ME-251: Thermodynamics and energetics I
Second Law IV

Zhengmao Lu

Energy Transport Advances Laboratory

EPFL Mechanical Engineering

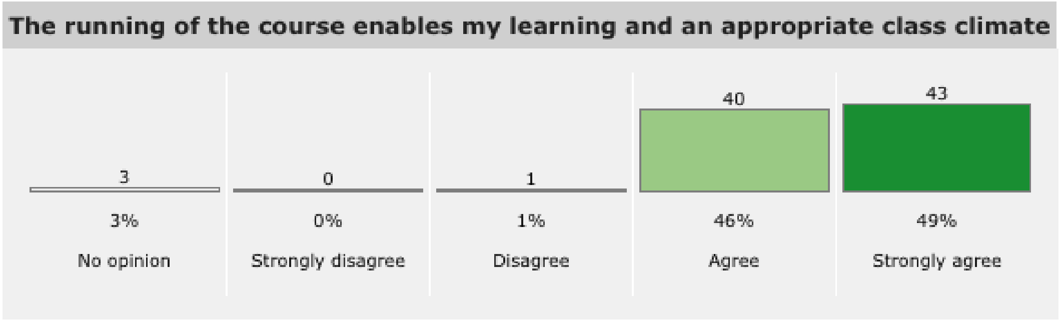
2025 Fall Semester

Photo Credit: Trougnouf

ETA-Lab
Energy Transport Advances

Your Indicative Feedback

Year	2025-2026
Course	Thermodynamics and energetics I
Questionnaire	Indicative feedback of teaching (since 2022-2023)
Nb Registered	345
Nb Answered	87



- Structure and pacing
- Use of CoolProp for exercise problems
- Other improvement suggestions (freezing previous slides, class noise level, writing clarity)

Last Time

- Entropy balance for closed systems

Entropy Balance for Closed Systems

change in the amount of entropy contained within the system during some time interval	=	net amount of entropy transferred in across the system boundary during the time interval	+	amount of entropy produced within the system during the time interval

$$S_2 - S_1 = \int_1^2 \left(\frac{\delta Q}{T}\right)_b + \sigma \qquad \sigma \geq 0$$

entropy change — entropy transfer — entropy production

Entropy balance is a re-interpretation of Clausius inequality

Entropy Statement of Second Law

***Entropy production* is non-negative for any system**

For an isolated system (closed system with no heat transfer), entropy can only go up or stay the same

Internally reversible system: $\sigma = 0$

Closed System Entropy Rate Balance

$$\frac{dS}{dt} = \sum_j \frac{\dot{Q}_j}{T_j} + \dot{\sigma}$$

dS/dt: rate of change of system entropy

$\frac{\dot{Q}_j}{T_j}$: entropy transfer transfer rate through the part of boundary that has temperature T_j

$\dot{\sigma}$: entropy generation rate in the system

Retrieving Entropy Data

Typical tabulated entropy values: a certain reference state is chosen (for water, the entropy of saturated liquid at 0.01 °C is set to zero); **only entropy difference has physical meanings in the tabulated data**

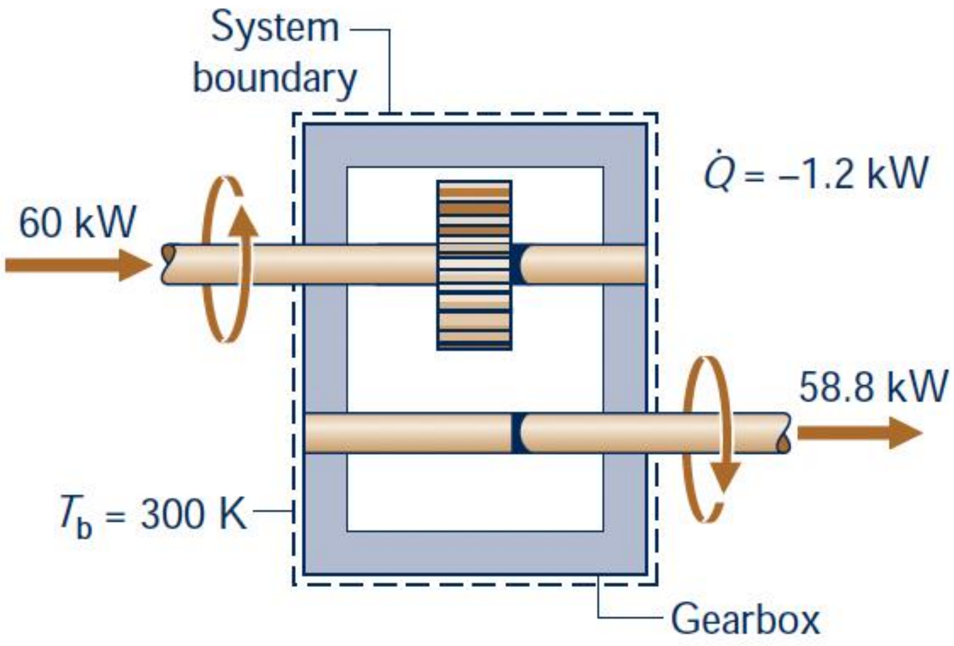
In two-phase region, we use the quality *x* in the same way as we retrieve *u, h, v, etc.*

