### Short tube conductance

\[ A_0 \rightarrow 0 : 1/C_e \]

\[ A_0 \] is the cross section of the upstream vessel

\[ 1 / C_{st} = 1 / C_{lt} + 1 / C_e \]

**Short tube \equiv \text{series of long} \text{tube and aperture}**

\[ C_{st} = C_{lt}/ \left[ 1 + \left( \frac{C_{lt}}{C_e} \right) \right] \]

\[ C_{st} = C_{lt} K'' = C_{lt} \left[ 1 + C_{lt} / C_e \right]^{-1} \]

**Diaphragm effect**

\[ \frac{C_{lt}}{C_e} = \frac{3.44 \cdot 10^4 \left( \frac{T}{M} \right)^{1/2} \left( \frac{A^2}{BL} \right)}{3.64 \cdot 10^{3} \left( \frac{T}{M} \right)^{1/2} A / \left[ 1 - A / A_0 \right]} \]

**\( K'' \) correction factor**

Called of Knudsen

---

### Conductance of an aperture

<table>
<thead>
<tr>
<th>( n )</th>
<th>Vacuum</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A )</td>
<td>( \phi = \frac{1}{4} n v_{ave} )</td>
</tr>
</tbody>
</table>

How many molecules travel through \( A \) in a time \( t \)?

\[ q = \phi A = 3.64 \cdot 10^3 (T/M)^{1/2} nA \quad [\text{mol/sec}] \]

**Volume of gas passing through \( A \)?**

\[ \frac{dV}{dt} = q/n = 3.64 \cdot 10^3 (T/M)^{1/2} A \quad [\text{cm}^3/\text{sec}] \]

\[ P_1 \quad P_2 \]

\[ Q_{(1,2)} = P_{(1,2)} dV/dt = 3.64 \cdot 10^3 (T/M)^{1/2} A P_{(1,2)} \quad \mu \text{bar} \quad \text{cm}^3/\text{sec} \]

\[ Q = Q_1 - Q_2 = 3.64 \cdot 10^3 (T/M)^{1/2} A (P_1 - P_2) \]

\[ C = Q / \Delta P = 3.64 \cdot (T/M)^{1/2} A \quad 1/\text{s} \]

\( C \) independent from \( P \)

\[ C = Q / \Delta P = (P_1 - P_2) \frac{dV}{dt} / \Delta P = \frac{dV}{dt} q / n = \phi A / n = \frac{1}{4} v_{ave} A \equiv \frac{1}{4} \overline{v} A \]

---

Vacuum technology

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Correction factors

- Short tube:
  - Knudsen factor: molecule impinging on the surface of the tube come out with a $\cos \theta (K''')$ spatial distribution.
  - Clausing factor: Higher probability for the molecule to come out in the flow direction ($K'$).

Described as: $P_r = C / C_0$ (Roth),

or (equivalent) $C = a' \frac{\sqrt{A}}{4}$ (O’Hanlon)

where $C_0$ is the conductance of the aperture.

Accuracy of calculations

Clausing 1%

Assuming the big dimension of chamber upstream and downstream

Knudsen 5%

$1 / C_{st} = 1 / C_{lt} + 1 / C_A$
**Analytical description for tubes**

\[
C_{lt} = 3.81 \left( \frac{T}{M} \right)^{1/2} \left( \frac{D}{L} \right)
\]

\[
C_{st} = C_{lt} K'' = 3.81 \left( \frac{T}{M} \right)^{1/2} \left( \frac{D}{L} \right) \cdot K''
\]

\[
K'' = \frac{1}{\left\{ 1 + 1.33 \cdot \left( \frac{D}{L} \right) \cdot \left[ 1 - \left( \frac{D}{D_v} \right)^2 \right] \right\}}
\]

If the volume is bigger respect to the tube diameter

\[
K'' = \frac{1}{\left\{ 1 + 1.33 \left( \frac{D}{L} \right) \right\}}
\]

\[
C = 3.81 \left( \frac{T}{M} \right)^{1/2} \left( \frac{D}{L} \right) \left[ L + 1.33 D \right]
\]

\[
P_r = 1 / \left\{ 1 + \left( \frac{3}{4} \right) \left( \frac{L'}{D} \right) \right\}
\]

\[
L' = L \left\{ 1 + 1 / \left[ 3 + \left( \frac{6}{7} \right) (L/D) \right] \right\}
\]

**Comparison**

- **Cylindrical tube** \( l = 10 \text{ cm}, \ d = 1 \text{ cm} \)

\[
C_{st} = \frac{3.44 \cdot 10^4}{\sqrt{\pi}} \left( \frac{T}{M} \right)^{1/2} \left( \frac{A^2}{BL} \right)^{-1} \cdot \left[ 1 + 5.3 \cdot \frac{A}{BL} \right]^{-1}
\]

CGS units.

