Venting of Vacuum Systems

R Gordon Livesey

1st Vacuum Symposium UK

11/02/2010

Lynthorpe Consultancy

Outline

Bringing a vacuum chamber back up to atmosphere (or some intermediate pressure) appears to be a simple process. However, in rapid venting, there is more to consider than might be thought.

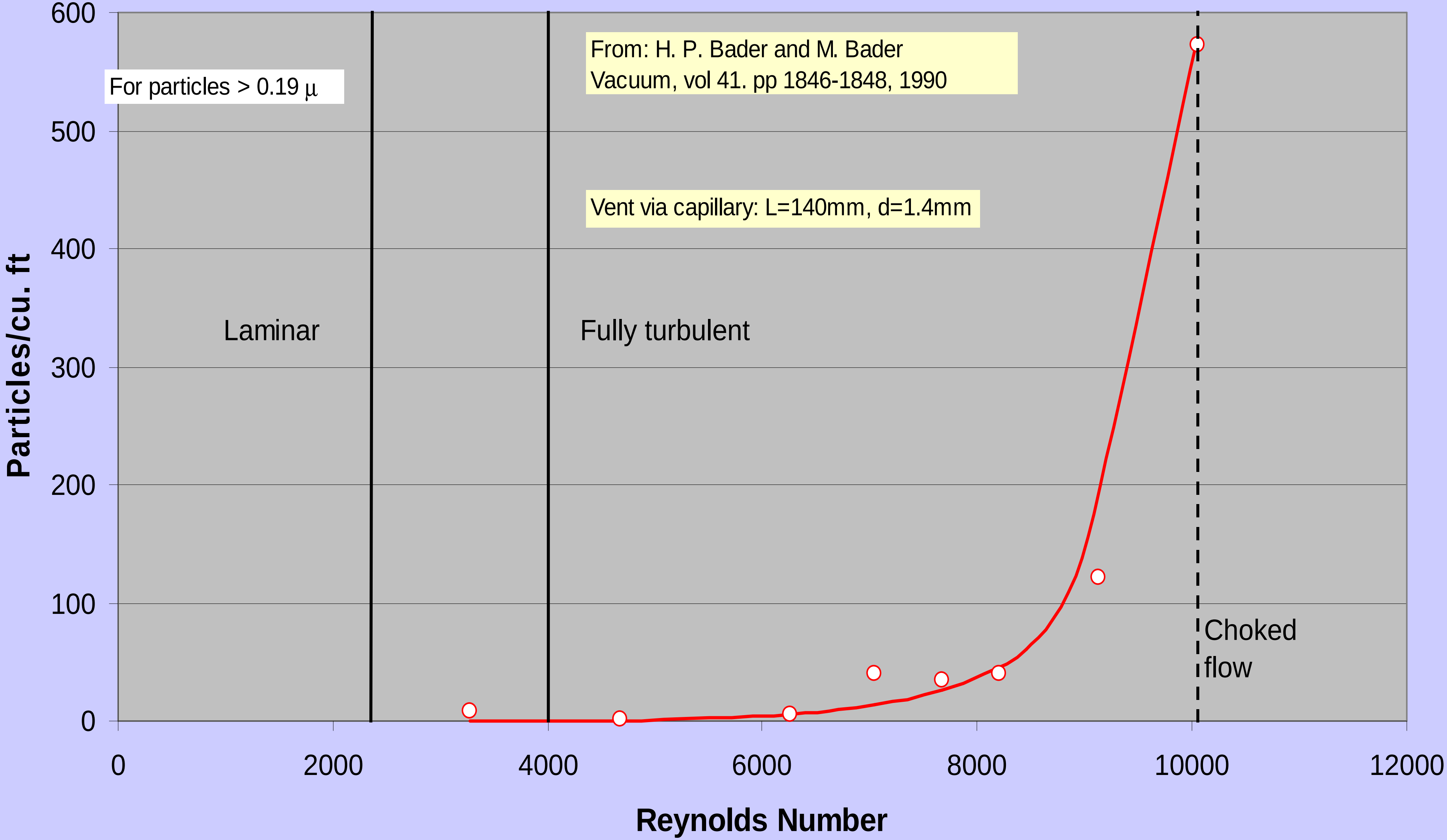
The talk will cover:

- Dust movement
- Temperature effects
- Relations for Vent time

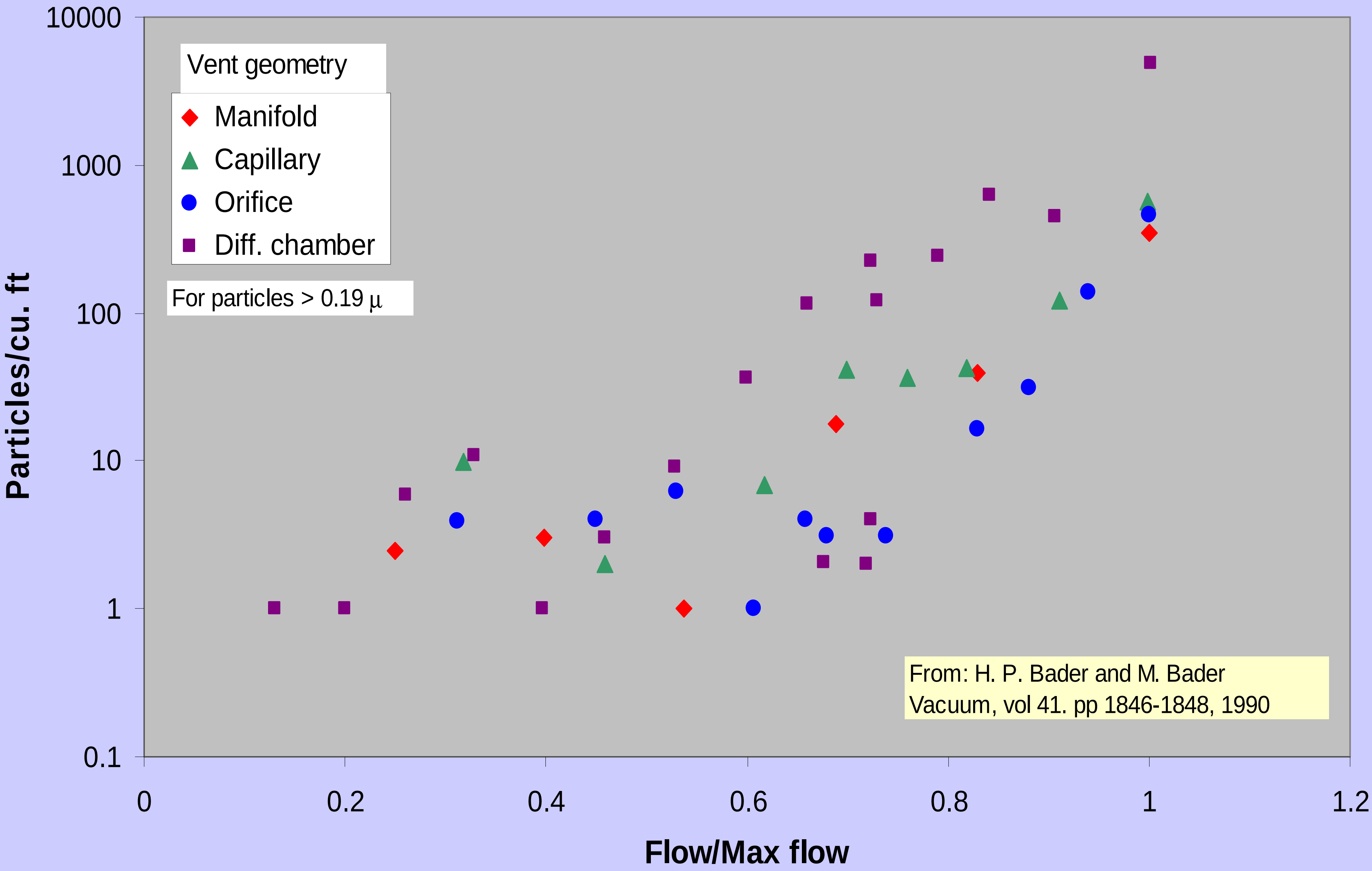
Particulates

- Dust particles are a serious problem in many vacuum processes e.g. semiconductor, telescope mirror coaters
- Venting may introduce dust or cause resuspension - since it is difficult to avoid turbulent gas eddies
- Historically, the guideline adopted has been to ensure that Reynolds numbers are kept below 2300
- However, experimental evidence indicates that Reynolds numbers ≤ 5000 or gas flow velocities $\leq$ ½ maximum do not cause resuspension of particles in vent lines (and, by implication, in the vacuum chamber)

Resuspension of particles in vent line



Resuspension of particles in vent line



Particles subject to molecular drag

Drag force on a spherical particle*: $F = \left(\frac{8+\pi}{3}\right)\sqrt{\frac{2\pi M}{R_0 T}}\, r^2 P u$

M, T, P = molecular mass, temperature and pressure of gas through which particle is travelling, r = radius and u = velocity of particle

