in pumping speed at high pressure
  - high pumping speed at low pressure
- In series
  - lower ultimate - limited by outgassing
  - higher pumping speed at high pressure
  - limits pumping speed at lower pressures



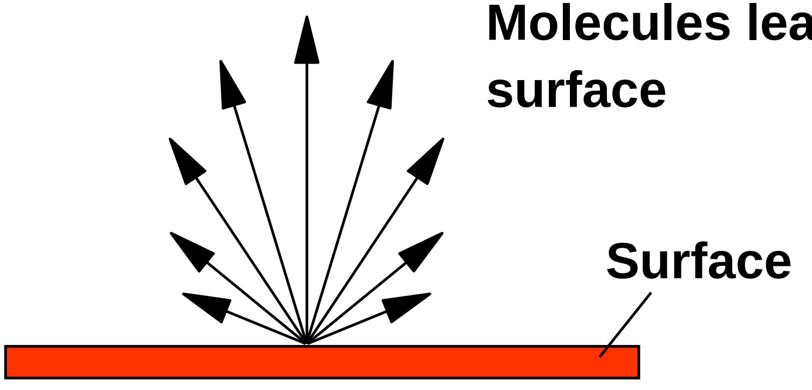
Turbomolecular pumps

Full bladed



Compound turbo/drag

Principle of Operation

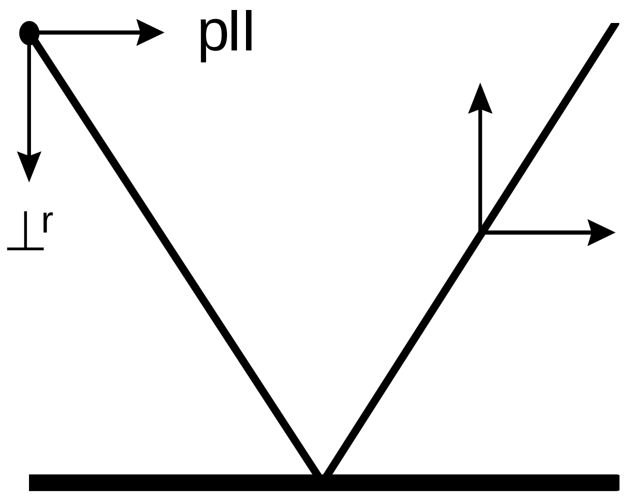


1. The direction of the arrow indicates the direction of travel of the molecule.

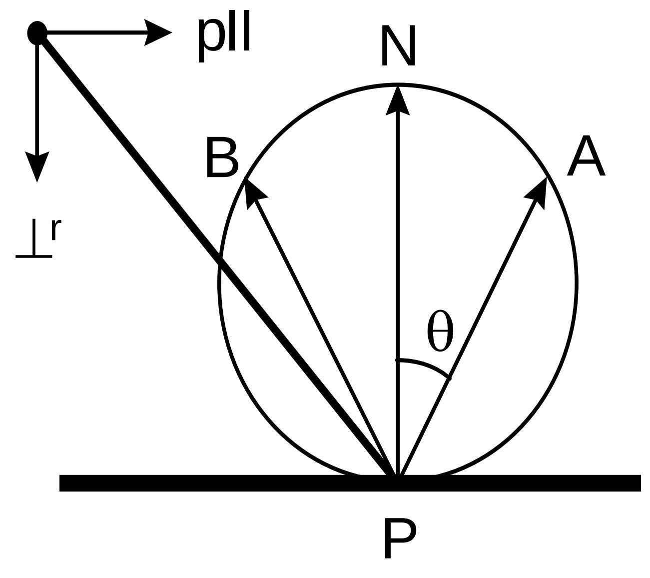
2. The length of the arrow indicates the 'probability' that the molecule will depart in that direction - Knudsen

Molecular collisions with surfaces

Consider (a) text book collision and (b) reality



(a)

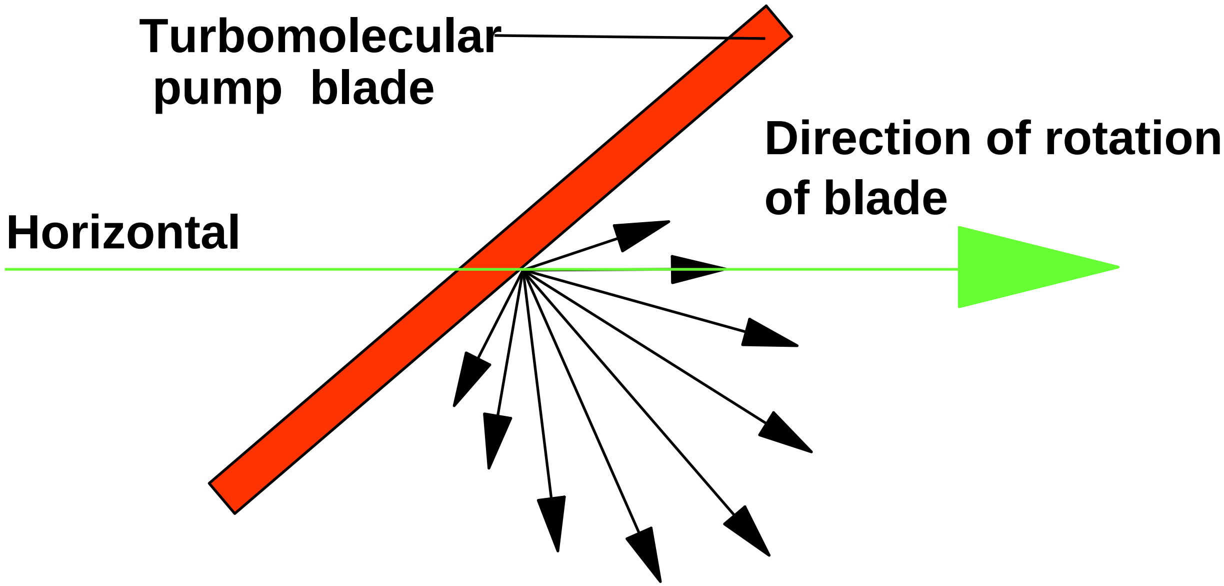


(b)