- **H\(_2\)** 300 K

  - Long tube: 4.67 l/s, 10%
  - Knudsen short tube: 4.11 l/s, 5%
  - Clauing: 3.96 l/s, 1%

\[
C = 1 \cdot 4.5 \cdot 10^4 \left( \frac{T}{M} \right)^{1/2} \cdot \left( \frac{A}{BL} \right)^{-1} \text{ cm}^3 / \text{sec}
\]
Monte Carlo Methods

Molecules randomized

\[ P_r = C / C_0 \]

match well with the Monte Carlo Methodes

Fig. 3.3 A computer graphical display of the trajectories of 15 molecules entering an elbow in free molecular flow. Courtesy of A. Appel, IBM T. J. Watson Research Center.

K'' Knudsen correction factor

K' Clausing correction factor

Fig. 3.18 Transmission probability \( P_r \) for tubes with circular cross section. Continuous curve: calculated by using eq. (3.109); dotted curve: calculated by using eq. (3.107); points: Monte-Carlo calculations; x—experimental values. After Levenson et al. (1960).
**Example-exercise: He lamp**

He discharge

He I: 22.21 eV at 1 Torr
He II: 40.8 eV at 0.1 Torr

\[
S_{\text{eff}} \text{ of 500 l/s in the vacuum chamber } P_{\text{base}} = 10^{-10} \text{ Torr without He flow.}
\]

a) Calculate the length of a capillary (d = 2 mm) in order to have
\[ P_{\text{work}} = 10^{-8} \text{ Torr} \] in the chamber in working condition of 1 Torr discharge.

b) Which S are required in II e III stages if the capillary lengths are \[ L_{\text{II-III}} = L_{\text{I-II}} = 5 \text{ cm} \]?

c) Once the length of the whole capillary is designed, calculate the pressures in any stage for the discharge at 0.1 Torr.

**Check \( \lambda/d \) for He and flow regime? \( t_c = 25 ^\circ \text{C} \)**

---

**Proposed by a student**
**Viscous (Flow) just mention**

- $Q = p v A$ where $v$ velocity and $Q = p S$
  
  - $C = Q/\Delta P$
  
- $Q$ through an aperture $A$, adiabatic expansion
  
  - $C = f(P_1, P_2, \gamma, T, M)$
  
- For air at $20 \degree C$ $C = 20 A/(1 - P_2/P_1)$ if $1 \geq P_2/P_1 \geq 0.525$

  - $C = 20 A \ l/ (s \ cm^2)$ if $P_2/P_1 < 1$

- $C$ of a tube of diameter $D$ and length $L$
  
  - $C_{\text{tube}} = [\pi D^4/(128 \eta L)] P_{\text{ave}}; [D]=[L]=[\text{cm}], [P_{\text{ave}}]= \text{dyne/cm}^2$ and $[C]=\text{cm}^3/\text{s}$
  
- For air at $20 \degree C$

  $$C_{\text{tube}} = 182 D^4/L P_{\text{ave}}; \ D \ & L \ [\text{cm}], \ P_{\text{ave}} \ [\text{Torr}], \ and \ C \ [\text{l/s}]$$

**Another example: towards the experience**

- Base Pressure
  
  - $P_b = 5 \cdot 10^{-8} \text{ mbar}$

- Max Pressure allowed
  
  - $P_{\text{max}} = 5 \cdot 10^{-4} \text{ mbar}$

- Found the max throughput which can be supported by the system.

$S$ of turbo for $N_2$ 1600 $\text{l/s}$, and is connected by a tube of $D = 250 \text{ mm}$ and $L = 128 - 173 \text{ mm}$. 

