VACUUM PRINCIPLES

and

PRACTICE

VACUUM PUMPS

Vacuum pumps can be classified as

(i) GAS TRANSFER PUMPS

(ii) ENTRAPMENT PUMPS

Examples of (i) are rotary vane pumps,
Roots vacuum pumps,
ejector/diffusion pumps

Examples of (ii) are cryopumps (also cold traps)
SIP and getter pumps

Gas transfer pumps can be divided into:

Positive displacement pump

Kinetic pumps

VACUUM PUMPS

(Principles; Description)

A pumpset has to

- evacuate system from atmospheric pressure to a specified pressure in a given time
- maintain that pressure during the operation of the process

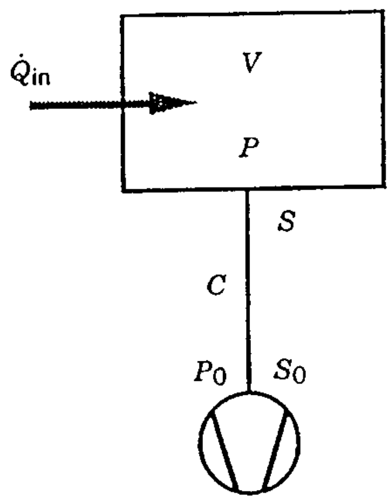

Fig. Schematic diagram - basic vacuum system

Pumpset has speed S_o at its inlet.

Effective speed (S_1, S_{eff}) is defined as $\dot{Q}_{in} / p$ where p is the system pressure.

S can be found from a steady-state flux balance between the flow entering the component and the flow into the pump and the pressure drop across the component determined from its conductance

$$S_{eff} = \frac{1}{\left(\frac{1}{S_o}\right) + \left(\frac{1}{C}\right)}$$

$$\frac{S_{eff}}{S_o} = \frac{1}{\left(1 + \frac{S_o}{C}\right)}$$

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ROUGH VACUUM (10^{+3} - 1mbar)

Oil-sealed rotary pumps (with/without gas ballast)

For continuous operation >about 100mbar, oil-sealed rotary pumps have a high OIL-, POWER CONSUMPTION.

At <100mbar, rotary vane-, rotary piston pumps.

For high throughputs at ≤40mbar, Roots + rotary combinations can be used.

Dry pumps e.g. ALLex can also be used.

Pumping speed needed is determined by:

P required, evacuation time, Q_{IN} ($q_{process} + q_{leakage}$)

Where dust and contamination arise, pumps should be protected by INLET- and OIL FILTERS.

HIGH VACUUM REGION (10^{-3} - 10^{-7}mbar)

Outgassing has a great influence. The quantity of gas/vapour released by inner walls depends on S(m^2) and contamination.

Higher demands for leak tightness (<10^{-5}mbar ls^{-1})

Pumps = DP ; TMP ; cryopanels (LN_2) may significantly reduce pump-down time because H_20(V) tends to be main outgassing species.

High vacuum pumps and associated backing pumps must be correctly chosen (size/specifications).

OIL-SEALED ROTARY PUMPS

1. ROTARY VANE

2. ROTARY PISTON

   (also known as
   rotary plunger pumps)