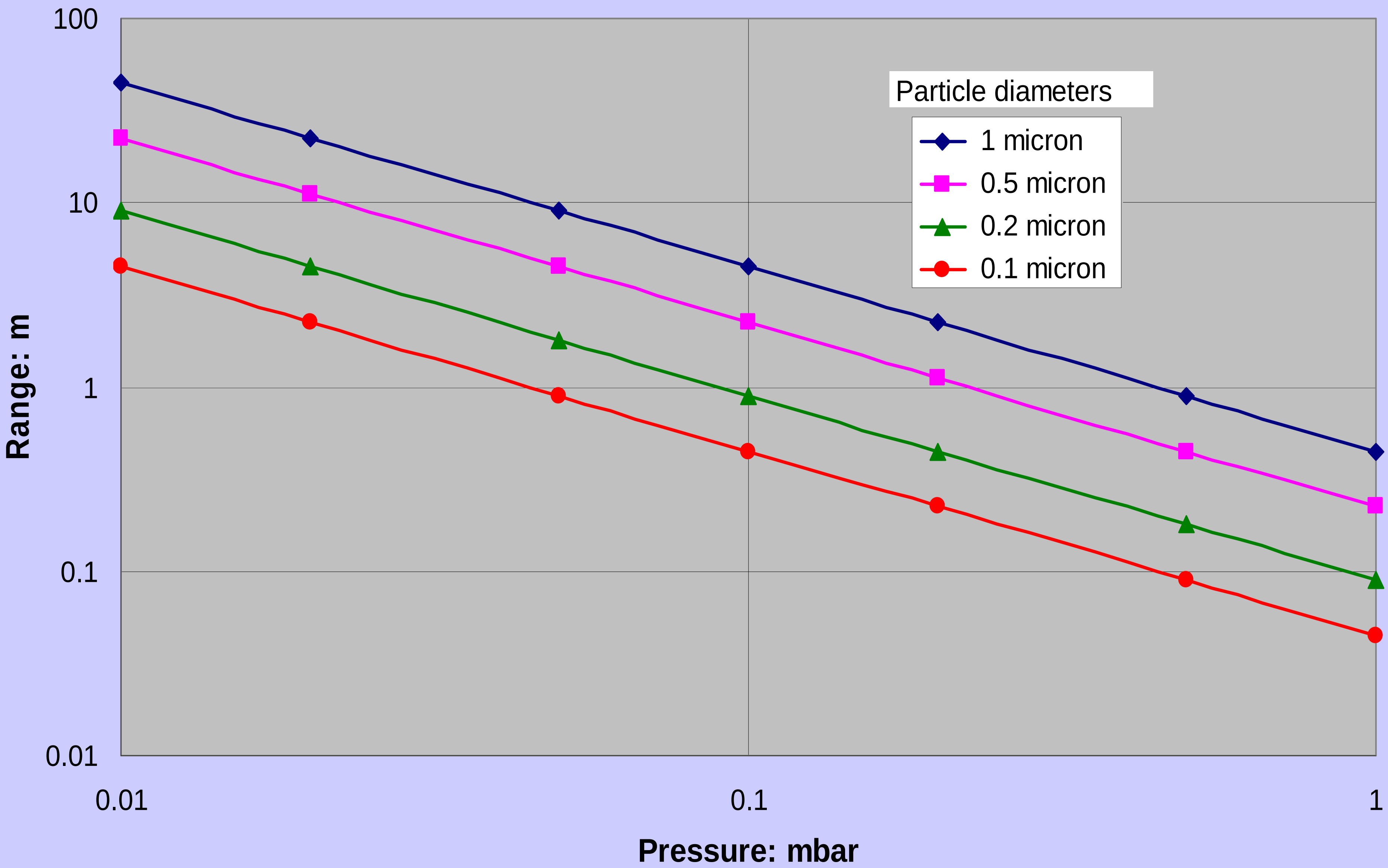
Range: $X_{max} = U_0 \frac{2}{8+\pi}\sqrt{\frac{2\pi R_0 T}{M}}\,\frac{\rho r}{P}$ Velocity: $u = U_0\left(1 - \frac{X}{X_{max}}\right)$