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**Dimension of the chamber for next steps**

![Diagram of chamber dimensions]

**Dimensioning vacuum system: in stationary condition**

- Maximum allowed (required) pressure in the chamber?
  - $P_{ch} = \frac{Q}{S_{ch}}$
  - $\frac{1}{S_{ch}} = \frac{1}{S_{hv}} + \frac{1}{C_{hv}}$

- $P_{hv-out} = \text{maximum allowed pressure at the outlet of HV pump.}$
- $C_{bp} = \text{conductance between HV pump and back pump.}$
- $P_{bhv-out} = \frac{Q}{S_{hv-out}}$
- but
  - $\frac{1}{S_{hv-out}} = \frac{1}{S_{bp}} + \frac{1}{C_{bp}}$
We have two possible model of HV pumps one requires at the outlet a pressure below $5 \times 10^{-1}$ mbar, the other a pressure below $8-9$ mbar.

For the connection between the HV pump and the back pump assume a 40 mm in diameter tube having a length of 1 m.

Check which turbo pump is required?

In which regime are we?

$\textit{d} = \text{dimension of ducts, chamber}$

<table>
<thead>
<tr>
<th>State of the gas</th>
<th>$k$</th>
<th>Flow regime</th>
<th>$R_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscous</td>
<td>$d/\lambda &gt; 110$</td>
<td>Turbulent</td>
<td>2100 Air admitted in vacuum</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Laminar</td>
<td>1100;</td>
</tr>
<tr>
<td>Transition</td>
<td>$1 &lt; d/\lambda &lt; 110$</td>
<td>Intermediate</td>
<td></td>
</tr>
<tr>
<td>Rarefied</td>
<td>$d/\lambda &lt; 1$</td>
<td>Molecular</td>
<td></td>
</tr>
</tbody>
</table>

For air we have

$d \cdot p > 5 \times 10^{-1}$ cm Torr

$5 \times 10^{-3} < d \cdot p < 5 \times 10^{-1}$ cm Torr

$d \cdot p < 5 \times 10^{-3}$ cm Torr
Comparison between viscous and molecular regimes

\[ C_A = 3.64 \cdot \left( \frac{T}{M} \right)^{1/2} \cdot A; \quad [A] = \text{cm}^2, \ [C] = \text{l/s}. \]

- For air at 20 °C \( C_A = 11.6 \ \text{Al/s}, \ \ C_A = 9.16 \ D^2 \ \text{l/s}, \)

Pumping speed through an aperture: \( S = \frac{Q}{P_1} \)

\[ S = \frac{Q}{P_1} = C(P_1 - P_2) / P_1 \text{ for } P_2 < 0.1 \cdot P_1 \text{ (usual case):} \]

\[ S = C = 11.6 \ \text{Al/s} \]

The maximum pumping speed in molecular regime is

11.6 Al/(s cm²),

if compared to the viscous regime: \( S = C = 20 \ \text{Al/(s cm²)} \)

Intermediate regime

\( C = (c_1 D^4 P_{ave} + c_2 D^3) / L \)

\[ c_1 = \pi / 128 \eta \quad c_2 = (\pi / 16) [((\pi / 2)(R_0 T / M)^{1/2} [(2-f)/f] \]

If the pressure \( P_{ave} \) is sufficiently high the term \( D^4 \) dominates (viscous flow).

When the two terms are equal:

\[ P_{ave} = P_t = c_2 / (c_1 D) \text{ transition pressure.} \]

When the pressure becomes low according:

\[ D \cdot P_{ave} < 5 \cdot 10^{-3} \text{ Torr cm molecular regime} \]
Evacuation from the atmosphere, Only useful in case of big chamber, or frequently opened

Evacuation from a volume $V$

\[ Q = - \frac{d}{dt} \left( PV \right) = - \frac{dP}{dt} V = P_S \Rightarrow \]

\[ \Leftrightarrow \quad P = P_0 e^{-\frac{S}{V}t} \]
Evacuation in viscous regime

\[ \frac{1}{S} = \frac{1}{S_p} + \frac{1}{C} \]

\[ C = \left( \frac{\pi}{128} \right) \frac{D^4}{(\eta L)} P_{ave} \]

\[ P_{ave} = \frac{(P + P_p)}{2} \]

\[ Q = PS = -V\left( \frac{dP}{dt} \right) \]

Equation can be solved and plotted by using as a parameter

\[ \frac{D^4}{L} = \left( \frac{128}{\pi} \right) \eta E \]

---

**Example Calculation**

- \( V = 100 \text{ l} \)
- \( D = 2 \text{ cm} \)
- \( L = 200 \text{ cm} \)
- \( \frac{D^4}{L} = 8 \cdot 10^{-2} \)

If \( S_p = 2 \text{ l/s} \), then we have \( t/V = 6 \) then \( t = 600 \text{ sec} \)

Assuming \( L = 0 \), we have \( t/V = 4.5 \) then \( t = 450 \text{ sec} \)

---
**Throughput (Q) sources in vacuum systems**

The following sources of throughput appear in a vacuum system:

![Diagram showing potential sources of gases and vapors in a vacuum system.](image)

Fig. 4.1 Potential sources of gases and vapors in a vacuum system.

