Vacuum technology: Flow, throughput, conductance, and pumping speed

- Gases flowing in a pipe are characterized by the *nature* of the gas (Knudsen's number) and by the *relative quantity* of gas (Reynold's number).

- **Knudsen's number**:

$$K n = \frac{\lambda}{d} \tag{1}$$

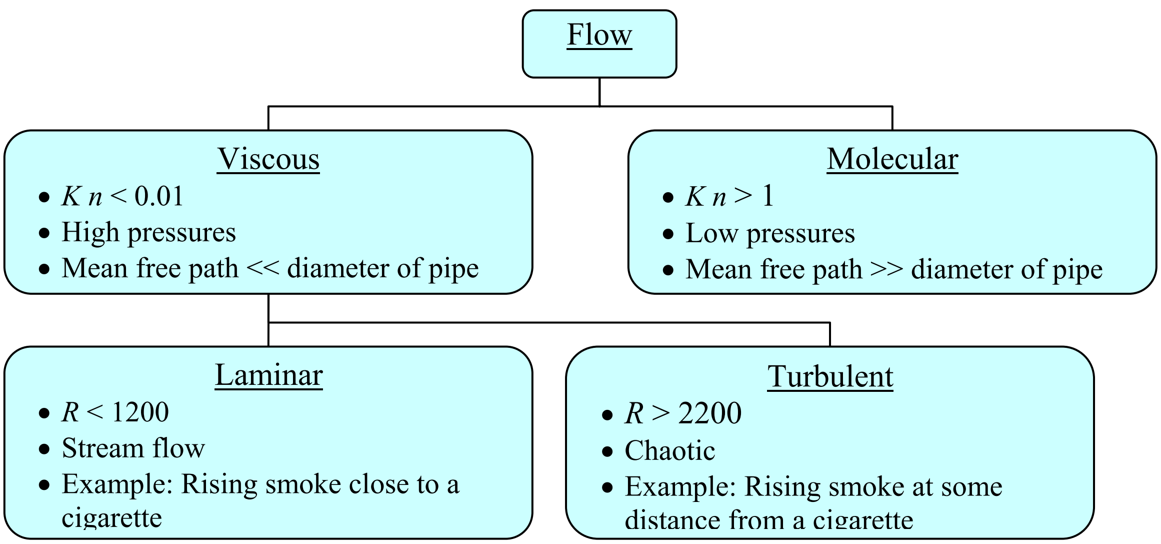
Where, λ = mean free path of gas molecules, d = pipe diameter.

- **Reynold's number**:

$$R = \frac{U \rho d}{\eta} \tag{2}$$

where, U = stream velocity, ρ = mass density, d = pipe diameter, η = gas viscosity.

- Various flow regimes are illustrated in the chart below:



- **Throughput** of a gas is defined as the quantity of gas (the volume of gas at a known pressure) that passes a plane within a known time.

$$Q = \frac{\mathrm{d}}{\mathrm{d}t}(P V) \tag{3}$$

where, P = gas pressure and V = gas volume.

Units: Pa m^3/s, Torr liters/s.

The throughput can be considered as the gas load.

- **Conductance:** The flow of gas in a duct or pipe, at constant temperature, is dependent on the pressure drop across the object as well as its cross-sectional geometry.

$$C = \frac{Q}{P_2 - P_1} \quad (4)$$

where $P_2 - P_1$ = pressure drop across the component (duct or pipe).

Units: m^3/s, liters/s.

