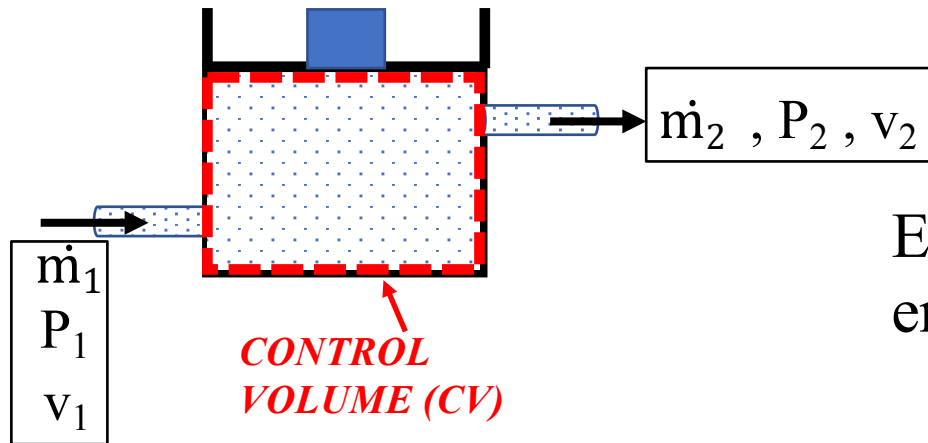


OPEN SYSTEM:

Recap...



1st Law open system

$$\Rightarrow \Delta \dot{U}_{CV} = \dot{q} + \dot{w} + \frac{d}{dt} [\text{Stream flow energy}]$$

Closed system

Each unit of stream carries with a total

$$\text{energy} = \underbrace{u}_{\text{Internal energy}} + \underbrace{\frac{1}{2} v^2}_{\text{Kinetic energy}} + \underbrace{z g}_{\text{Potential energy}}$$

v = velocity

z = elevation from the ground

g = gravitational acceleration

Thus, stream of mass “ m ” transport energy as the rate = $\dot{m} (u + \frac{1}{2} v^2 + z g)$

$$\Rightarrow \Delta \dot{U}_{CV} = \dot{q} + \dot{w} + [\dot{m}_1 (u_1 + \frac{1}{2} v_1^2 + z_1 g) - \dot{m}_2 (u_2 + \frac{1}{2} v_2^2 + z_2 g)]$$

Work rate (\dot{w}) $\dot{w} = \dot{w}_{cv} + \text{Flow work}$

$$\text{Flow work} = P A v$$

$$\dot{m} = \rho A v$$

$$\text{Flow work} = P A v = P \dot{m} \bar{V}$$

Recap...

Mass of the system within the control volume is constant

$$\dot{m}_1 = \dot{m}_2 = \dot{m}$$

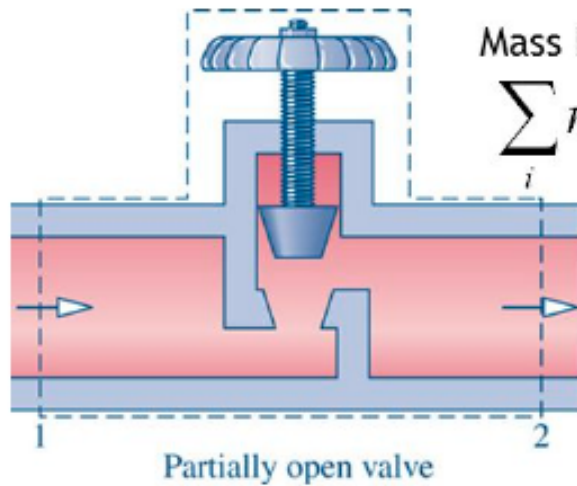
$$\Delta \dot{U}_{CV} = \dot{q} + \dot{w}_{cv} + \dot{m} \Delta (\bar{H} + \frac{1}{2} v^2 + zg)$$

Steady Flow $\Delta \dot{U}_{CV} = 0$

$$\dot{q} + \dot{w}_{cv} + \dot{m} \Delta (\bar{H} + \frac{1}{2} v^2 + zg) = 0$$

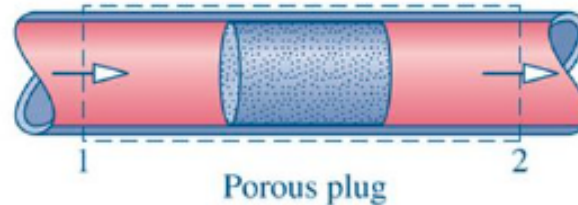
RECAP...