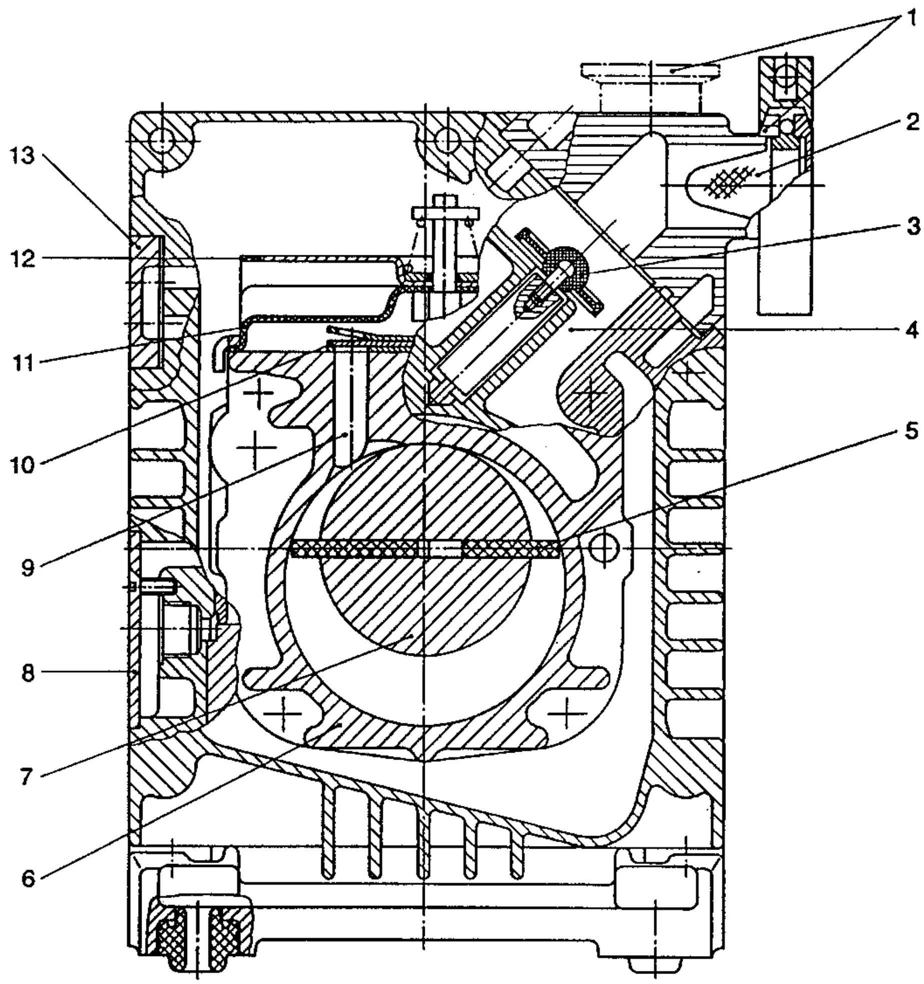


Fig. 2 Sectional drawing of a TRIVAC B

Key to Fig. 2

1. Intake port
2. Dirt trap
3. Anti-suckback valve
4. Intake channel
5. Vanes
6. Pump cylinder
7. Rotor
8. Cover plate, connection for inert gas ballast
9. Exhaust channel
10. Exhaust valve
11. Internal demister
12. Frame
13. Connection for oil filter

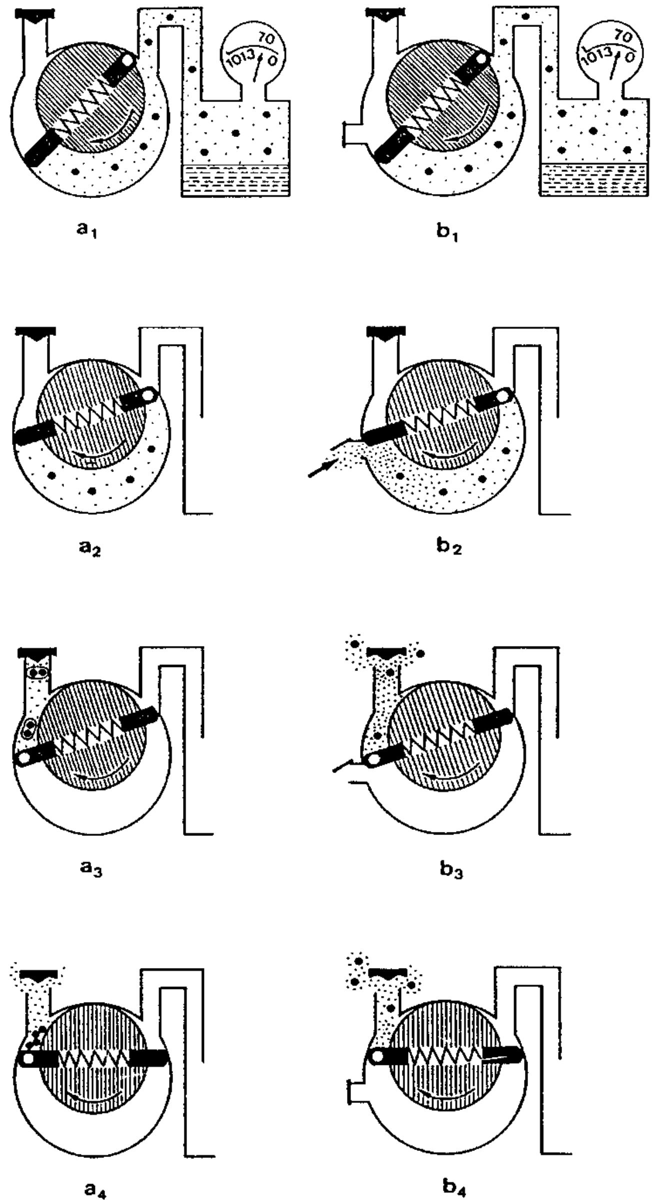


Fig. 13.1 Illustration of the pumping process in a rotary vane pump without (left) and with (right) gas ballast device when pumping condensable substances.
● vapour particles

Without gas ballast

a_1) The pump is connected to the vessel which is already almost empty of air (approx. 70 mbar). It must therefore transport mostly vapour particles. It works without gas ballast.

a_2) The pump chamber is separated from the vessel. Compression begins.

a_3) The content of the pump chamber is already so far compressed that the vapour condenses to form droplets. Overpressure is not yet reached.

a_4) The residual air only now produces the required overpressure and opens the discharge outlet valve. But the vapour has already condensed and the droplets are precipitated in the pump.