**Q sources: vaporization**

In a closed system

<table>
<thead>
<tr>
<th>Saturated vapour pressure</th>
<th>Liquid</th>
</tr>
</thead>
</table>

Open system / Vacuum system

<table>
<thead>
<tr>
<th>Vapour Pressure</th>
<th>Liquid</th>
</tr>
</thead>
</table>

\[
\Phi (\text{molecules/s}) = \frac{n v_{\text{ave}} A}{4} \quad \text{with} \quad n = \frac{P}{kT} \quad \text{and} \quad v_{\text{ave}} = \left(\frac{8kT}{\pi m}\right)^{1/2}
\]

\[
\Phi = 2.63 \times 10^{24} \frac{P_v A}{\sqrt{M T}}
\]

\[\text{SI units: } [P_v] = \text{Pa}, \quad [A] = \text{m}^2 \quad [T] = \text{K}\]
Outgassing of gases adsorbed in atm. and or finale stage of diffusion and permeation

Typical law of rate of lost proportional to the initial

$$\frac{dC}{dt} = -K_1 C(t) = -\frac{e^{-E_a/RT}}{\tau_0} C(t)$$

$$\frac{1}{K_1} = \frac{\tau_r}{\tau_0} = \frac{e^{E_a/RT}}{\tau_0}$$

$$C(t) = C_0 e^{-K_1 t} = C_0 e^{-t/\tau_r}$$

\[4.2 \text{ THERMAL DESORPTION}\]

<table>
<thead>
<tr>
<th>System</th>
<th>Desorption Energy (MJ/(kg-mole))</th>
<th>77 K (s)</th>
<th>22°C (s)</th>
<th>450°C (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O/H₂O</td>
<td>40.6</td>
<td>10¹⁵</td>
<td>10⁻³</td>
<td>10⁻⁵</td>
</tr>
<tr>
<td>H₂O/metal</td>
<td>96</td>
<td>-</td>
<td>10³</td>
<td>10⁻⁵</td>
</tr>
<tr>
<td>H₂/Mo</td>
<td>160</td>
<td>-</td>
<td>10¹⁷</td>
<td>1</td>
</tr>
</tbody>
</table>

2⁰ order

$$\frac{dC}{dt} = -k_2 C(t)^2$$

$$\frac{dC}{dt} = - \frac{k_2 C_0^2}{(1 + C_0 K_2 t)^2}$$

**Q sources: diffusion**

Process slower than desorption

$$q = C_0 \left( \frac{D t}{D} \right)^{1/2} \left[ 1 + \sum_{n=0}^{\infty} (-1)^n \exp \left( - \frac{n^2 d^2}{D t} \right) \right]$$

Initial concentration

$$t \to 0 : q = C_0 \left( \frac{D t}{D} \right)^{1/2} \approx t^{1/2}$$

$$t \to \infty : q = \frac{2 DC}{d} e^{- \frac{\pi D t}{2 d^2}} \approx t^{1/2} \cdot e^{-at}$$

The diffusion constant is function of the activation energy and \(T\)

$$D = D_0 e^{-E/kT}$$

\(E = \) Activation Energy

Then increasing the \(T\) speed up the process of diffusion in the bulk.

AA 2011/2012 Vacuum technology
To speed up the time of reduction of outgassing: Bake-out

Increasing $T$ diffusion coefficient $D$ increases exponentially!

$$D = D_0 e^{-E_D / kT}$$

Baking-out a vacuum chamber we can get less outgassing in a very short time.