High rotational speeds (>1000Hz) tip velocity = molecular thermal velocities

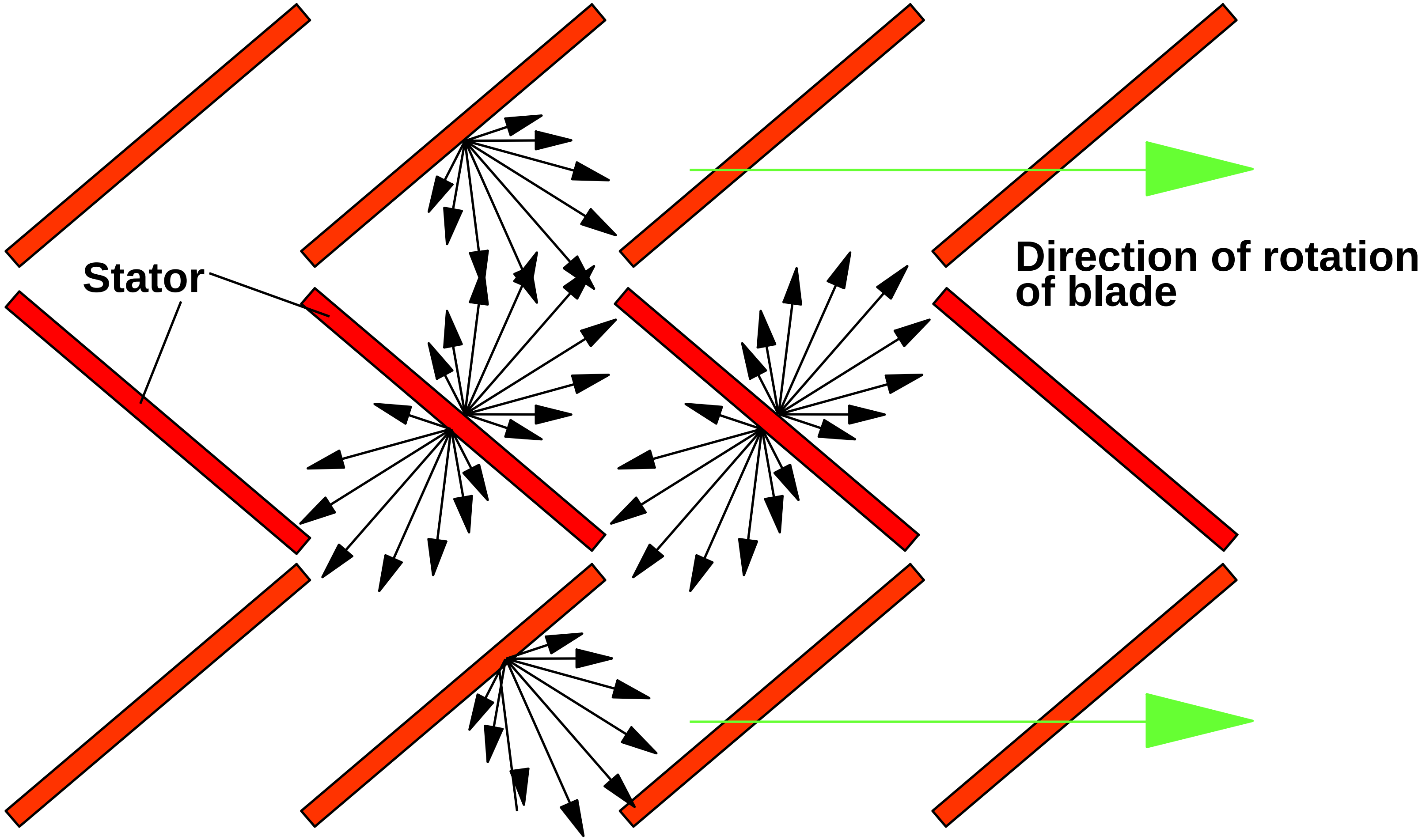
Molecules leaving a surface

Blade speed needs to be of same order as molecular velocity to influence motion



In the position shown, there is a higher probability that the molecules will leave the blade in a downward direction.

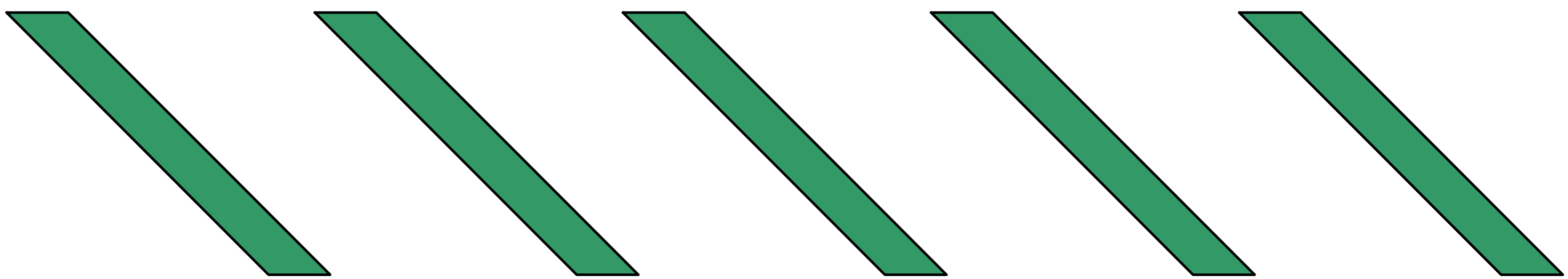
Molecules leaving Rotors/Stators



Stators help reduce sideways movement of the molecules

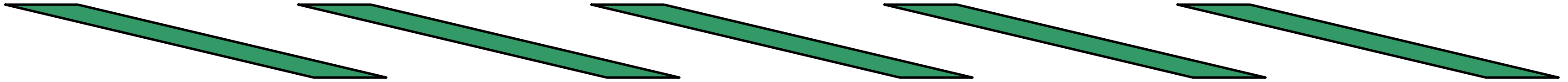
Open blade structure

- The blades at the top of the pump have an open blade structure.
- This gives a high pumping speed and low compression ratio.



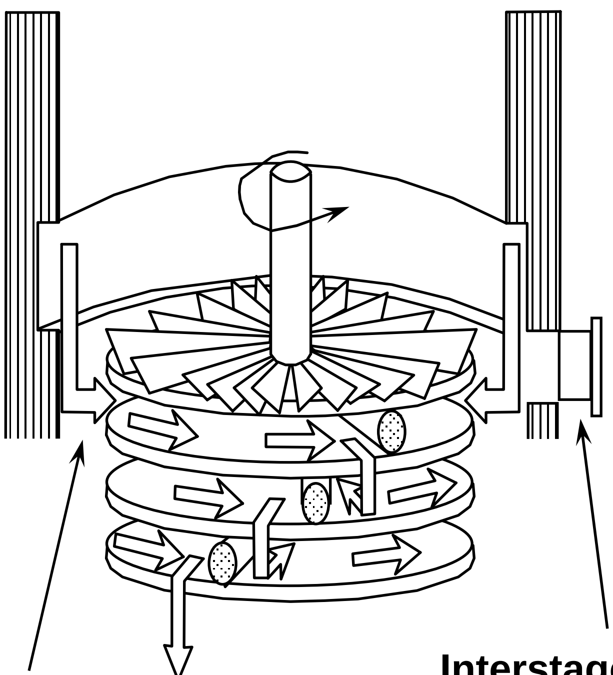
Closed blade structure

- The blades at the bottom of the pump have a closed blade structure.
- This gives a low pumping speed and high compression ratio.