$$s_x(T) = s_f(T)(1 - x) + s_g(T)x$$

saturation liquid — saturation vapor

Example 6.4

A gearbox operates at steady state



Evaluate the entropy production rate $\dot{\sigma}_g$ inside the gearbox

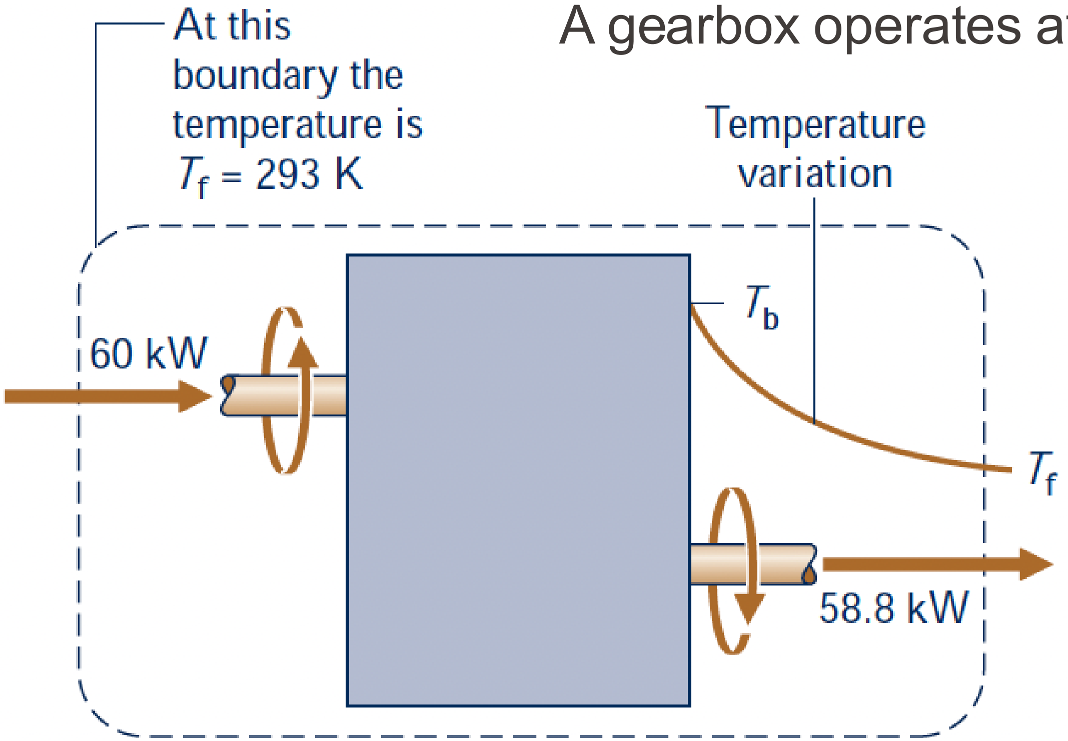
$$\frac{dS}{dt} = \frac{\dot{Q}}{T_b} + \dot{\sigma}_g$$