With gas ballast

b_1) The pump is connected to the vessel which is already almost empty of air (about 70 mbar). It must therefore transport mostly vapour particles.

b_2) The pump chamber is separated from the vessel. Now the gas-ballast valve opens, through which the pump chamber is filled with additional air from outside. This additional air is called "gas ballast".

b_3) The discharge outlet valve is pressed open; particles of vapour and gas are pushed out. The overpressure required for this to occur is reached very early because of the supplementary gas-ballast air, as at the beginning of the whole pumping process. Condensation cannot occur.

b_4) The pump discharges further air and vapour.

OIL-SEALED PUMPS

2. **Rotary piston vacuum pumps**

Can be 1- or 2-stage

Cover the size range 75-250m3 h-1

Example

Single-stage	E 75	E 150	E 250
Two-stage	DK 100	DK 200	

They are tolerant of dirt and contamination.

They have a high water vapour tolerance

Typical applications:

- coating
- metallurgy
- chemical industry

They can also be used as backing pumps for Roots pumps in diffusion-pumped systems.

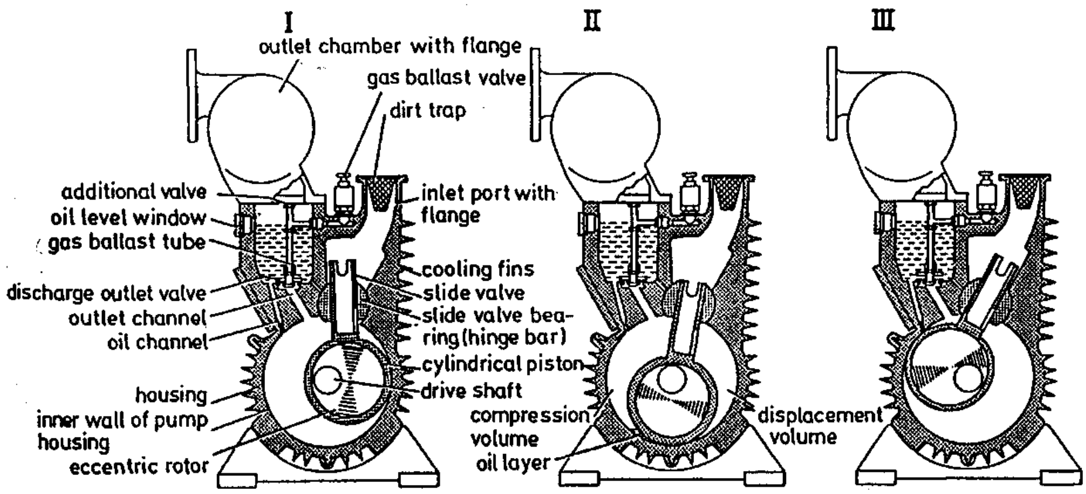


Fig. Rotary plunger pump showing pumping phases I to III

In the pump chamber, a ROTARY PISTON with an integral, hollow SLIDE VALVE attached to an eccentric rotor, turns and brings about periodic changes in the volume of the pump chamber. The ROTOR is rigidly connected to the drive shaft of the pump via a gearbox.

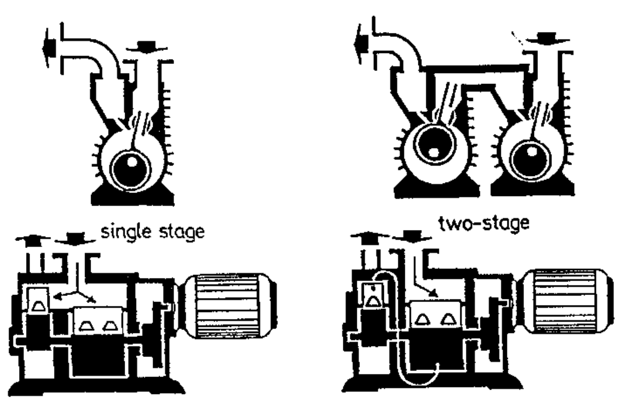


Fig. 5.18
Gas inter-connections for a rotary plunger pump arranged to operate as a single-stage or two-stage pump.