Throttling Device: Reduces Pressure



Mass Balance:

$$\sum_i \dot{m}_{in} = \sum_i \dot{m}_{exit} \rightarrow \dot{m}_{in} = \dot{m}_{exit} = \dot{m}$$



Typical Energy Balance simplifications,

$$\frac{dU_{cv}}{dt} = \dot{Q}_{cv} + \dot{W}_{cv} + \dot{m}_i \left(h_i + \frac{v_i^2}{2} + gz_i \right) - \dot{m}_e \left(h_e + \frac{v_e^2}{2} + gz_e \right)$$

Steady State $\rightarrow \frac{dU_{cv}}{dt} = 0$
 No heat transfer $\rightarrow \dot{Q}_{cv} = 0$
 No work $\rightarrow \dot{W}_{cv} = 0$
 $\Delta v \approx 0 \rightarrow \frac{v_i^2}{2} \approx \frac{v_e^2}{2}$
 Horizontal Section (or very short vertical) $\rightarrow gz_i \approx gz_e$
 $h_i = h_e$

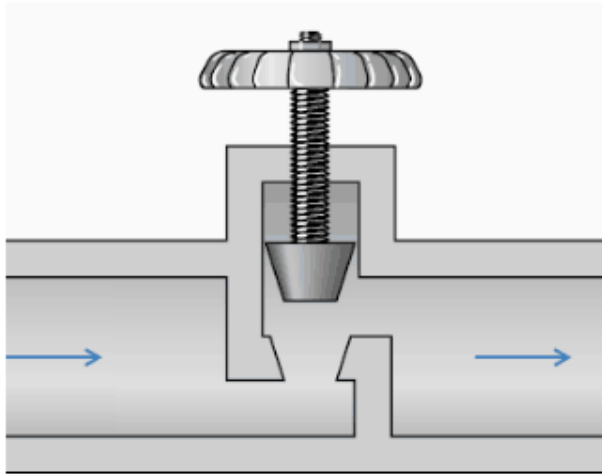
Throttling devices

$$H_1 = H_2 \text{ (isoenthalpic)}$$

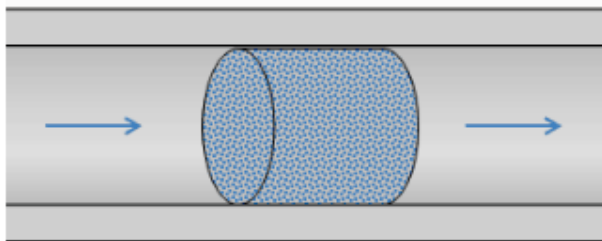
Throttling process

$$p_{in} > p_{out}$$

$$h_{in} = h_{out}$$



partially open valve



porous plug

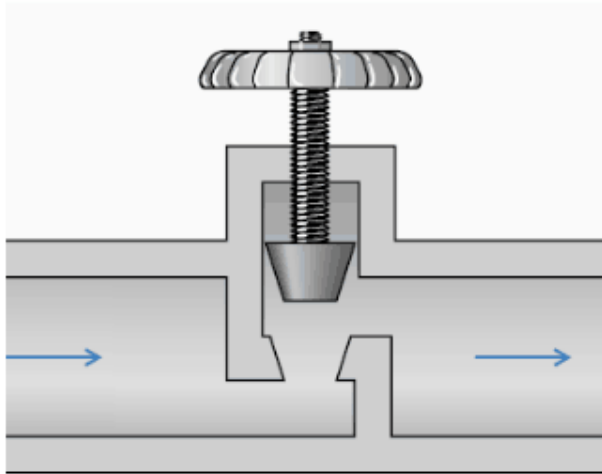
Joule–Thomson effect (also known as the **Joule–Kelvin effect** or **Kelvin–Joule effect**) describes the temperature change of a *real* gas or liquid (as differentiated from an [ideal gas](#)) when it is forced through a [valve](#) or [porous plug](#) while keeping it insulated so that no heat is exchanged with the environment.