**Permeation**

Ideal behavior of permeation rate as function of time, assuming we expose a chamber (absolute vacuum) at $t=0$ to an external pressure.

$$d: \text{wall thickness}$$

$$D: \text{diffusion coefficient}$$

**Permeation is a three processes phenomenon**
**Contribution to the throughput**

\[ P = P_0 e^{-\frac{s}{T}} + \sum_i \frac{Q_i}{S} \]

- \( Q_L = \text{leaks} \)
- \( Q_D = \text{gas desorbed} \) \& \( \text{diffused} \)
- \( Q_V = \text{vapor} \)
- \( Q_p = \text{permeation} \)

\[ Q_{\text{leaks}} = \text{gas} \text{leaks} \]

\[ Q_{\text{permeation}} = \text{gas permeation} \]

\[ V_{\text{diffused/or desorbed gas}} = \text{gas diffused/or desorbed} \]

\[ 2' = 110 \text{ g} \]

3.2 \(10^5\) aa

---

**Evacuation in molecular regime.**

\[ P = (P_i - P_u) \cdot e^{-\left\{\frac{(S_p/V)}{[1+(S_p/C)]}\right\}} + P_u \]

Transition: \( P = P_i \cdot e^{-\left\{\frac{S_{\text{eff}}}{V}\right\}t} \)

\[ S_{\text{eff}} = S_p \cdot C \div \left( S_p + C \right) \]

Time evolution: \( P(t) = \frac{Q_G(t)}{S} \)

Ultimate pressure: \( P(t) = \frac{Q_G}{S} \)
Real Surfaces

Theoretical description quite complex different monolayer coverage, different interaction energy and chemical-physical bonding, dependence on the concentration.

For Vacuum design we “use” tables where are reported

\[ q = \text{throughput per area} \]

\[ q_n = \frac{q}{t^{a_n}} \]

and its time relation after 1 h

Or time relation after 10 h

\[ q_n = \frac{q_{10}}{t^{a_{10}}} \]

From the tables we estimate (measuring the inner surface of our system) we estimate the throughput from the chamber, usually we call this base pressure, its depends on the materials used and the processes of bake out Ex-sity or in-situ.

Outgassing of materials

Material Properties

Appendix C.1  Outgassing Rates of Vacuum Baked Metals

<table>
<thead>
<tr>
<th>Material</th>
<th>Treatment</th>
<th>( q ) (10(^{-11}) W/m(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum (^a)</td>
<td>15 h at 250°C</td>
<td>53.0</td>
</tr>
<tr>
<td>Aluminum (^b)</td>
<td>20 h at 100°C</td>
<td>53.0</td>
</tr>
<tr>
<td>6061 Aluminum (^c)</td>
<td>20 h at 100°C</td>
<td>53.0</td>
</tr>
<tr>
<td>Copper (^d)</td>
<td>20 h at 100°C</td>
<td>53.0</td>
</tr>
<tr>
<td>304 Stainless Steel (^e)</td>
<td>30 h at 250°C</td>
<td>53.0</td>
</tr>
<tr>
<td>Stainless Steel (^f)</td>
<td>2 h at 850/900°C vac. furnace</td>
<td>53.0</td>
</tr>
<tr>
<td>316L Stainless Steel (^g)</td>
<td>2 h at 800°C vac. furnace</td>
<td>53.0</td>
</tr>
<tr>
<td>U15C Stainless Steel (^h)</td>
<td>3 h vac. furn. 1000°C + 25-h</td>
<td>53.0</td>
</tr>
<tr>
<td></td>
<td>in situ vac. bake at 360°C</td>
<td>53.0</td>
</tr>
</tbody>
</table>

Source. Adapted with permission from Vacuum, 25, p. 347, R. J. Eisey. Copyright 1975, Pergamon Press.

\(^a\) J. R. Young, J. Vac. Sci. Technol., 6, 398 (1969);
\(^b\) G. Moraw, Vacuum, 24, 125 (1974);
\(^c\) H. J. Halama and J. C. Herrera, J. Vac. Sci. Technol., 13, 463 (1976);
\(^d\) R. L. Samuel, Vacuum, 20, 295 (1970);
\(^e\) R. Nuvolone, J. Vac. Sci. Technol., 14, 1210 (1977);
Which is the base (ultimate) pressure we can reach after 10 h of pumping (or in-situ bake-out)?

Use the yellow labelled data in previous tables.
1st part

- Estimate $Q_G$ due to the material of the chamber.

- $S_{eff}$ (effective pumping speed) and then $P(t)$ base pressure after 10 h or $P_u$ ultimate pressure (after bake-out treatments).