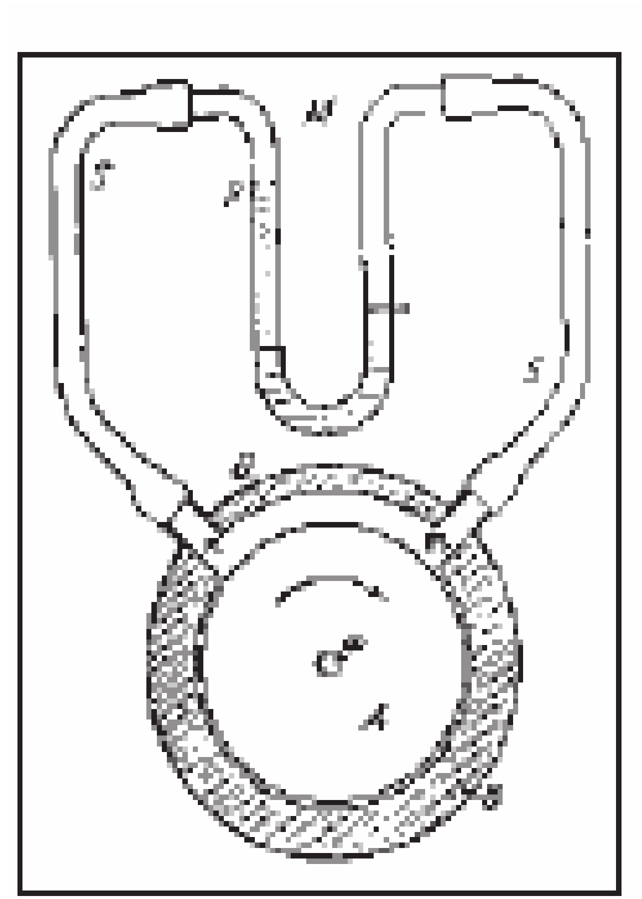
Compound pumping technologies

GAEDE



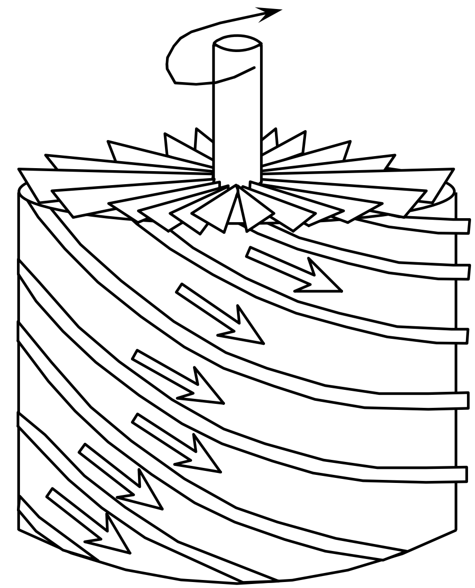
Gas flows from turbo stages into collection channel and then into the first Gaede stage

- Spinning discs
- Stationary “fingers” (supported by envelope)



Gaede 1912

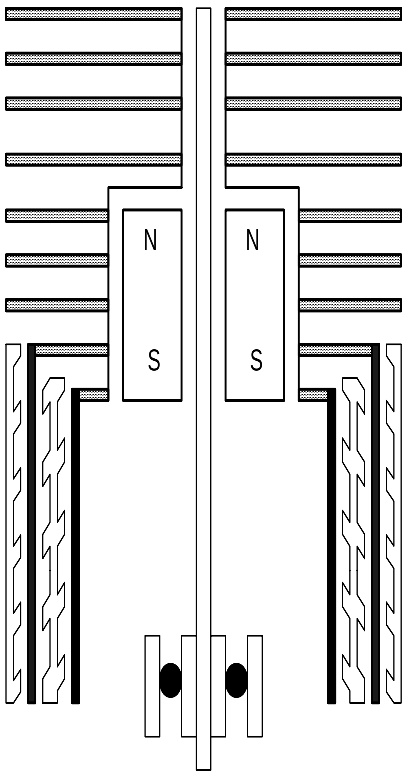
HOLWECK



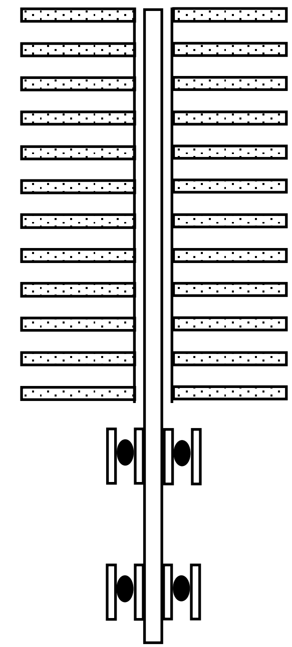
For ease of explanation mechanism is shown with spinning helix. Most pumps use spinning wall and stationary helix.

- Spinning Helix
- Stationary wall (pump envelope)