This procedure is called a *throttling process* or *Joule–Thomson process*

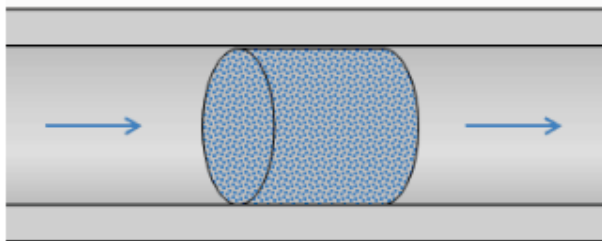
Throttling process

$$p_{in} > p_{out}$$

$$h_{in} = h_{out}$$



partially open valve



porous plug

Joule–Thomson
coefficient

$$\mu_{JT} = \left(\frac{\partial T}{\partial P} \right)_H \quad \text{Isoenthalpic}$$

$$\mu_{JT} = \left(\frac{T_2 - T_1}{P_2 - P_1} \right)_H$$

$$\Rightarrow T_2 = T_1 + \mu_{JT}^* (P_2 - P_1)$$

$$\Rightarrow T_2 = T_1 - \mu_{JT}^* (P_1 - P_2)$$

$$P_1 = P_{in}$$

$$P_2 = P_{out}$$

$$(P_1 - P_2) > 0 \quad (\text{Always})$$

Case I: $T_2 < T_1$ if $\mu_{JT} > 0$ (**cooler**)

Case II: $T_2 > T_1$ if $\mu_{JT} < 0$ (**Warmer**)

Case III: $T_2 = T_1$ if $\mu_{JT} = 0$ (**No change**)

Ideal Gas (μ_{JT}) ?

$$H(T,P)$$

$$\Rightarrow dH = \left(\frac{\partial H}{\partial T}\right)_P dT + \left(\frac{\partial H}{\partial P}\right)_T dP$$

$$\Rightarrow dH = C_p dT + \left[V - T \left(\frac{\partial V}{\partial T}\right)_P \right] dP$$

$$\Rightarrow 0 = C_p dT + \left[V - T \left(\frac{\partial V}{\partial T}\right)_P \right] dP$$

$$\Rightarrow \left(\frac{\partial T}{\partial P}\right)_H = - \frac{\left[V - T \left(\frac{\partial V}{\partial T}\right)_P \right]}{C_p}$$

$$\Rightarrow \mu_{JT} = - \frac{\left[V - T \left(\frac{\partial V}{\partial T}\right)_P \right]}{C_p}$$

(Isoenthalpic process)

Lecture 6

- At constant P , the energy added as heat is q_p , ($\Delta H = q_p$)

$$C_p = \left(\frac{\partial H}{\partial T}\right)_P \approx \frac{\Delta H}{\Delta T} = \frac{q_p}{\Delta T}$$

$$H = U + PV$$

$$\Rightarrow dH = dU + PdV + VdP$$

$$\Rightarrow dH = dq + VdP \text{ (1st Law)}$$

$$\Rightarrow dH = TdS + VdP \text{ (2nd Law)}$$

$$\Rightarrow \left(\frac{\partial H}{\partial P}\right)_T = T \left(\frac{\partial S}{\partial P}\right)_T + V$$

$$\Rightarrow \left(\frac{\partial H}{\partial P}\right)_T = - T \left(\frac{\partial V}{\partial T}\right)_P + V \text{ (Maxwell relation)}$$

$$\Rightarrow \left(\frac{\partial H}{\partial P}\right)_T = V - T \left(\frac{\partial V}{\partial T}\right)_P$$