2nd part

Max $P$ inlet (in order to have $Q_{max}$)

Max $P$ outlet

### 1.2 Technical data

<table>
<thead>
<tr>
<th>TURBOVAC</th>
<th>T 1600</th>
<th>T 1600</th>
<th>T 1601</th>
<th>TW 1600</th>
<th>TW 1600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. permissible high vacuum pressure ($p_{HV}$) for continuous operation(^1)</td>
<td>mbar</td>
<td>5-10(^{-2})</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pumping speed for N(<em>2) at $p</em>{HV} \leq 10^{-3}$ mbar</td>
<td>l/s(^{-1})</td>
<td>1280</td>
<td>1550</td>
<td>1550</td>
<td>1000</td>
</tr>
<tr>
<td>Forevacuum port</td>
<td>DN</td>
<td>40 KF</td>
<td>40 KF / 63 ISO-K</td>
<td>40 KF</td>
<td>40 KF</td>
</tr>
<tr>
<td>Max. permissible forevacuum pressure ($p_{V}$) at the forevacuum port for N(_2) for continuous operation(^1)</td>
<td>mbar</td>
<td>5-10(^{-1})</td>
<td>5-10(^{-1})</td>
<td>5-10(^{-1})</td>
<td>9</td>
</tr>
<tr>
<td>Max. gas throughput for N(_2) for continuous operation(^1)</td>
<td>scm mbar l/s(^{-1})</td>
<td>1500</td>
<td>1500</td>
<td>1500</td>
<td>440</td>
</tr>
</tbody>
</table>

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**Pumping speed of back pump**

Pumping speed - Ecodyne M15 with world motor
230 V - 50 Hz - M 15 with silencer, without gas ballast
Converter pre-set to 750 rpm - 1000 rpm - 1200 rpm
Dimensioning the back pump depends on the needs.

\[
\text{Max } P \text{ inlet} \quad (\text{in order to have } Q_{\text{max}})
\]

- \(S_p\) required in order to pump down the maximum throughput and have right pressure required on the outlet of the HV pump.
- Or for UHV another parameter compression factor \(K_0\)?

\[
K_0 = \frac{P_{\text{outlet}}}{P_{\text{inlet}}}
\]

This is ideal parameter for \(Q=0\), use this for cross-check \(P_u\).

### Specification of T 1600 and TW 1600

<table>
<thead>
<tr>
<th>Technical Data</th>
<th>TURBOVAC T 1600 / T 1601</th>
<th>Technical Data</th>
<th>TURBOVAC TW 1600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet flange</td>
<td>DN</td>
<td>DN</td>
<td></td>
</tr>
<tr>
<td>Pumping speed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(N_2)</td>
<td>1 x 10^{-3}</td>
<td>1550</td>
<td>1430</td>
</tr>
<tr>
<td>(Ar)</td>
<td>1 x 10^{-3}</td>
<td>1410</td>
<td>1200</td>
</tr>
<tr>
<td>(He)</td>
<td>1 x 10^{-3}</td>
<td>1500</td>
<td></td>
</tr>
<tr>
<td>(H_2)</td>
<td>1 x 10^{-3}</td>
<td>720</td>
<td></td>
</tr>
<tr>
<td>Max. gas throughput</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(N_2)</td>
<td>mbar x 1 x 10^{-3}</td>
<td>30</td>
<td>7.4</td>
</tr>
<tr>
<td>(Ar)</td>
<td>mbar x 1 x 10^{-3}</td>
<td>20</td>
<td>6.8</td>
</tr>
<tr>
<td>(He)</td>
<td>mbar x 1 x 10^{-3}</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>(H_2)</td>
<td>mbar x 1 x 10^{-3}</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Compression ratio</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(N_2)</td>
<td></td>
<td>5 x 10^{6}</td>
<td></td>
</tr>
<tr>
<td>(Ar)</td>
<td></td>
<td>1 x 10^{6}</td>
<td></td>
</tr>
<tr>
<td>(He)</td>
<td></td>
<td>1 x 10^{4}</td>
<td></td>
</tr>
<tr>
<td>(H_2)</td>
<td></td>
<td>2 x 10^{2}</td>
<td></td>
</tr>
<tr>
<td>Ultimate pressure</td>
<td>mbar (Torr)</td>
<td>&lt; 3 x 10^{10}</td>
<td>&lt; 3 x 10^{10}</td>
</tr>
<tr>
<td>Max. foreline pressure for (N_2)</td>
<td>mbar (Torr)</td>
<td>0.6 x 376</td>
<td>0.6 x 376</td>
</tr>
<tr>
<td>Purge/vent port</td>
<td>DN</td>
<td>G 1/4&quot;</td>
<td>G 3/8&quot;</td>
</tr>
<tr>
<td>Weight, approx.</td>
<td>kg (lbs)</td>
<td>100 - 240</td>
<td>40 (88)</td>
</tr>
<tr>
<td>Max. power consumption</td>
<td>VA</td>
<td>700</td>
<td>700</td>
</tr>
</tbody>
</table>