‘Conventional’ bearing mechanisms



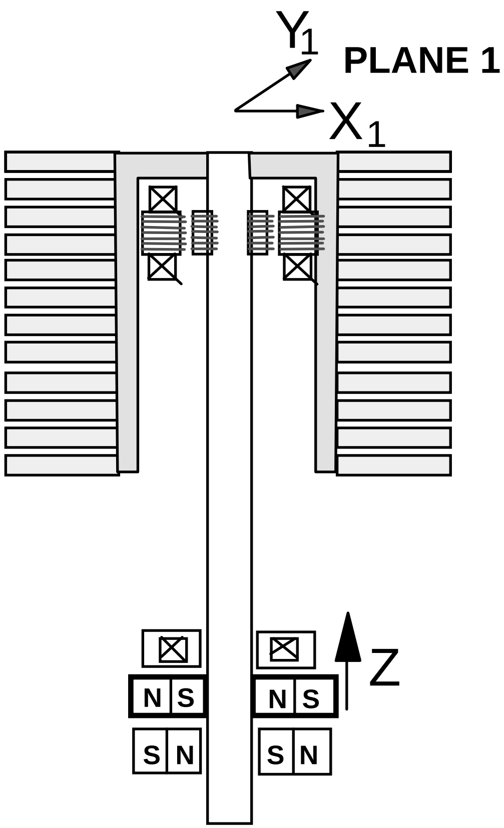
Ceramic/permanent magnet



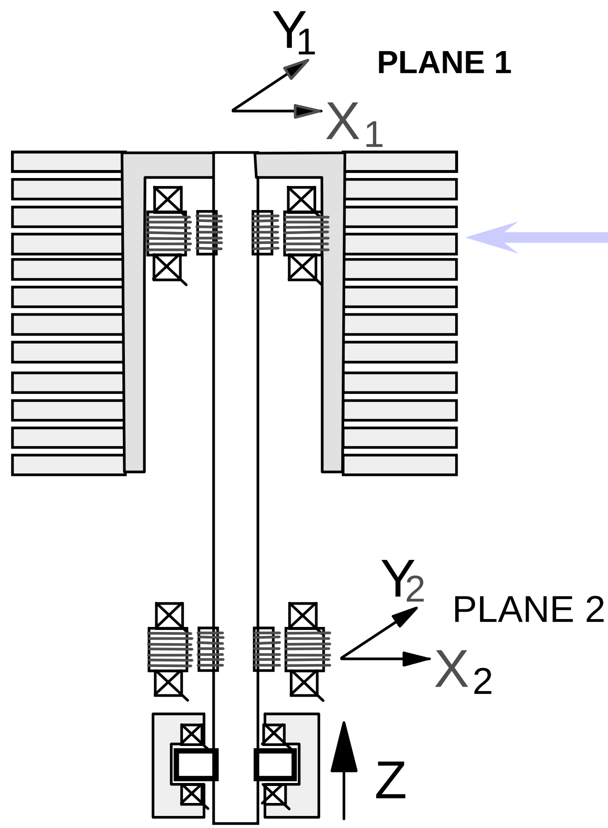
Grease

Magnetic bearings

3 active axis



5 active axis

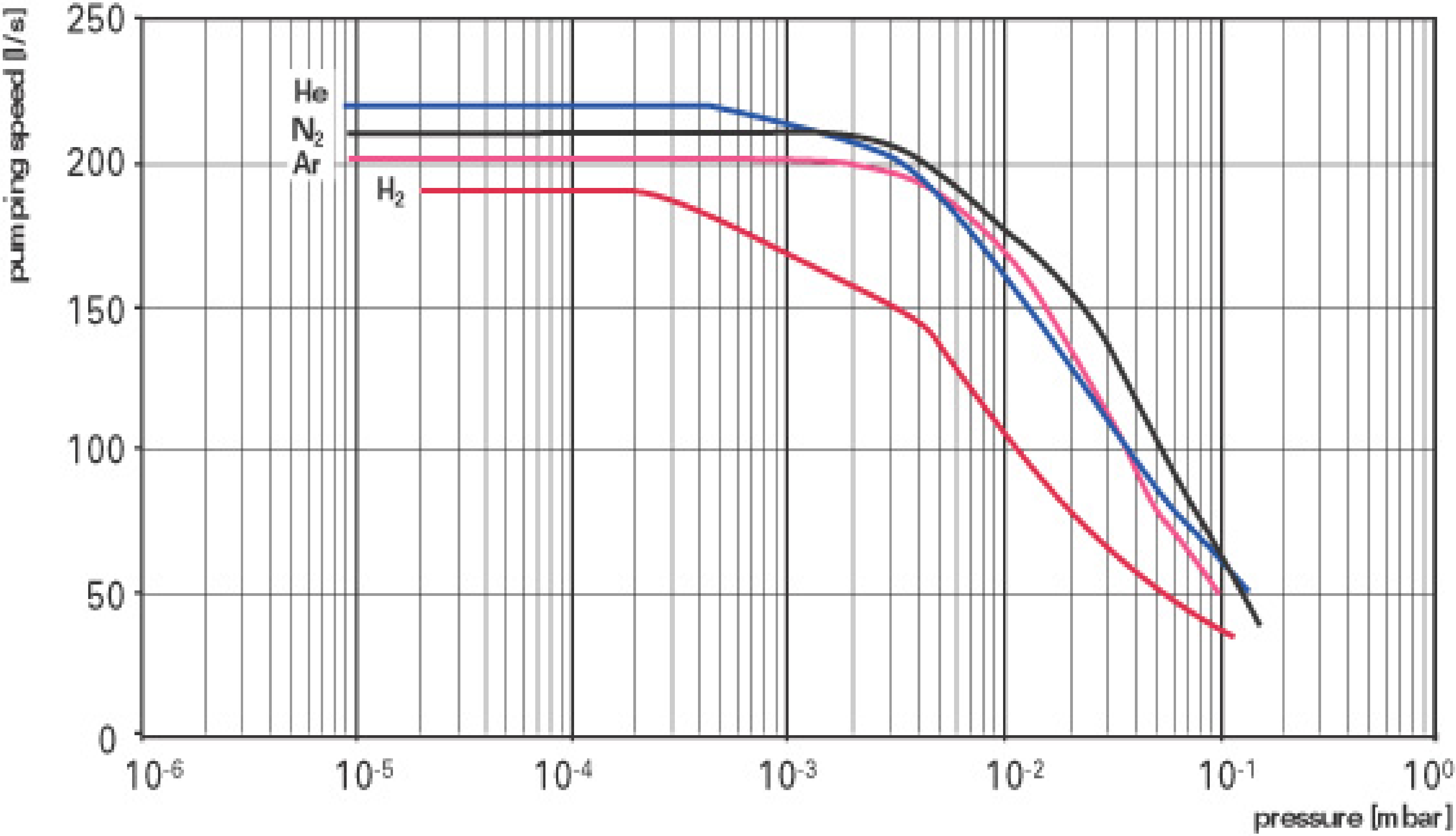


Cross section
of 5 – axis STP

Magnetic levitation

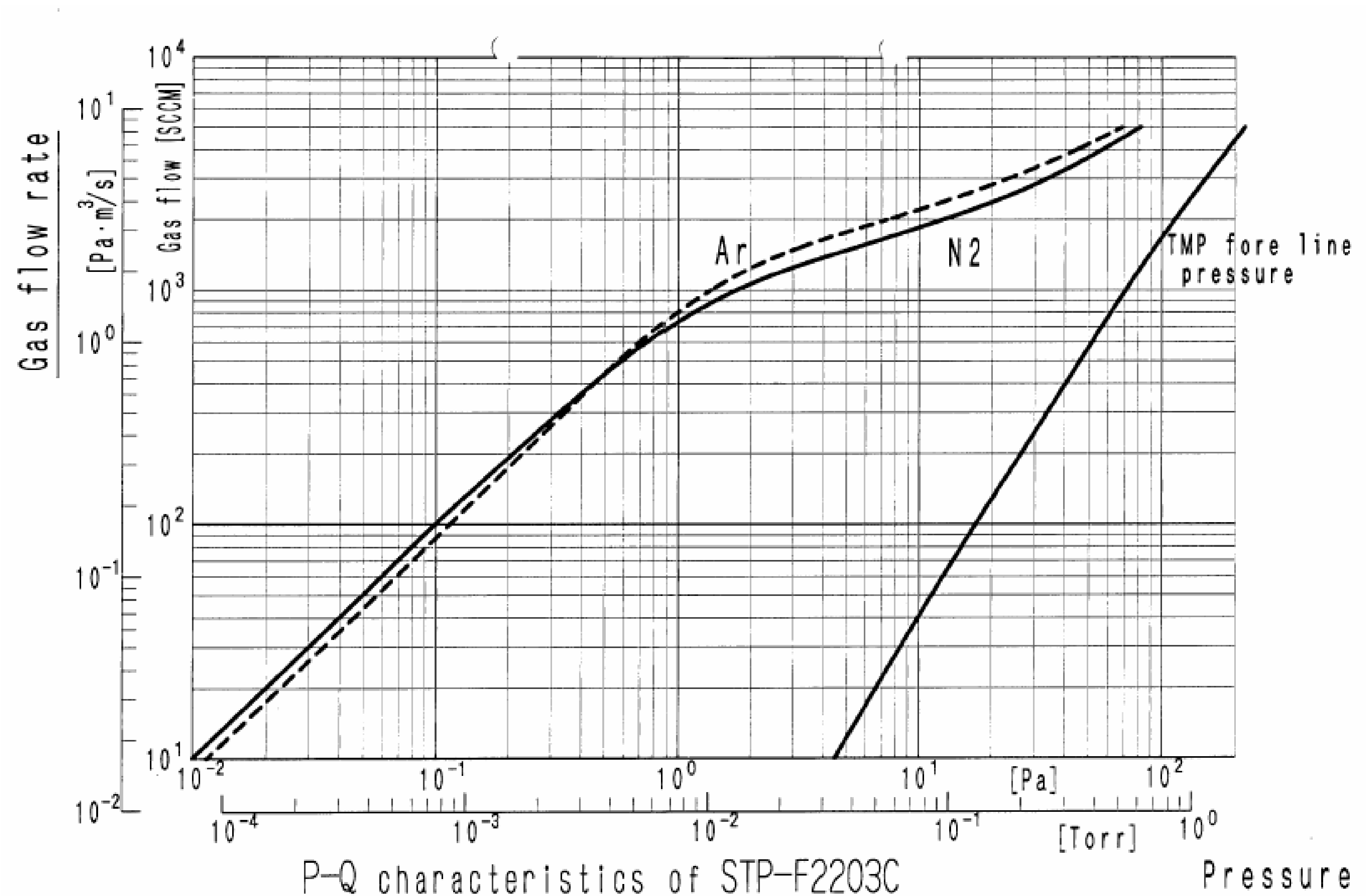
- Rotor suspended by a system of magnets
- No contact - nothing to wear out and high reliability
- Permanently low vibration characteristic
  - Conventional bearing vibration characteristics drifts with time
- No hydrocarbon lubricants present - pump is hydrocarbon free
- Can be mounted in any orientation
- Designed to work with semiconductor process gases/radiation environments