Oil-sealed Rotary Pumps

Vane-

- Vanes in contact with pump bore
- Rotational speed high (~ 1000rpm)
- Limited oil volume

Piston-

- Larger internal clearances (handles dirt well)
- Low rotational speed 500-700rpm) (lower wear)
- Larger oil volume (fewer oil changes)

Function of the oil in oil-sealed vacuum pumps

The fluid used in mechanical pumps has three functions:

LUBRICATION (of the bearings and sliding surfaces)

SEALING (the oil must form a vacuum seal between the vanes, for example, and the pump-chamber wall)

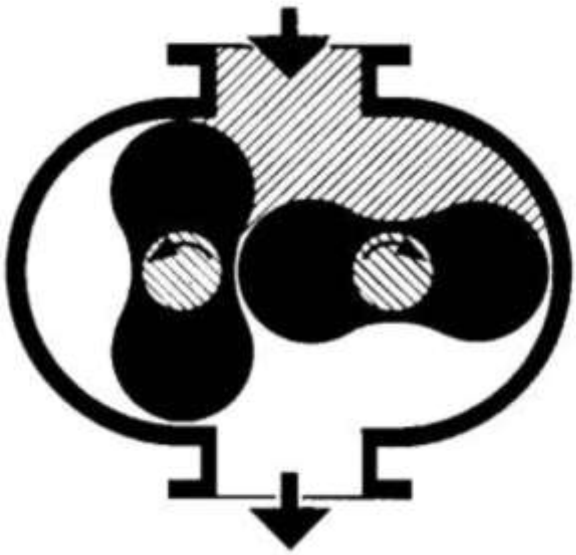
HEAT TRANSFER (from the pump chamber to the outer walls of the pump).

If the fluid fails to fulfill any of these or if the function is impaired through CHEMICAL, THERMAL or MECHANICAL interference, then pump performance may decline.

Vacuum pump oils must:

- Seal the moving parts
- Lubricate
- Have thermal stability (to ca. 100°C)
- Have good wetting ability
- Have good resistance to a range of compounds
- Have some solvent properties

Roots Pumps



1 Intake flange
2 Rotors
3 Chamber
4 Exhaust flange
5 Casing

DESY
Helium Pump System

Roots pump system with 32000 m³/h pumping speed

DESY

Helium Pump System

Technical Data II

Base pressure:

without gas ballast: < 1 x 10-4 mbar
with gas ballast: < 1 x 10-4 mbar

Set-up:

Four -stage vacuum pump system consisting of two
RA 16,000 Roots pumps in parallel, gas cooler,
RA 13,000 Roots pumps, gas cooler, four SOGEVAC
SV 1200 rotary vane vacuum pumps in parallel.