$$\dot{\sigma}_g = -\frac{\dot{Q}}{T_b} = 4 \left[\frac{W}{K}\right]$$

Irreversibility within the gearbox

Example 6.4

A gearbox operates at steady state



Evaluate the entropy production rate $\dot{\sigma}_s$ for an enlarged system consisting of the gearbox and enough of its surroundings such that the new boundary has temperature T_f = 293 K

$$\frac{dS}{dt} = \frac{\dot{Q}}{T_f} + \dot{\sigma}_s$$

$$\dot{\sigma}_s = -\frac{\dot{Q}}{T_f} = 4.1 \left[\frac{W}{K}\right]$$

Irreversibility within the gearbox and associated with heat transfer to ambient

EPFL

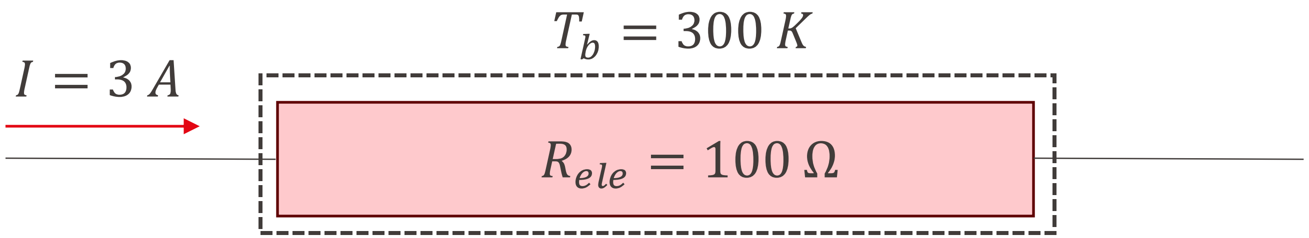
ETA-Lab
Energy Transport Advances

Joule Heating

Scan the QR code with your device
Or go to **echo360poll.eu**

Enter Code

luepfl



Assuming steady-state, what is the entropy generation rate in the CV drawn around the resistor

A. 0 [W/K]

B. 1 [W/K]

C. 3 [W/K]

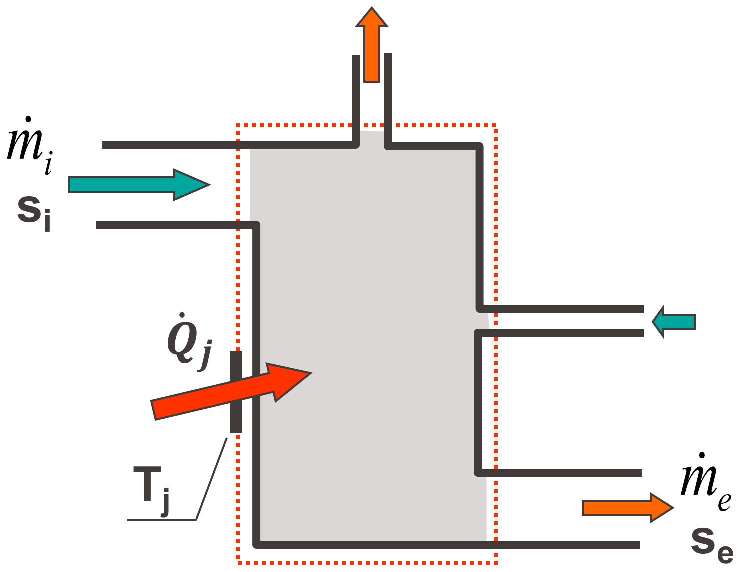
D. I don't know

ILOs Today

- Open system entropy rate balance
- Isentropic process and isentropic efficiency
- Internally reversible, steady-state flow processes

- Reading: 6.9-6.13

Open System Entropy Rate Balance



$$\frac{dm_{cv}}{dt} = \sum_i \dot{m}_i - \sum_e \dot{m}_e$$

$$\frac{dE_{cv}}{dt} = \sum_j \dot{Q}_j - \dot{W}_{cv} + \sum_i \dot{m}_i \left(h_i + \frac{\vec{V}_i^2}{2} + g z_i \right) - \sum_e \dot{m}_e \left(h_e + \frac{\vec{V}_e^2}{2} + g z_e \right)$$

$$\frac{dS_{cv}}{dt} = \sum_j \frac{\dot{Q}_j}{T_j} + \sum_i \dot{m}_i s_i - \sum_e \dot{m}_e s_e + \dot{\sigma}_{cv} \qquad \text{[W/K]}$$