Speed curves ISO100

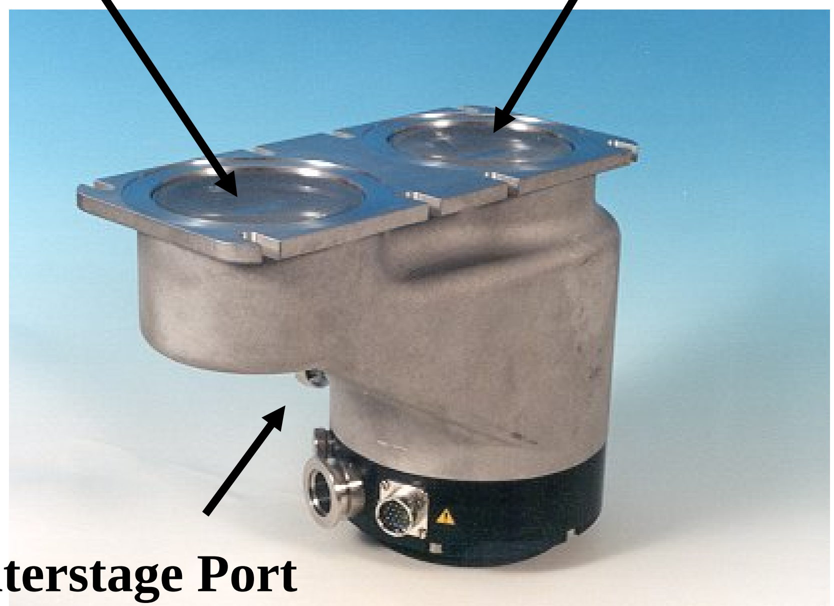


Pfeiffer TMU261P

Magnetic pump example



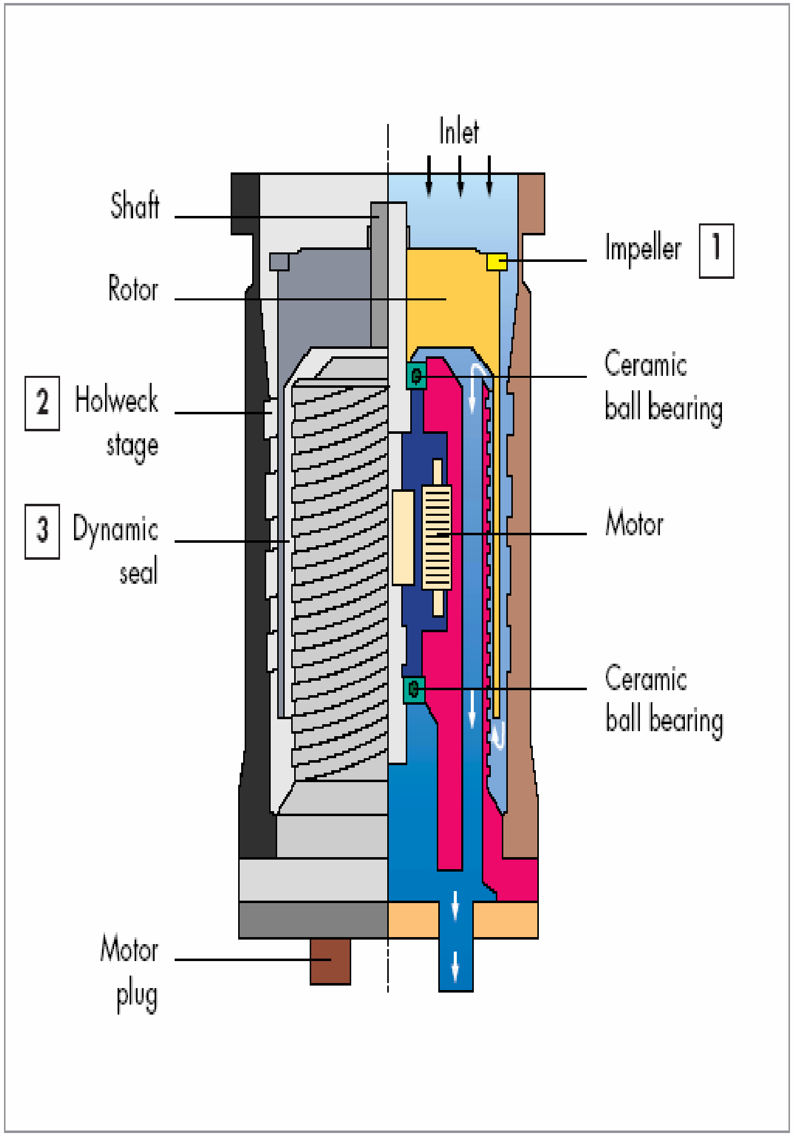
Split flow pumps – Mass Spectrometry

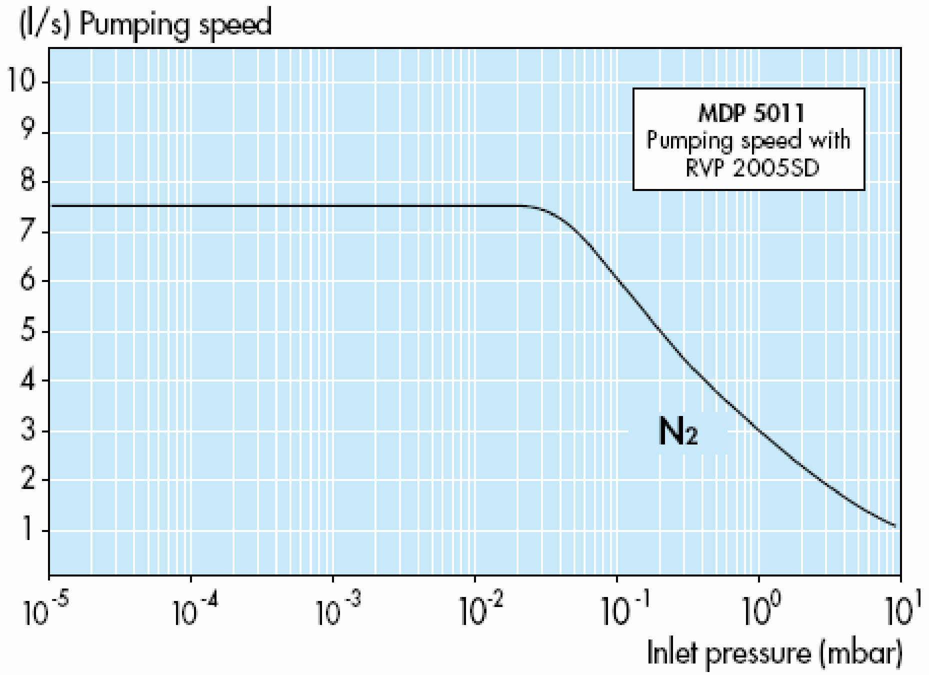


With Cast Envelope

The Interior