U_0 = initial velocity and ρ = density of particle

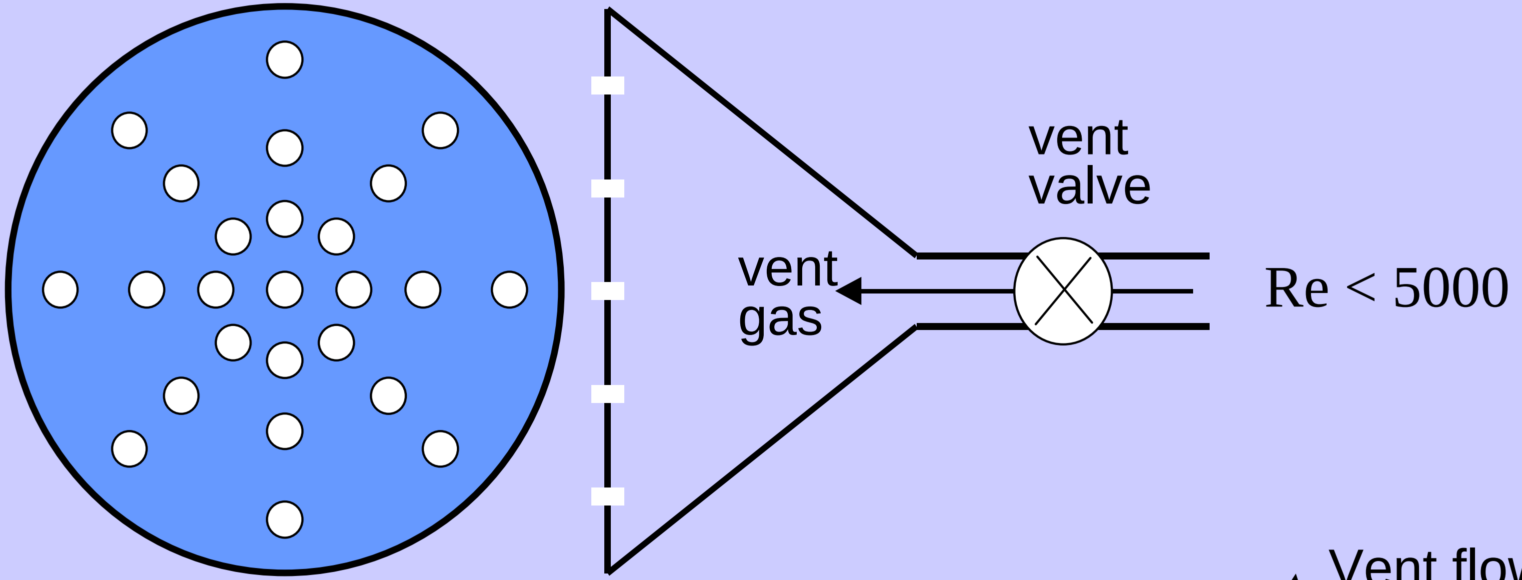
- Particles injected into a vacuum chamber at high velocity can travel large distances and may damage delicate equipment
- In the next slide the air inlet flow is taken to be choked, so its exit temperature will be 244K and velocity 313 m/s. Chamber air is assumed to be at 293K

* Epstein P. S. Phys. Rev. 23, 710-733 (1924)

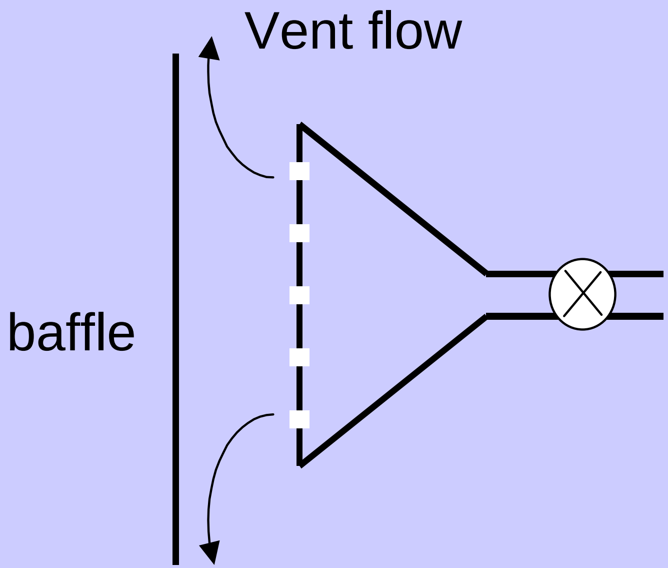
Range of silica particles injected at 313 m/s