Entropy change — Entropy transfer — Entropy generation

Steady State

$$\cancel{\frac{dS_{cv}}{dt}} = \sum_j \frac{\dot{Q}_j}{T_j} + \sum_i \dot{m}_i s_i - \sum_e \dot{m}_e s_e + \dot{\sigma}_{cv}$$

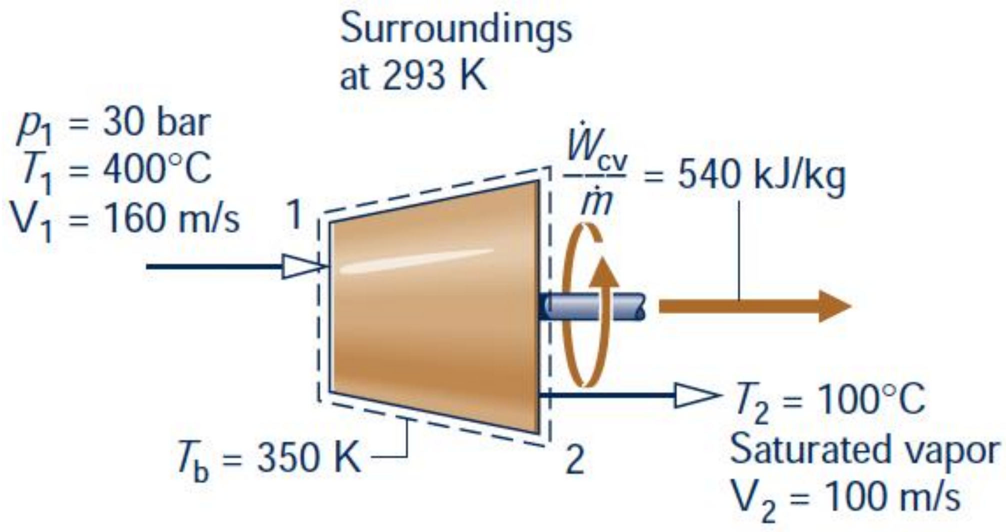
One inlet (1), one exit (2) control volume

$$0 = \sum_j \frac{\dot{Q}_j}{T_j} + \dot{m}(s_1 - s_2) + \dot{\sigma}_{cv}$$

$$0 = \frac{1}{\dot{m}} \sum_j \frac{\dot{Q}_j}{T_j} + s_1 - s_2 + \frac{\dot{\sigma}_{cv}}{\dot{m}}$$

Example 6.6

1 bar = 10^5 Pa

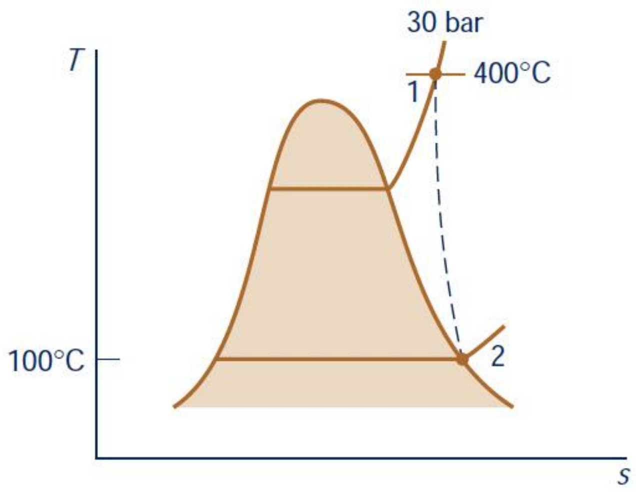


Steam expands through a turbine at steady state (change of potential energy ignored)

Determine the entropy generation per kg of steam flowing through turbine $\frac{\dot{\sigma}_{cv}}{\dot{m}}$

$$0 = \frac{\dot{Q}_{cv}}{\dot{m}T_b} + (s_1 - s_2) + \frac{\dot{\sigma}_{cv}}{\dot{m}}$$