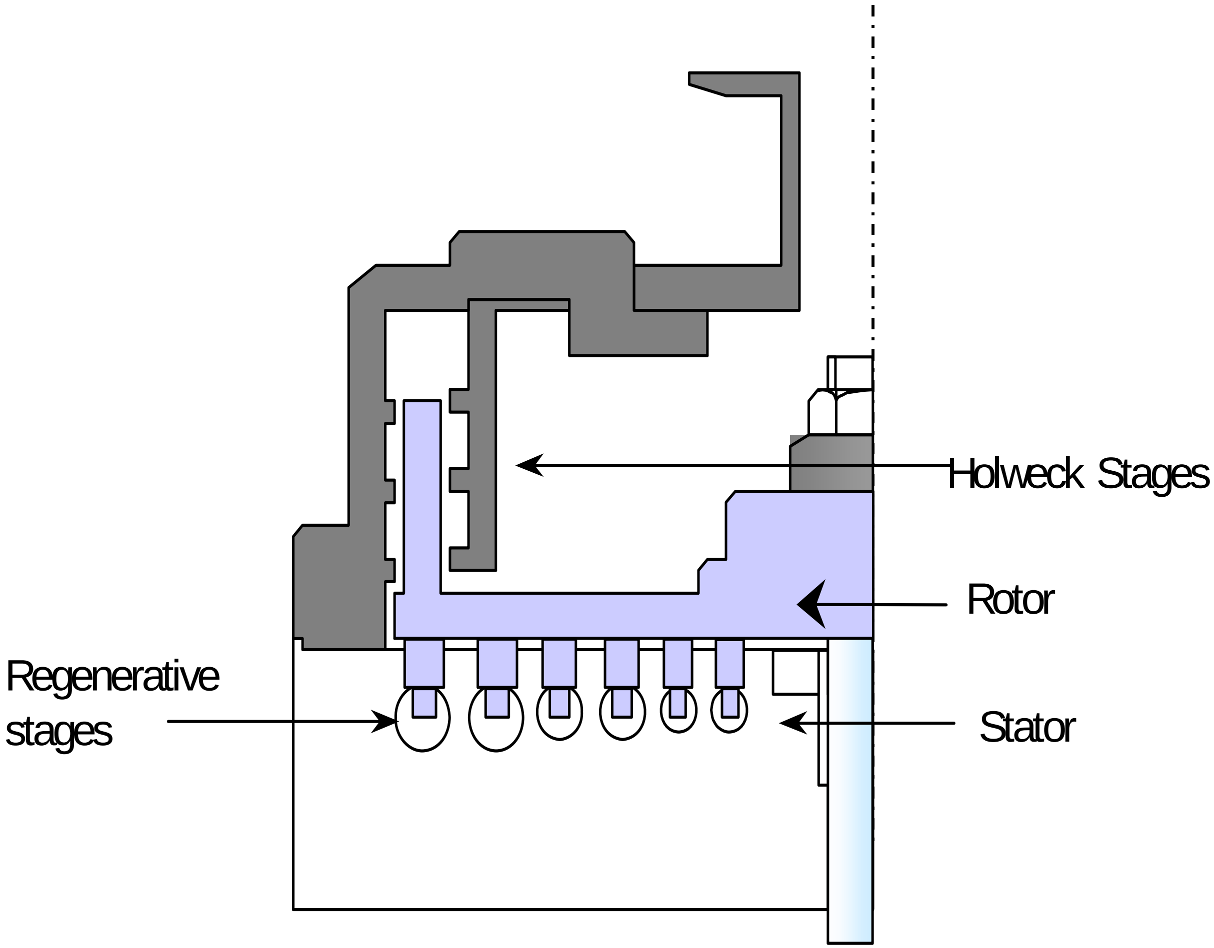
Drag pump





Adixen MDP 40 mbar exhaust pressure

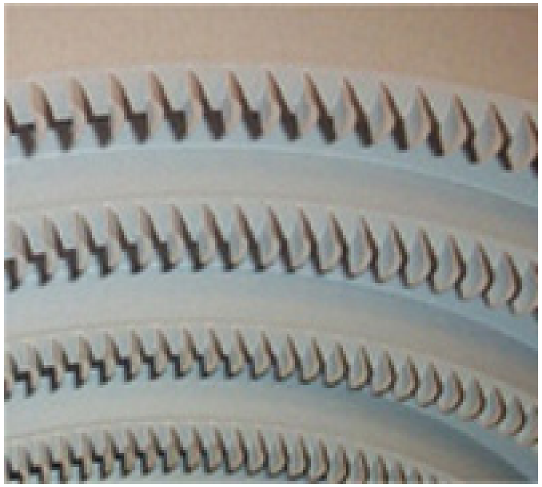
Regenerative/drag mechanism



Regenerative mechanism

Epx.exe

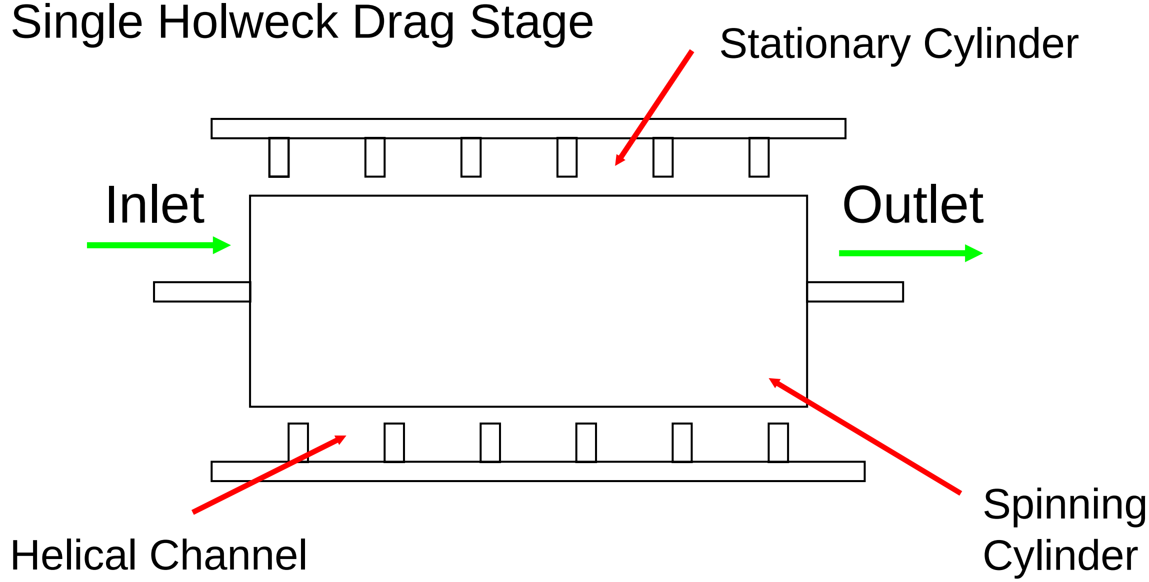
Exhausts to atmosphere



Holweck drag mechanism to <10^{-6} mbar