Ideal Gas (μ_{JT})

$$\mu_{JT} = - \frac{[V - T \left(\frac{\partial V}{\partial T}\right)_P]}{C_p}$$

$$PV = nRT$$

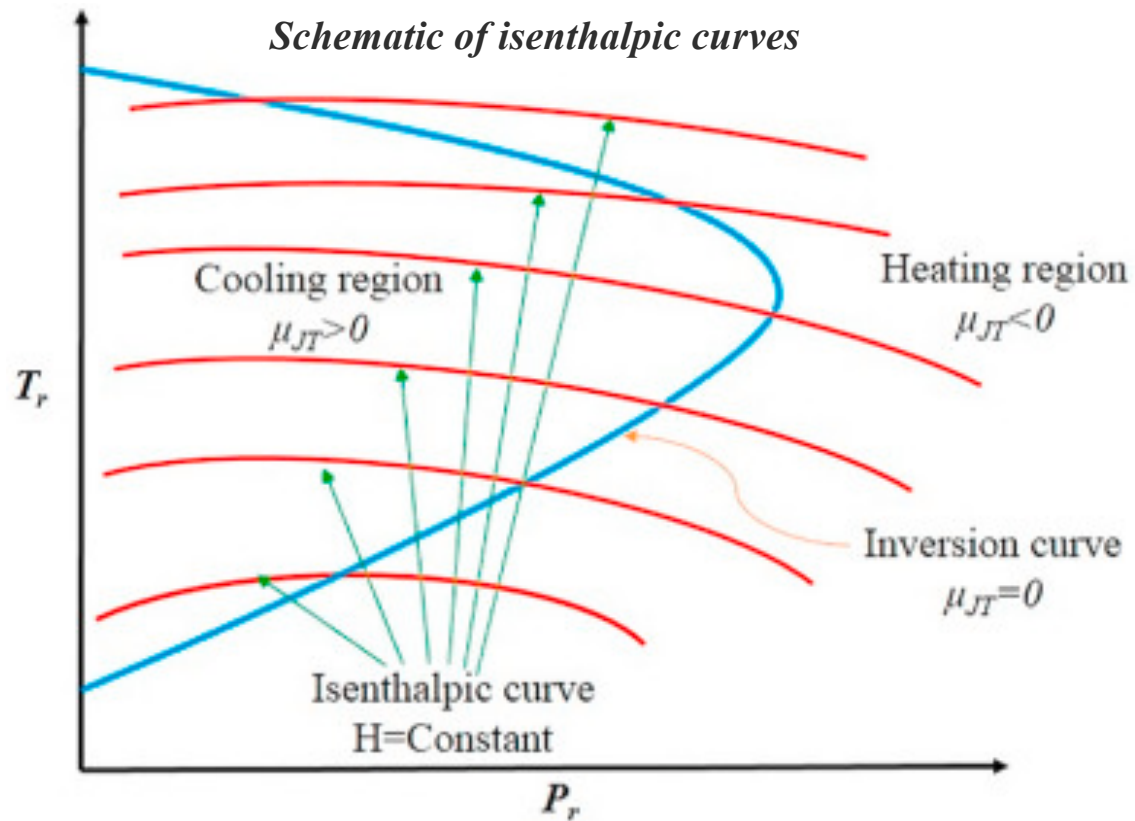
$$\Rightarrow V = (nRT/P)$$

$$\Rightarrow \left(\frac{\partial V}{\partial T}\right)_P = \frac{nR}{P}$$

$$\mu_{JT} = - \frac{[V - T \frac{nR}{P}]}{C_p} = - \frac{[V - V]}{C_p} = 0$$

Conclusion: No change in Temp for Ideal Gas during *throttling*

Real Gas (μ_{JT}) ?