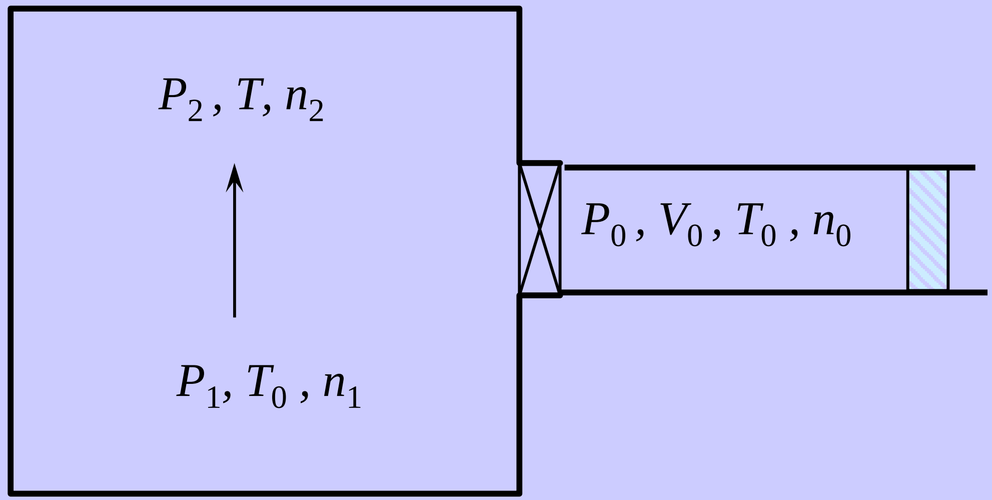
Suggested vent arrangement



‘Showerhead’



Thermodynamics of venting



n_0 moles of gas enter the chamber, and the pressure and temperature rise from P_1 , T_0 to P_2 , T

From the first law: $\Delta Q = \Delta U + \Delta W = 0$ for an adiabatic process

ΔU = change in internal energy

ΔW = Work done on the gas = - $P_0 V_0$

Adiabatic temperature on venting

$$U_{final} - U_{start} = P_0 V_0$$

$$n_2 C_v T - (n_1 C_v T_0 + n_0 C_v T_0) = P_0 V_0 = n_0 R_0 T_0$$

$$n_2 C_v T - n_1 C_v T_0 = n_0 T_0 (C_v + R_0) = n_0 C_p T_0$$

$$(n_2 - n_1) C_p T_0 = n_2 C_v T - n_1 C_v T_0$$

$$\left(\frac{P_2 V}{T} - \frac{P_1 V}{T_0} \right) \gamma T_0 = P_2 V - P_1 V$$

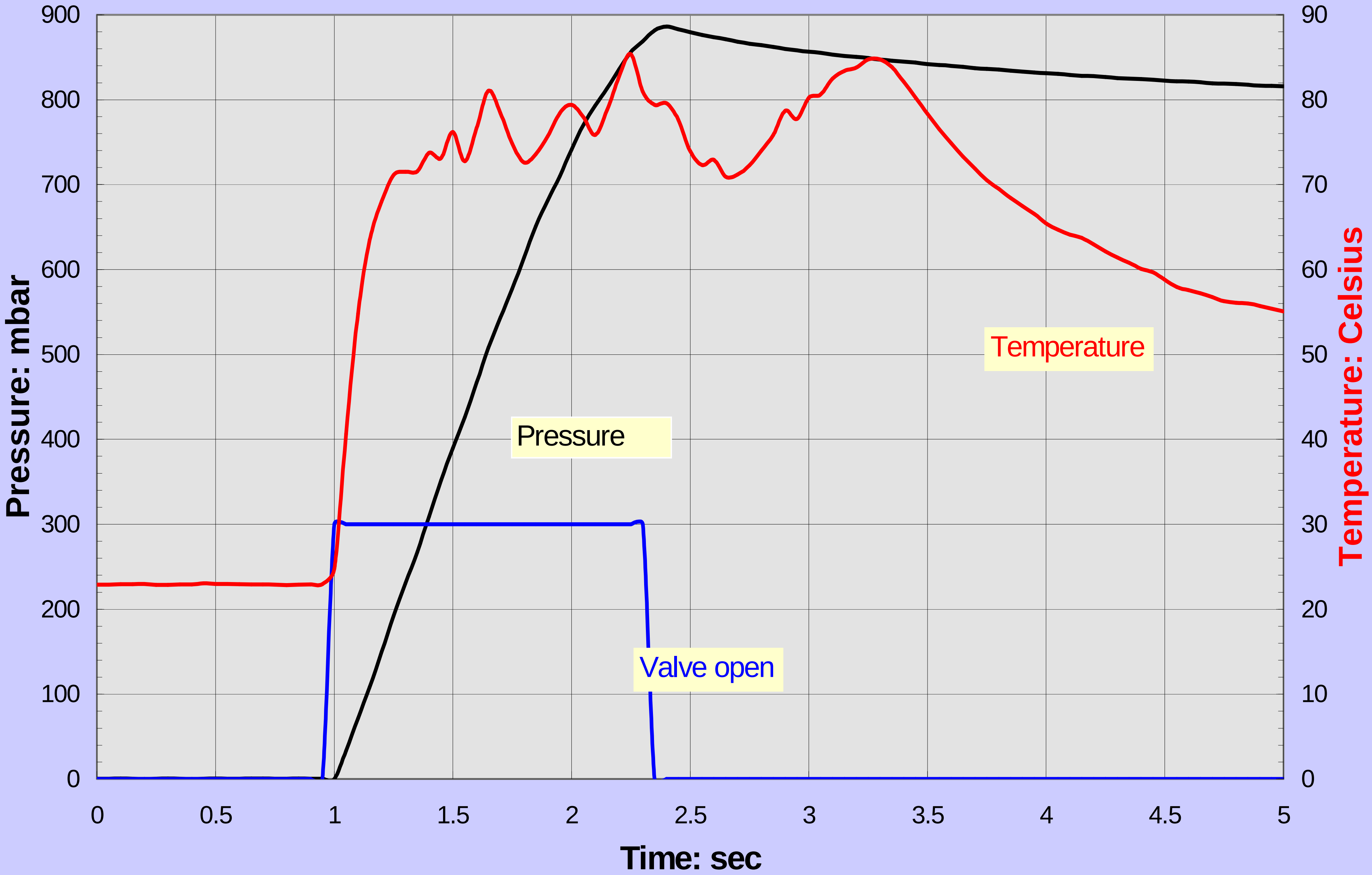
$$\therefore \quad T = T_0 \frac{\gamma P_2}{P_2 + (\gamma - 1) P_1}$$