Drag Stator

Single Holweck Drag Stage



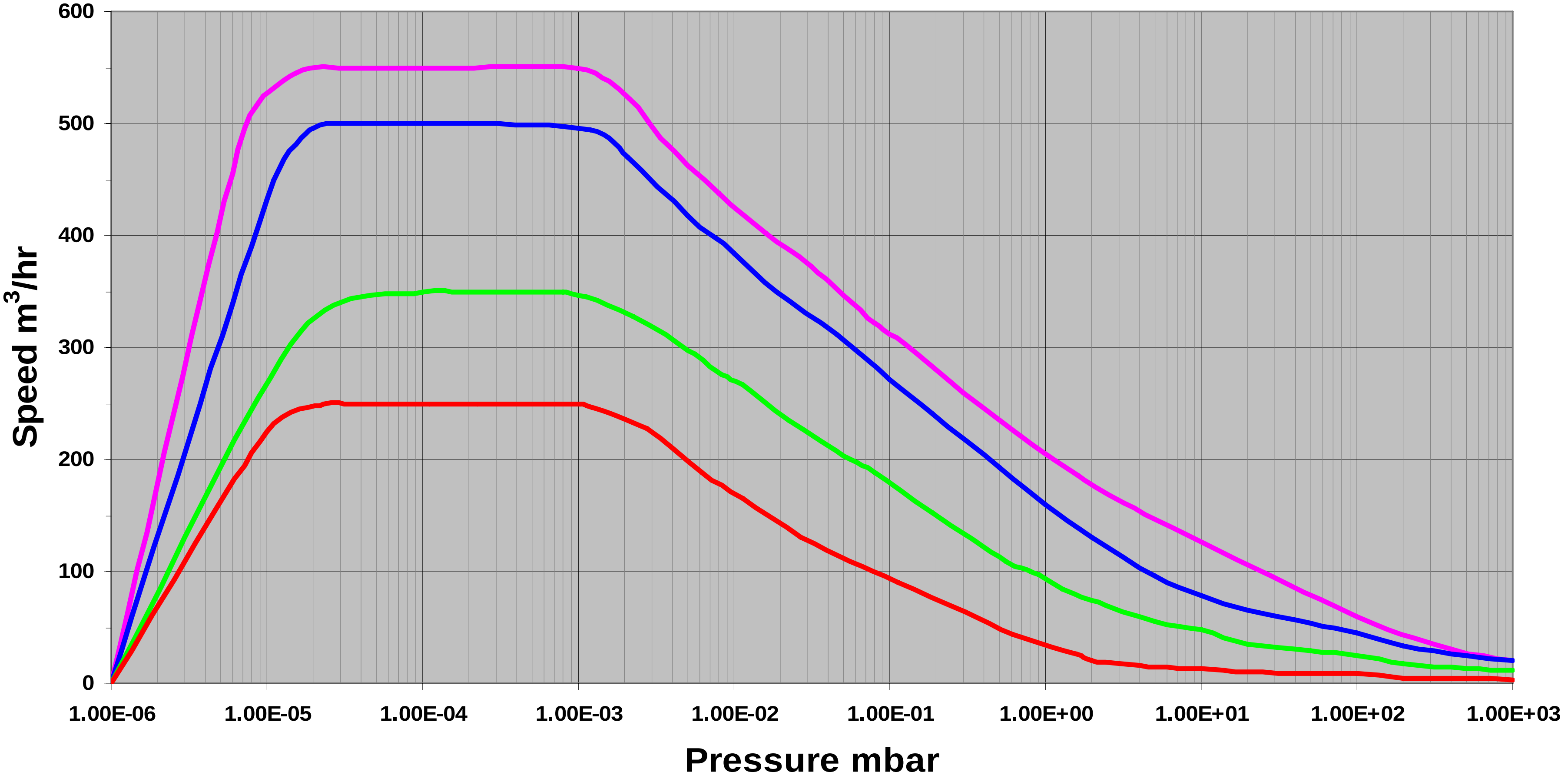
Drag Rotor

- Each Holweck stage has parallel helical grooves forming a set of parallel pumping channels.

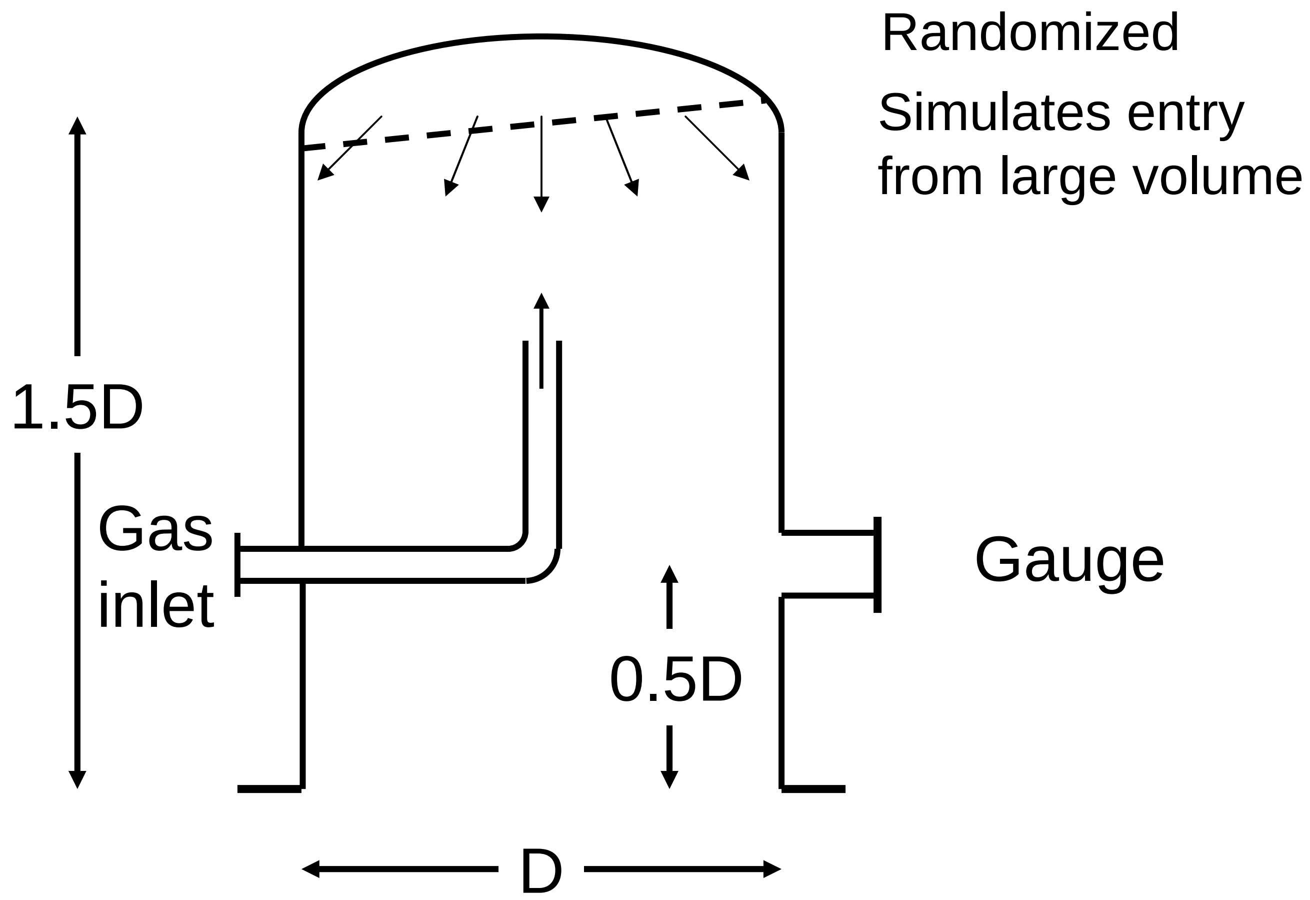
Utilizes two configurations:

1. Plane cylinder rotor with stationary helical grooves
2. Helical grooves in rotor and stationary plane cylinder

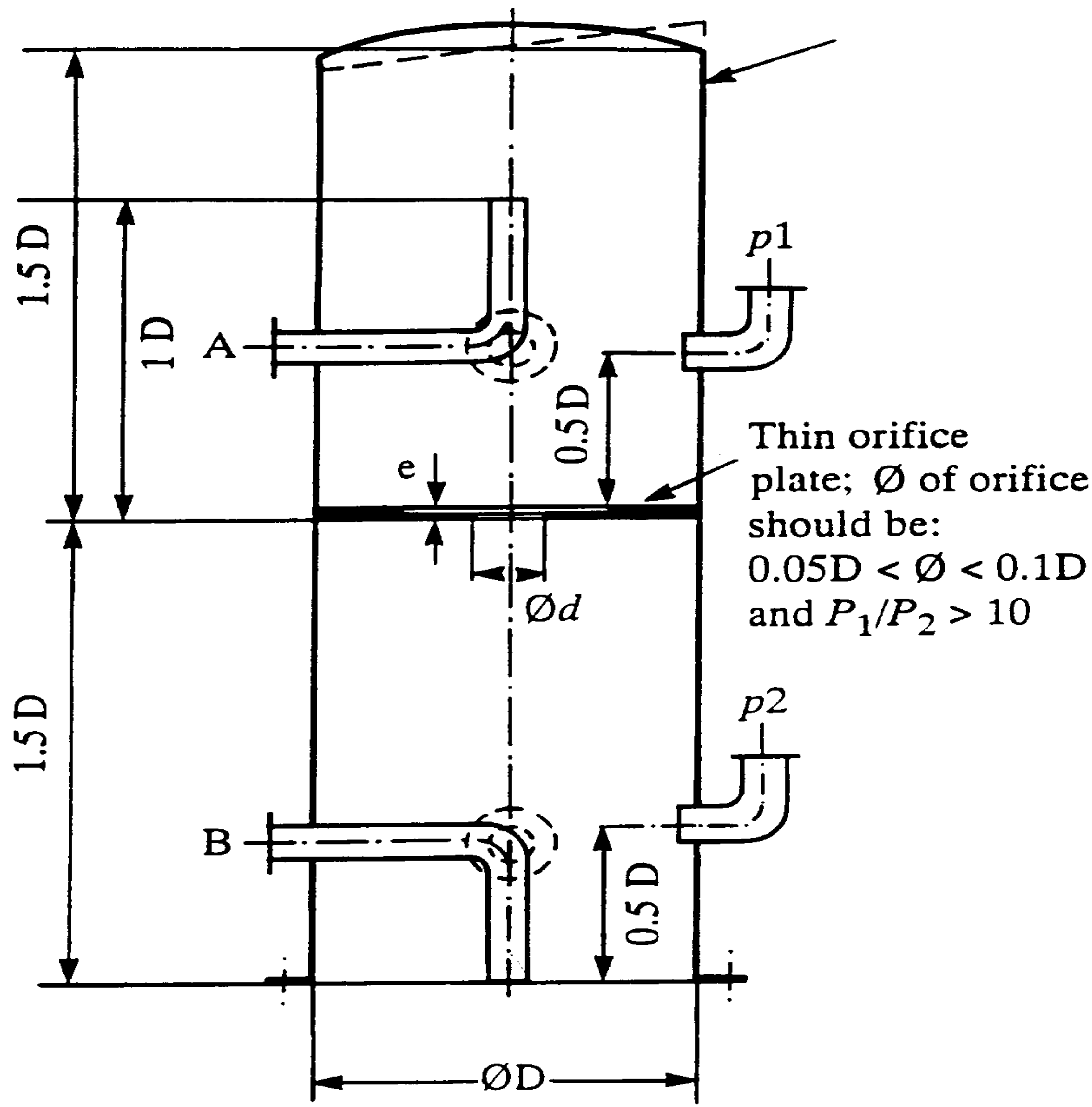
EPX500 speed curve



Speed Measurement



Recommended test dome ($P < 10^{-6}$ mbar)



Speed testing for < 10^{-6} mbar

Problem can't accurately measure flow rate at low flows -

e.g. pump of 100 l/s at 10^{-9} mbar (10^{-7} mbarl/s):

Q = 0.0006 sccm (e.g. MFC of 0.1 sccm has 0.0001 sccm - approx 10^{-6} mbar l/s resolution)

Continuity: use $Q = SP_2 = C(P_1 - P_2)$

$$S = C\left(\frac{P_1}{P_2} - 1\right)$$

ISO versus AVS

- In old AVS standard dome gauge position is closer to pump mouth and hence due to molecular flow/cosine distribution variations older AVS speed is 10 to 15% higher than the ISO speed

- Current AVS and ISO standards are same

- But some manufacturers still quote speeds to old AVS standard

Selected reading

- **High Vacuum technology – A Practical Guide MH Hablanian**
- **Foundations of Vacuum Science and Technology – ed J M lafferty**
- **Theory and Practice of Vacuum Technology – M Wutz, H Adam and W Walcher**
- **Handbook of Vacuum Science and Technology – D M Hoffman, B Singh and JH Thomas**

Specific recent articles….

- **A D Chew**, M Galtry, RG Livesey and I Stones, '*Towards the Single Pump Solution - Recent Development in High Speed Machines for Dry Vacuum Pumping.'* Published in *Journal of Vacuum Science and Technology A* **23 (5),** 1314 (2005)

- **A D Chew**, A Cameron, D Goodwin, J Hamilton, T Hawley-Jones, P Meares, J Pumfrey, J Ramsden and D Steele '*Considerations for Primary Vacuum Pumping in Mass Spectrometry Systems.'* Published in *Spectroscopy* **20 (1),** 2005