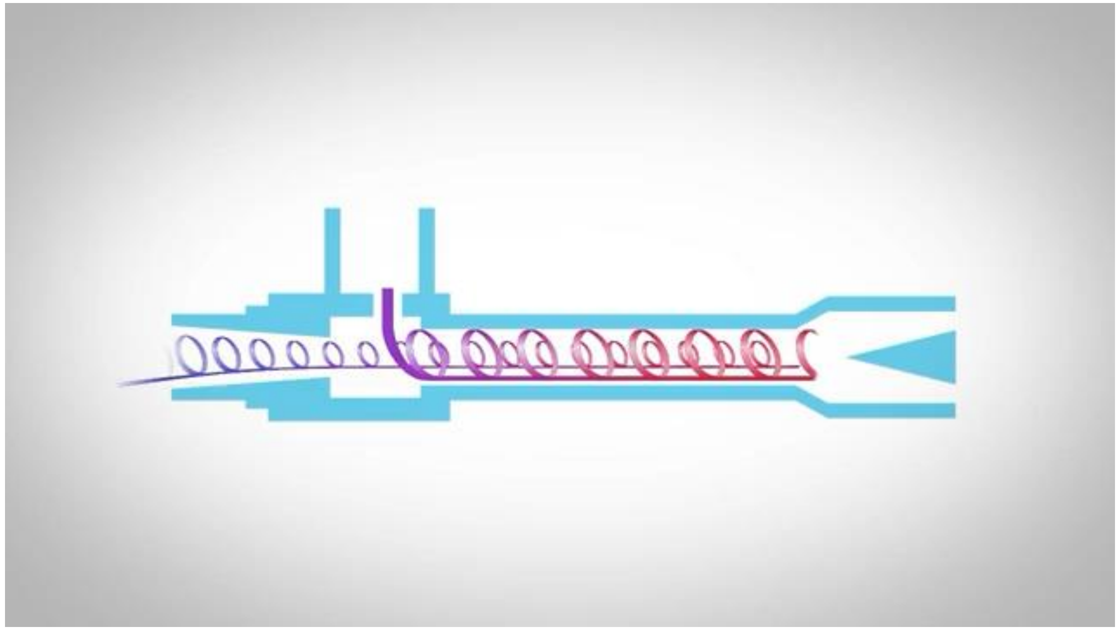
$$0 = \frac{\dot{Q}_{cv}}{\dot{m}} - \frac{\dot{W}_{cv}}{\dot{m}} + \left(h_1 + \frac{\vec{V}_1^2}{2} - h_2 - \frac{\vec{V}_2^2}{2}\right)$$