If $P_1 << P_2$ then $T \rightarrow \gamma T_0$

Venting temperatures

- This implies an adiabatic bulk temperature of ~ 410K, 137^{o}C (for source air at 293K) - a temperature rise of almost 120K
- But this is only the bulk mean temperature of the gas in the chamber, local temperatures in parts of the incoming jet can significantly exceed this temperature
- The actual bulk mean temperature will be < 410K due to heat transfer to the chamber walls and this temperature will generally be greatest in larger chambers
- Note that, once the vent valve is closed, the pressure in the chamber will fall as the gas cools

Venting of a 10 litre chamber (Air)



Vent time formulas - assumptions

- Derivation of vent time expressions make the following assumptions:
  - Source gas pressure and temperature are constant
  - Inflow is through a short duct or orifice
  - Formulas for gas flow rate through vent tubulation are given by thermodynamic analysis
  - Entrance to vent tubulation is smooth (orifice coefficient = 1)
  - Isothermal case assumes gas accommodates to chamber temperature after inrush
  - Adiabatic case assumes no heat transfer in chamber

Vent time - vacuum to source pressure

Isothermal: $t_{vi} = \tau\sqrt{2(\gamma+1)}$

Adiabatic: $t_{va} = t_{vi}/\gamma$

where $\tau = \dfrac{V}{Ac}$

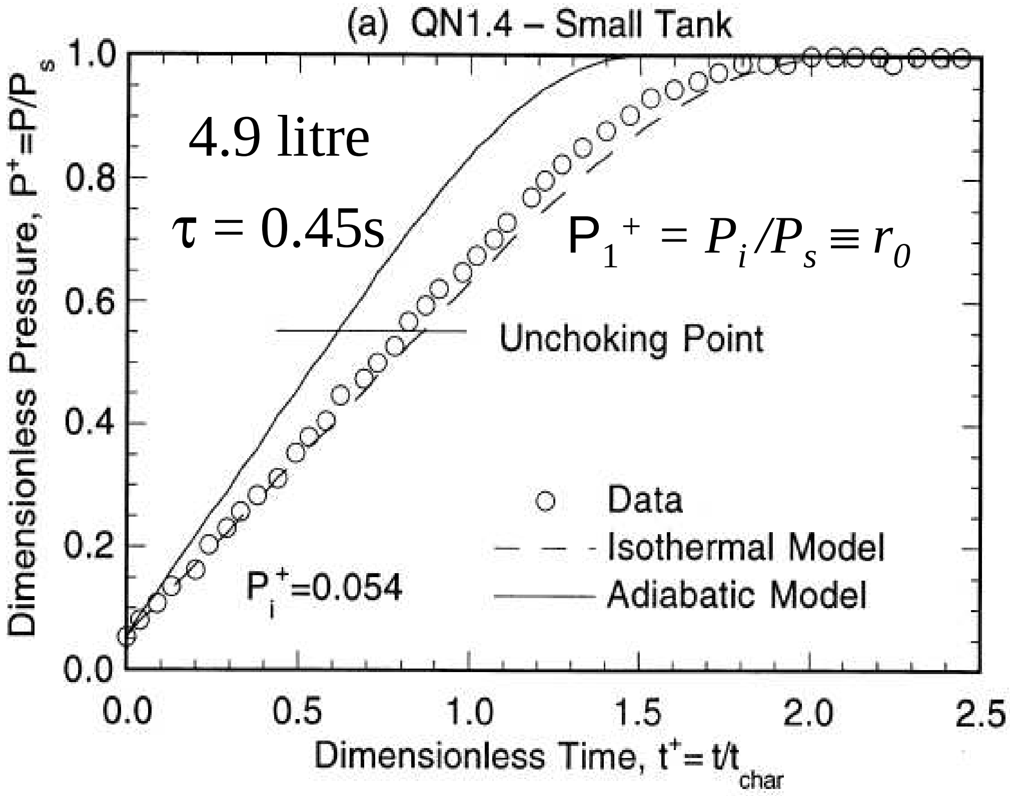
V = chamber volume
A = vent port cross-section area
c = velocity of sound (at source condition)
= 343 m/s for air at 20^{o}C