- The conductance of a long round tube in the molecular flow regime is given by,

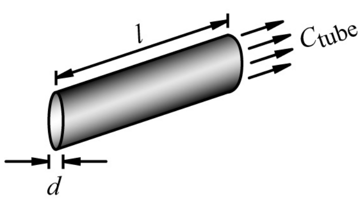
$$C_{tube} = \frac{\pi}{12} v \frac{d^3}{l} \quad (5)$$

where, d = tube diameter, l = tube length, and

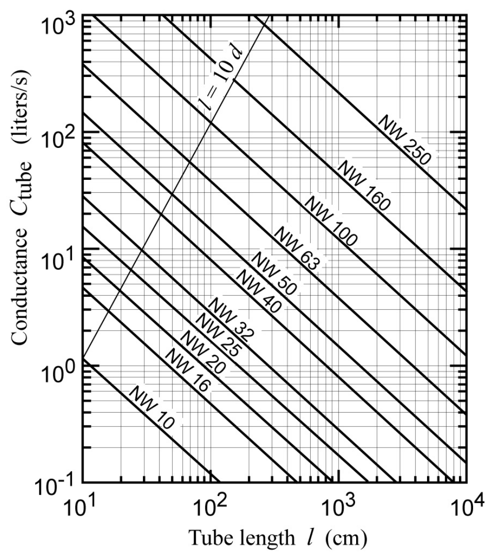
$$v = \left(\frac{8\,kT}{\pi\, m}\right)^{1/2} \quad (6)$$

where, v = average particle velocity and m = particle mass.

For air at 22 °C, v = 445 m/s and $C_{tube} = 121 \frac{d^3}{l}$ m^3/s. (7)



Conductance through a long round tube



Tube conductances for molecular flow of air

- Series and parallel conductances: The conductance of tubes connected in parallel can be obtained from $C_T = C_1 + C_2 + C_3$ … and that of tubes connected in series can be obtained from $1/C_T = 1/C_1 + 1/C_2 + 1/C_3$ … This is analogous to resistors in electronics.
- **Pumping speed:** Pumping speed is the volumetric rate at which gas is transported across a plane.

$$S = \frac{Q}{P} \quad (8)$$

where, Q = gas throughput and P = pressure at the plane of pressure gauge.

Units: m^3/s, liters/s (same as conductance).

Unlike conductance, pumping speed is not a property of a passive component like the length of a pipe.

- Pumping speed under load for mechanical pumps:

$$S = \frac{Q}{P - P_b} \qquad (9)$$

where, P = measured pressure and P_b is the base pressure with zero gas flow.

- Effective pumping speed at the chamber:

$$\frac{1}{S_{Eff}} = \frac{1}{S_P} + \frac{1}{C} \qquad (10)$$

where, S_{Eff} = Effective pumping speed, S_p = speed of the pump, C = conductance between the pump and the chamber.

- **Example 1:** Consider a round tube of length 3 m and diameter 40 mm connected between the vacuum chamber and the roughing pump. What is the conductance of this tube for air in molecular flow regime?

  Solution: From (7) we find that C_{tube} = 2.6 liters/s.

- **Example 2:** If the roughing pump has a pumping speed of 23 liters/s, what is the effective pumping speed at the chamber?

  Solution: From (10) we get S_{Eff} = 2.3 liters/s. This is an order of magnitude less than the actual pump speed. Also note that the effective pumping speed is always lower than the least conductive component in series with the pump.

- **Example 3:** What can be done to increase the effective pumping speed at the chamber?

  Solution: Increase the pump speed or increase the conductance of connecting tubing.

- **Example 4:** If this pump is replaced with bigger pumps with pumping speeds of 100 liters/s and 1000 liters/s respectively, what is the effective pumping speed?

  Solution: 2.53 liters/s and 2.59 liters/s!

- **Example 5:** If the tube dimensions are changed to 1 m length and 60 mm diameter, what would be the effective pumping speed with the 23 liters/s pump?

  Solution: C_{tube} = 26 liters/s and S_{Eff} = 12 liters/s. Increasing the tube conductance is much more effective than increasing the pump speed.

- **Note:** For $C_{tube} = S_p$, $S_{Eff} = S_p/2$. For example, if a 40 mm diameter tube gives us the same conductance as our pump speed with a length of 0.5 m, our S_{Eff} drops by half for every 0.5 m of this tube.