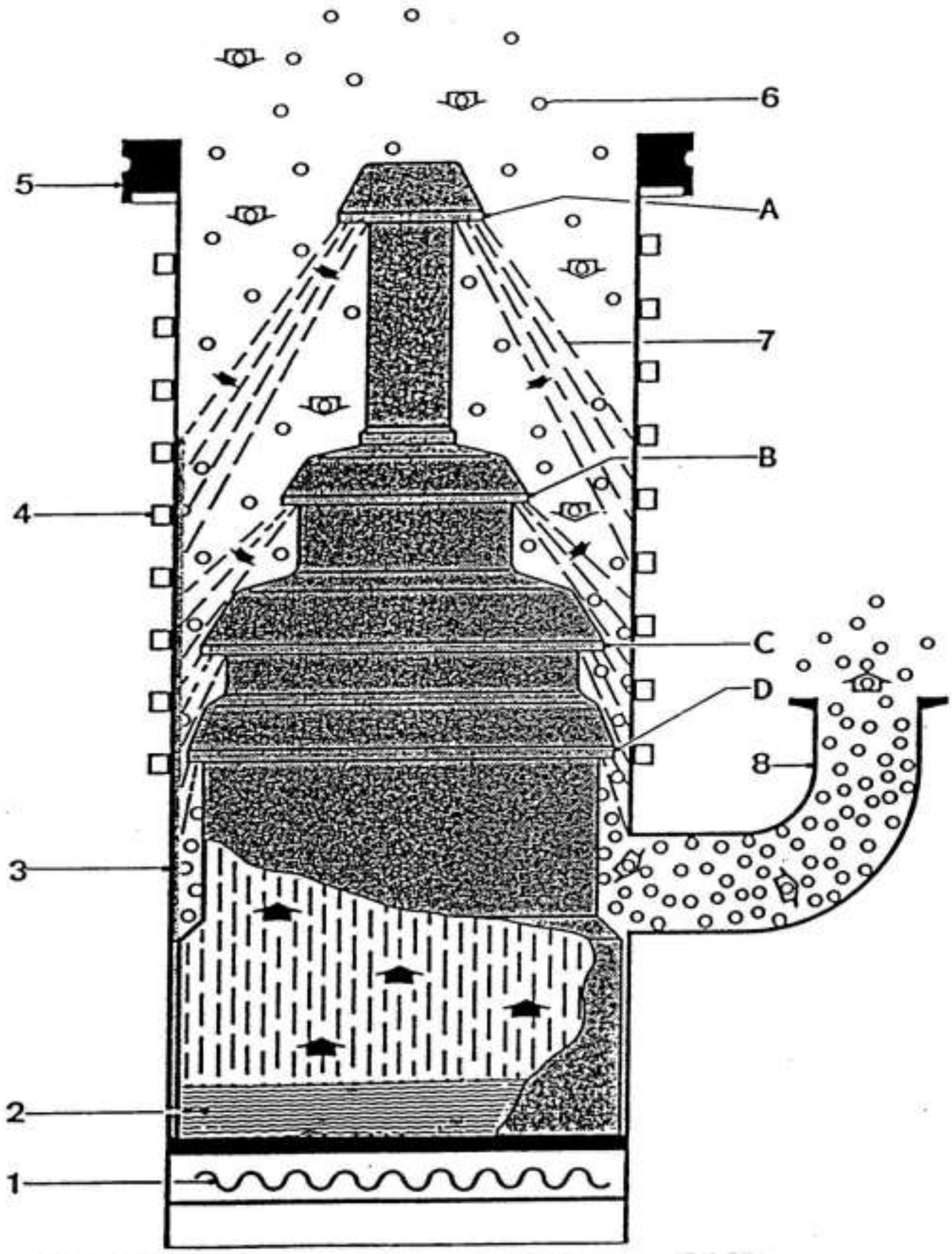
DIFFUSION PUMPS

DIFFUSION PUMPS

Diffusion pumps can be used to produce high- and possible ultra-high vacua.

They operate with a high-velocity stream of pump fluid vapour that transports pumped gas from a region of low pressure to one of higher pressure where further compression is carried out by a backing pump.

The working region of a diffusion pump is mainly below 10^{-3}mbar. Suitable pumps are required to maintain a relatively low pressure at the fore-vacuum port of the pump.



Mode of operation of a diffusion pump

1 Heater
2 Boiler
3 Pump body
4 Cooling coil

5 HV connection
6 Gas particles
7 Vapour jet
8 Connection port to backing line
9 A,B,C,D : nozzles

DIFFUSION PUMP

Working fluid is heated, vapour rises in the jet assembly.

The vapour accelerates as it passes through the jets. It forms a stream that is directed downwards and radially across the jet-wall interspace.

Gas penetrating the jet is eventually compressed to a pressure at which it can be removed by the backing pump at the discharge port.

$$\left(\frac{Pbacking}{Pinlet}\right)_o = (K_o) = \frac{n_L}{n_2} = \exp\left(U_2 L\right)/D$$

where K_o = compression ratio for zero flow rate

n = particle number density

U_2 = velocity of pump fluid vapour

L = the distance from the nozzle cap to the point of intersection of the pump fluid jet with the surface of the pump body

D = diffusion coefficient of the gas into the jet

Back-streaming of pump fluid is a major source of contamination in diffusion-pumped systems.

While the DP is operating, the backing pressure must not increase beyond a permissible maximum (critical backing pressure).

Fluids that are to be used in diffusion pumps should have certain properties:

- Low vapour pressure
- Resistance to thermal decomposition/oxidation
- High surface tension
- General chemical resistance
- High flash-point
- Low heat of vapourisation

Diffusion pump fluids fall into two categories:

(i) Hydrocarbon-based
(ii) Synthetic oils

(i) <u>Hydrocarbon-based fluids</u>

Produced by the molecular distillation of mineral oils. Several commercial oils are available.

The attainable ultimate pressure, after baking the vacuum system at 200°C for several hours, depends on the grade of the lubricant and also on the extent of the protection of the system from backstreaming.

Mineral-oil fluids may decompose on repeated exposure to oxygen-containing gases.