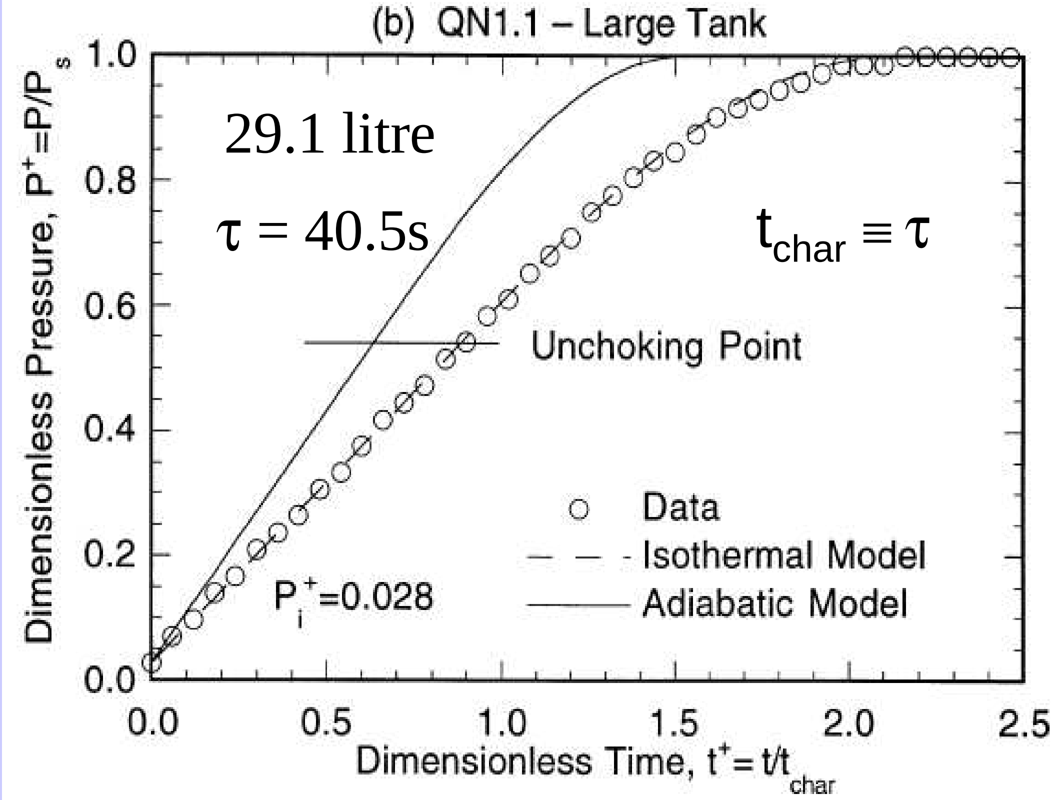
Isothermal: $= 2.19\tau$

Adiabatic: $= 1.56\tau$

for air at 20^{o}C

Vent time - published results





$t_v = 1.47\tau$ ← Calculated times allowing for initial finite pressure → $t_v = 1.51\tau$