AA 2011/2012
Stationary systems: distributed throughput

- Accelerators, beam pipes, ecc.

\[ -dQ = q_D B dx \]

\[ dQ = CL \frac{d^2 P}{dx^2} \]  
\[ d^2 P = \frac{dQ}{dx} = \frac{q_D B}{CL} \]

For \( x = L : \frac{dP}{dx} \bigg|_L = 0 \Rightarrow k_1 = q_D B / C \)

\[ \frac{dP}{dx} = - \left[ \frac{q_D B}{CL} \right] x + q_D B / C \]

\[ P = - \left[ \frac{q_D B}{2 CL} \right] \cdot x^2 + \left( \frac{q_D B}{C} \right) x + k_2 \]

For \( x = 0 : P_0 = q_D B L / S_p = k_2 \)

\[ P = q_D B \left( \frac{L}{S_p} + \left( \frac{x}{C} \right) - x^2 / (2 CL) \right) \]

\[ \Delta P = P_x - P_0 = q_D B \left[ \frac{x}{C} - x^2 / (2 CL) \right] \]

\[ P_L - P_0 = q_D B L / (2 C) \]

Distributed pumping

- Pressure drop \( \Delta p \) is independent from \( S_p \).

\[ Q(\ x\ ) \] throughputs \( \frac{t}{A} \) \[ q(x) \] \( \frac{m^3}{s} \] \( - \frac{dQ}{dx} = Bq \)

Outgassing \( \frac{q(x)}{A} \) \( \frac{Pa}{m} \) \( - \frac{dQ}{dx} = Bq \)

Superficie per unità di \( 1 \) \( \frac{A}{m} \) \( q(x) \)

Conduzzanza a specifica \( c \) \( \frac{m^2}{s} \) \( c = CL \)

Boundary condition

\[ \left. \left[ \frac{dP}{dx} \right] \right|_{x=L} = 0 \]

\[ P(0) = Q(0) / 2 S \]

\[ Q(0) = 2BqL \]
... Distributed pumping

\[ P(x) = Bq \left( \frac{2 Lx - x^2}{2c} + \frac{L}{S} \right) \]

\[ P_{\text{ave}} = \frac{1}{2L} \int_0^L P(x) \, dx = Bq \left( \frac{L^2}{3c} + \frac{L}{S} \right) \]

\[ P_{\text{max}} = Bq \left( \frac{L}{S} \right) \]

\[ P_{\text{min}} = Bq \left( \frac{L^2}{3c} + \frac{L}{S} \right) = Bq \left( \frac{L}{3C} + \frac{L}{S} \right) \]

\[ P_{\text{min}} \xrightarrow{S \to \infty} Bq \frac{L^2}{3c} = Bq \frac{L}{3C} \]

It is possible to have a more homogeneous pressure, where \( P_{\text{max}} \) can be “controlled” by the pumping speed \( S \) the distance in between the pumps and the conductance of the tube.

**Table of formula for rough design of vacuum system**

**usually tube or circle aperture**

<table>
<thead>
<tr>
<th></th>
<th>viscous</th>
<th>molecular</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture A</td>
<td>( 20 \frac{A}{1-P_2/P_1} )</td>
<td>( 3.64 \left( \frac{T}{M} \right)^{1/2} A )</td>
</tr>
<tr>
<td>Long tube</td>
<td>( \frac{\pi D^4}{128 \eta L} P_{\text{ave}} )</td>
<td>( 3.81 \left( \frac{T}{M} \right)^{1/2} \left( \frac{D^3}{L} \right) )</td>
</tr>
<tr>
<td>Short tube</td>
<td>( \frac{1}{1} \frac{C_{st}}{C_{lt}} + \frac{1}{1} C_A )</td>
<td>( 12.1 \frac{D^3}{L} )</td>
</tr>
</tbody>
</table>

\( P_{\text{ave}} = \) average pressure

In red air at \( T = 20 \, ^\circ C \)

\( L, D \) in cm, \( A \) in cm\(^2\), \( T \) in K and \( C \) in l/s