(ii) Synthetic Oils

These include:

Silicone fluids (e.g. DC 702/704/705)

PFPEs (Fomblin, Krytox)

Polyphenyl ethers (Ultralen, Santovac 5)

Synthetic hindered esters

Care should be taken with certain synthetic fluids:

- E.g. with silicone oils, the decomposition products are electrically insulating (SiO_2). This can lead to an alteration in the space-charge characteristics of ion sources, quadrupole systems etc.
- PFPE fluids may have desirable chemical and physical properties (e.g. resistance to gases such as F_2, O_2, O_3, UF_6 etc). Diffusion pumps charged with these oils may have their pumping speeds reduced considerably because of the low molar flow of fluid circulating in the jet system (low value of specific heat for PFPEs). If attempts are made to increase molar flow, turbulence occurs around expansion nozzle.

DIFFUSION PUMPED SYSTEMS

A basic, manually-operated diffusion-pumped system is shown in the diagram.

In capital-cost considerations, the components included are:

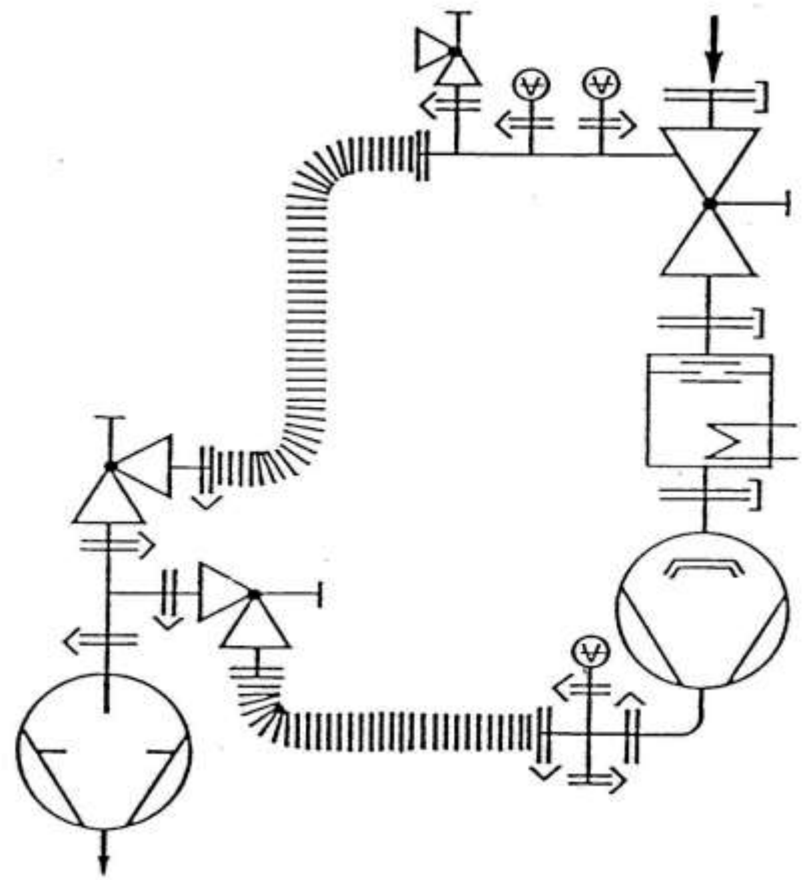


Fig. 4.1
Schematic diagram of an ordinary diffusion pump system

water-cooled D.P., baffles (see text), suitable backing pump, thermal switch, backing pump

To reduce backstreaming to a minimum, suitable traps and baffles must be inserted between the first- stage jet and the system being pumped.

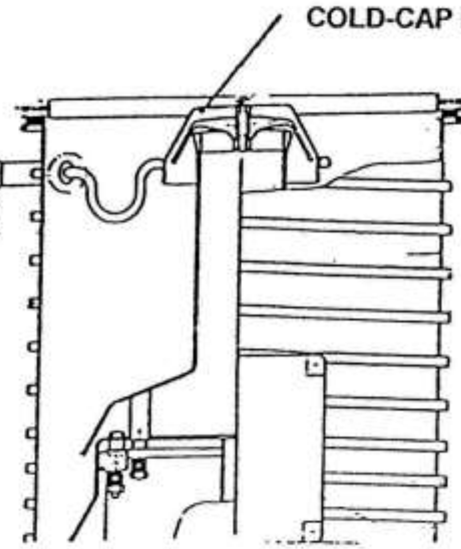


Fig. Cross-section of part of the jet assembly on a large diffusion pump (LEYBOLD DI 30000)

Power and Crawley (1954) devised a water-cooled guard-ring extending below the lip of the nozzle to intercept and condense the randomly-directed vapour molecules originating in the boundary layer adjacent to the nozzle surface.

- The use of a water-cooled cap with a long skirt placed over the first-stage nozzle and reaching down far enough to intercept the boundary layer (and reduce back-streaming) was described by Vekshinsky et al (1959).