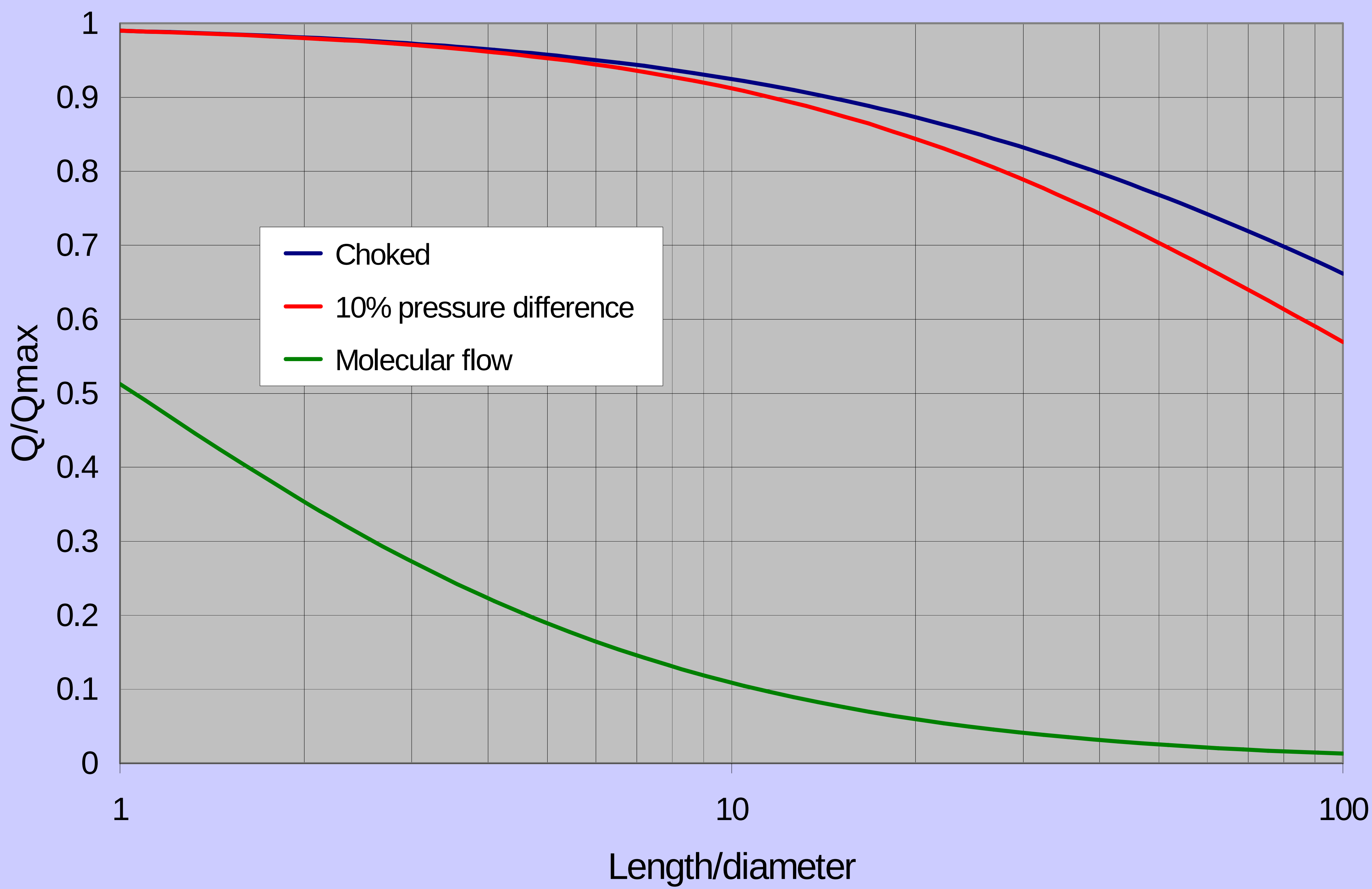
Even for rapid filling (small tank < 1 sec) the results are closer to isothermal

Dutton J.C. and Coverdill R.E., ‘Experiments to Study the Gaseous Discharge and Filling of Vessels’ Int. J. Engng Ed. Vol. 13, No. 2, p. 123-134, 1997

Inaccuracies in vent time formulas

- The time formulas assume isothermal or adiabatic conditions in the volume
- Actual time will lie between t_{vi} and t_{va}
- Again note that, once the vent valve is closed, the pressure in the chamber will fall as the gas cools
- The vent valve may have some length, which will tend to reduce vent flow rates. However, (continuum) flow rates through short ducts are very insensitive to length

Flow rate vs Tube Length



The End

Thank you

Thanks to EDWARDS for some of the material used in this presentation