$$\mu_{JT} = \left(\frac{\partial T}{\partial P} \right)_H$$

Journal of Natural Gas Science and Engineering 83 (2020): 103570

Joule-Thomson coefficient, μ

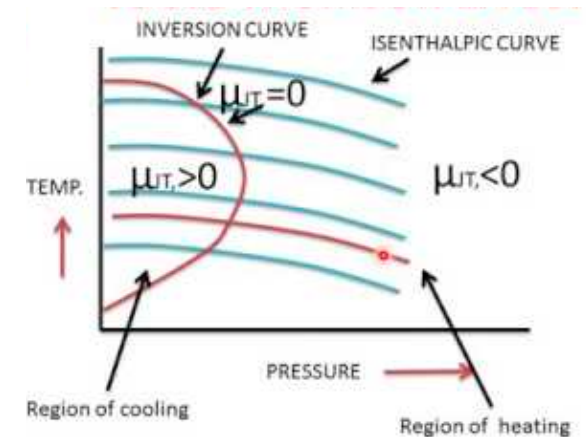
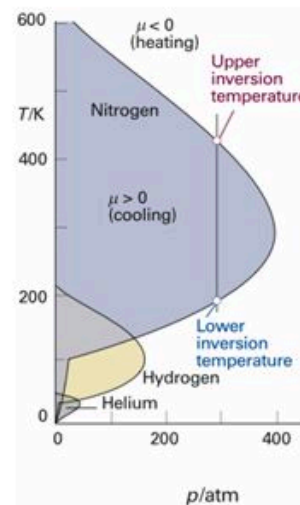
- For perfect gases $\mu = 0$

- For real gases

$\mu > 0$ gas cools on expansion

$\mu < 0$ gas heats on expansion

- Inversion temperature



Exception: **hydrogen, helium, and neon cool upon expansion** by the Joule–Thomson process when being throttled through an orifice.

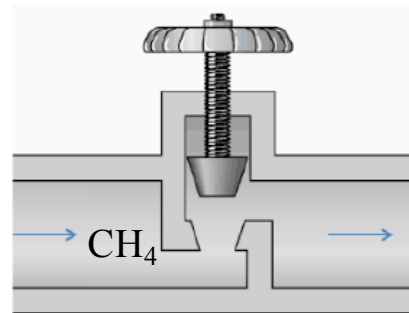
These gases **heated up** by the same process **only at lower temperatures**.

Effect in Natural-gas separation

JT effect: 7°F decrease per 100 psi pressure drop for CH₄ (natural gas).

1 atm = 14.6959 psi

T₁ = 100 °F
P₁ = 1100 psi



P₂ = 100 psi

T₂ = 30°F

Freezing point of water = 32°F

ΔP = 1000 psi

PREVENT FREEZING VALVES



Real Gas (μ_{JT}) : Derivation

From known equations of state, the sign and magnitude of the Joule-Thomson coefficient can be calculated.

The Van der Waals Equation serves as an example:

$$\left(P + \frac{an^2}{V^2}\right)(V - nb) = nRT$$

which can be differentiated after neglect of the smallest magnitude term to give:

$$\left(\frac{\partial V}{\partial T}\right)_P = \frac{nR}{P} + \frac{na}{RT^2}$$

And using the approximation: $\left(\frac{nR}{P}\right) = \frac{V - nb}{T} + \frac{na}{RT^2}$

leads to:

$$\left(\frac{\partial V}{\partial T}\right)_P = \frac{V - nb}{T} + \frac{2na}{RT^2}$$

So the Van der Waals form for the JT coefficient is:

$$\mu_{JT} = \frac{(2na / RT) - nb}{C_P}$$

with an inversion temperature of:

$$T_i = \frac{2a}{Rb}$$

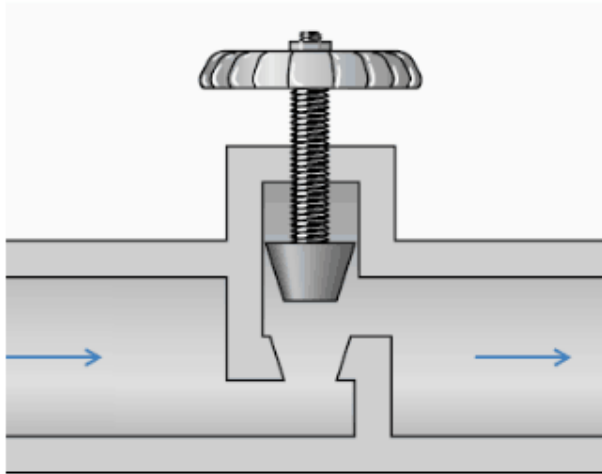
If the neglected term is included, the exact solution is:

$$T_i^2 - \frac{2a}{Rb}T_i + \frac{3a}{R^2} = 0$$

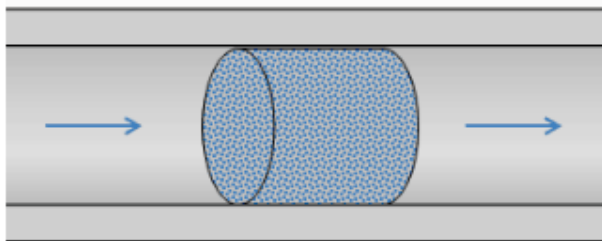
Throttling process

$$p_{in} > p_{out}$$

$$h_{in} = h_{out}$$



partially open valve



porous plug

Physical mechanism JT effect

$$H_1 = H_2 \text{ (isoenthalpic)}$$

$$\Rightarrow U_1 + P_1 V_1 = U_2 + P_2 V_2 \text{ (definition of enthalpy)}$$

$$\Rightarrow (KE_1 + PE_1) + P_1 V_1 = (KE_2 + PE_2) + P_2 V_2$$

$$\Rightarrow (KE_2 + PE_2) - (KE_1 + PE_1) = P_2 V_2 - P_1 V_1$$

Temperature is linked to KE.

Applications where the cooling of expanding gases is employed are:

- Refrigeration - The pressurisation and expansion of refrigerants in a closed loop systems are the basis of most refrigerators and freezers.
- Air conditioning - Identical to a refrigerator in principal, but optimised for a building, vehicle or other inhabitable space.
- Gas separations - By cooling a gas through an expansion the heavier components will condense into a liquid phase. This is often employed in LPG production, with cooling the first step before fractionation is used to refine the liquids further.
- Liquid Gas Production - The Liquefaction of Gases such as; Ammonia, Chlorine, Nitrogen, Oxygen and Argon is achieved through expansion of the pressurised gases. Often employing several expansion and compression steps.

QUESTIONS and ANSWERS

1. Consider a device with one inlet and one outlet. If the volume flow rates at the inlet and at the outlet are the same, is the flow through this device necessarily steady? Why ?

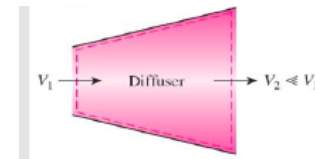
Ans 1: NO. Density of the fluid entering and leaving should be equal, i.e, mass flow rate is equal. NOT volume flow rate

2. Do fluids at rest possess any flow energy?

Ans 2: NO. Flow energy is not a state function. It is the work required to push a fluid through a control volume.

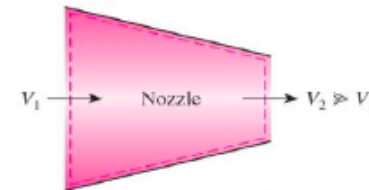
3. A diffuser is an adiabatic device that decreases the kinetic energy of the fluid by slowing it down.
What happens to this *lost* kinetic energy?

Ans 3: Kinetic energy is converted into enthalpy.



4. The kinetic energy of a fluid increases as it is accelerated in an adiabatic nozzle. Where does this energy come from?

Ans 4: From enthalpy.



5. Will the temperature of air rise as it is compressed by an adiabatic compressor? Why?

Ans 5: Yes. Work done increases the internal energy. Hence temp of air increases. Lecture 0 : Burning of cotton.

6. Would you expect the temperature of air (N_2) to drop as it undergoes a steady-flow throttling process? Explain.

Ans 6. No, temperature of air is not expected to drop. As air is a idea gas and during throttling process inlet and outlet enthalpy are equal i.e. $H_1 = H_2$ and h is function of temperature only. hence, air temperature is constant during throttling.

Quiz (BT 202)

Date: 9th Sept 2022 (Friday)

Time: 5 PM – 6 PM (No entry after 5:05 PM)

Venue: Lecture Hall 1

Syllabus: Up to Lecture 8 (L7.pdf)
10 Marks



Next: Review L9-L11, Tutorial 03