Diffusion-/ Vapour pump fluids

1. Properties of some hydrocarbon-based fluids

Hydrocarbon-based fluid + antioxidant e.g. AP201/ AP301 are used in medium pressure applications (VIM, VIDP, coating). Ultimate pressure (untrapped) ≈ 1×10^{-3} mbar. AP301 is resistant to oxidation/ radiation.

Mixed high- boiling point hydrocarbons such as Diffelen (-light, -normal, -ultra) give ultimate pressures from 1.3×10^{-5} mbar (light) to 6×10^{-7} mbar. Similar fluids are Apiezon A,-B, -BW and –C.

2. Properties of some synthetic fluids

DC 702 is a mixed phenylmethyl-dimethylcyclosiloxane (ultimate pressure 10^{-6} mbar).

DC 704 is tetramethyltetraphenyltrisiloxane + pentaphenyltrimethyltrisiloxane (ultimate pressure 10^{-7} to 10^{-8} mbar).

DC 705 is pentaphenyltrimethyltrisiloxane (ultimate pressure 10^{-9} to 10^{-10} mbar). Can be used for UHV applications

Polyphenylethers such as Ultralen 5 (ultimate pressure 10^{-9} to 10^{-10} mbar). Used in 'clean' HV and UHV systems

Backstreaming

The vapour jet emerging from a diffusion-pump nozzle cannot be regarded as well-defined and travelling in a downwards direction radially across the pump.

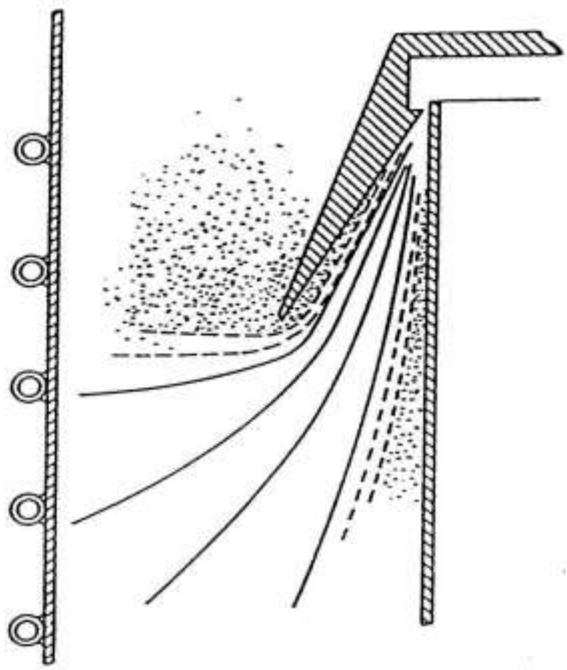


Fig. Representation of fluid jet emerging from a diffusion pump nozzle (Power & Crawley (1954))

Through random scattering or directional scattering from a coherent vapour jet, some molecules of the working fluid migrate in the direction of the vacuum chamber. This results in the BACKSTREAMING of pump fluid - a major source of contamination in diffusion-pumped systems.

Significant steps have been taken to reduce backstreaming in diffusion pumps.

Oil back-streaming may be a problem with diffusion pumps.

For example, with DC705 in a pump at p_{ult}, back-streaming values are:

without baffle	1×10^{-3} mg/cm^2 min
with cold cap baffle	1×10^{-4} mg/cm^2 min
with shell baffle (10°C)	1×10^{-6} mg/cm^2 min
with LN_2 (77K)	1×10^{-8} mg/cm^2 min

Incorporation of these devices has a significant effect on the effective pumping speed of the system cost and the cleanliness of the vacuum system.

RESIDUAL GAS ANALYSIS
WITH QUADRUPOLE MASS SPECTROMETERS

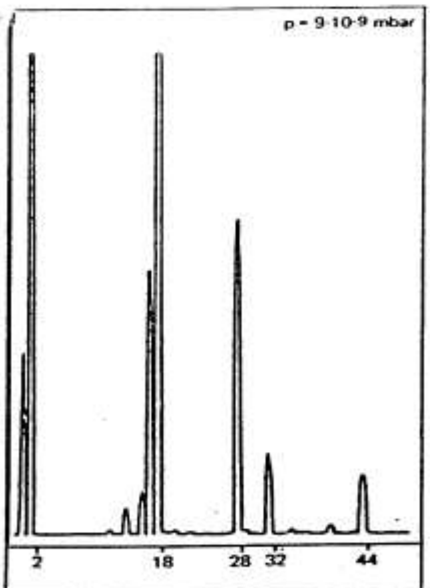
- The measurement of TOTAL PRESSURE in a vacuum system is a useful indication of the state of the system but insufficient as a guide to further improvement.

- Measurement of the PARTIAL PRESSURES of the component gases, the combined effects of which produce the gauge reading ($\Sigma_{PI} = p_{TOTAL}$), provides much more insight into the process and the system and stimulates ideas for further improvement.

- The first step in the establishment of partial pressures is the determination of the components present in the system. This is carried out using an analyser based on mass spectrometry.

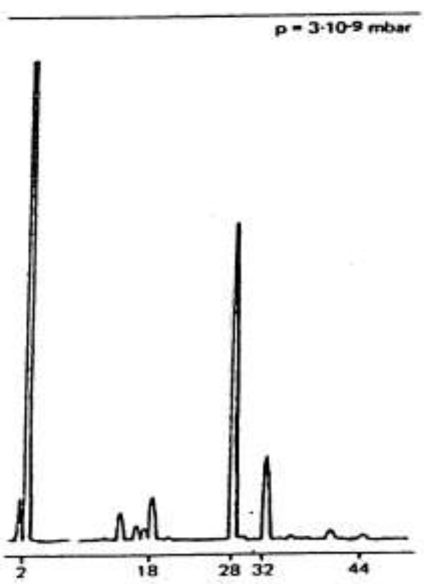
RGA of a Vacuum System -

Effect of different pumping methods



Turbo-molecular pump

TURBOMOLECULAR PUMP



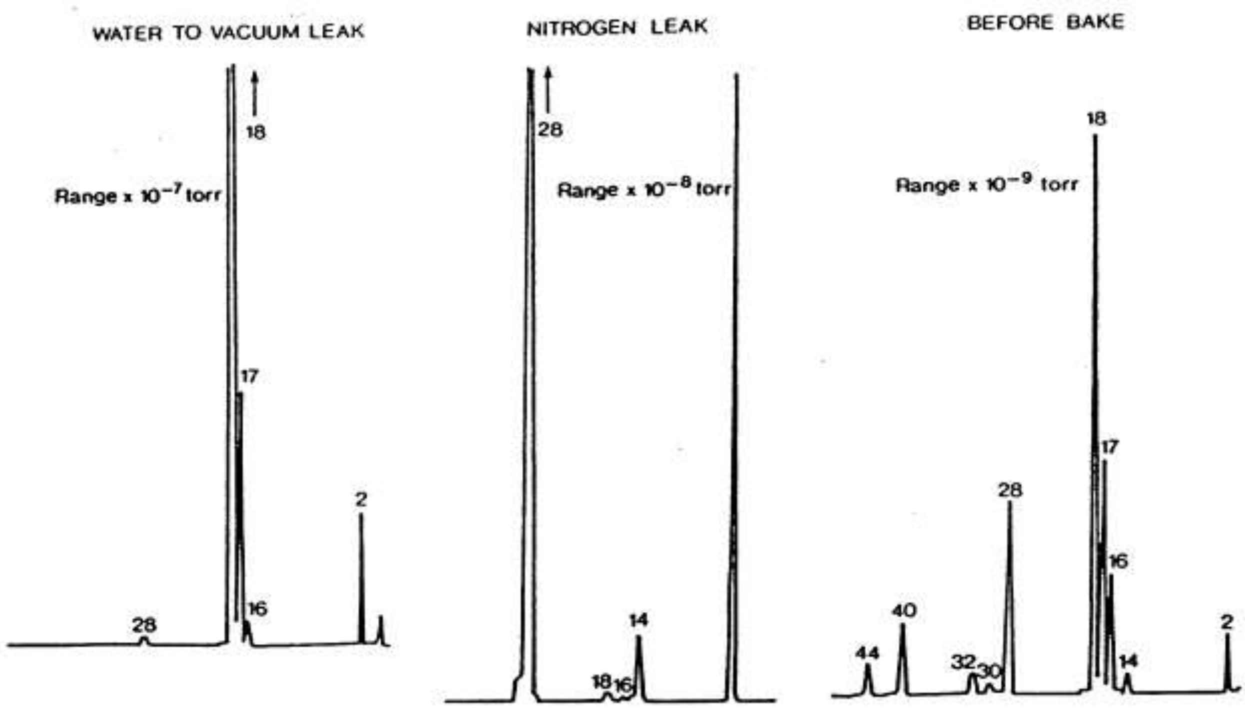
Turbo-molecular pump and cooling surface

TURBOMOLECULAR PUMP

+

COLD SURFACE

RGA on UHV system showing various problems



An accepted criterion for cleanliness in a vacuum system depends on an analysis of the residual gases it contains.

A system is clean if: $\sum_{pi,M} \leq 1\% p\ tot$