Evaluate s_1, h_1

Evaluate s_2, h_2

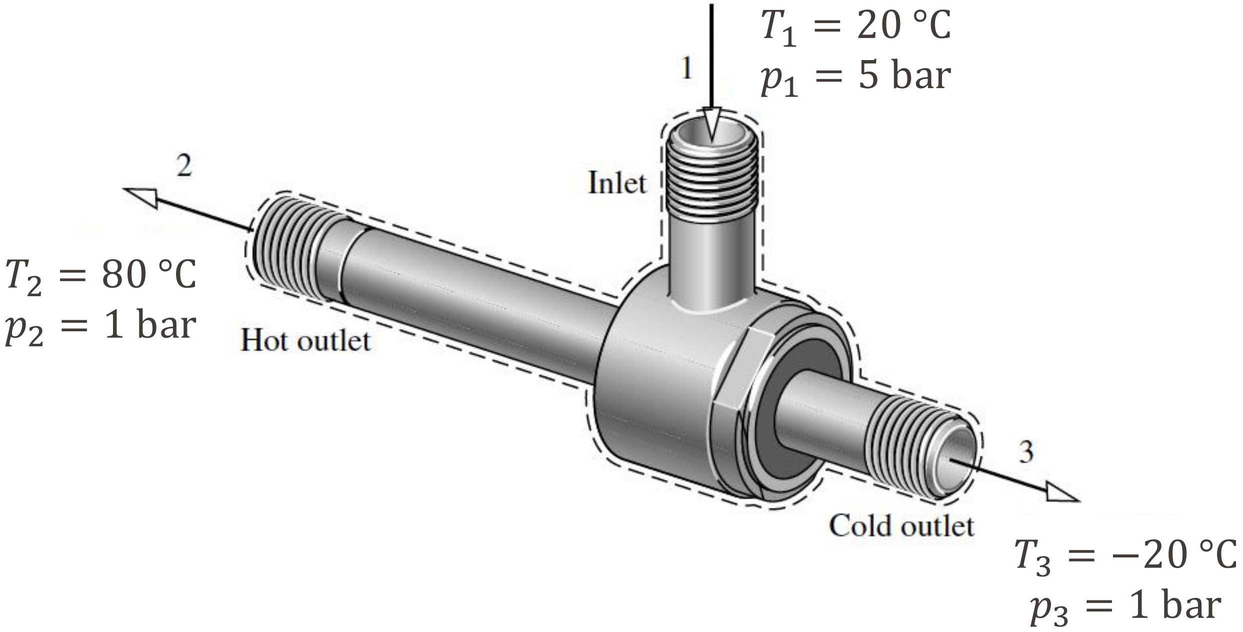
Vortex Tube



https://www.youtube.com/watch?v=ZpMe193KoHM

https://www.youtube.com/watch?v=Q_y2FvH2DHE

Example 6.7 (number adjusted)



Evaluate this invention claim

A device producing hot and cold stream of air flows without additional external heat or work transfer at a steady state?

Model air as perfect gas with $c_p = 3.5R$

Does this invention violate 2nd law?

$$\dot{m}_1 = \dot{m}_2 + \dot{m}_3$$

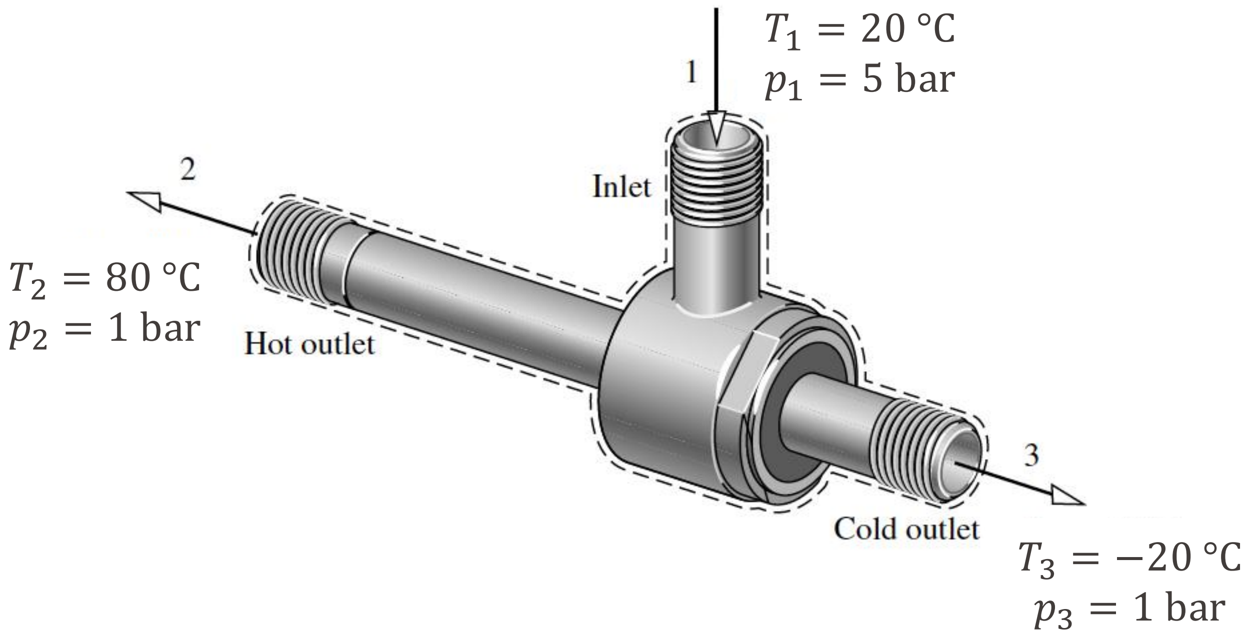
$$0 = \dot{m}_1 h_1 - (\dot{m}_2 h_2 + \dot{m}_3 h_3)$$

$$0 = \dot{m}_2(h_2 - h_1) + \dot{m}_3(h_3 - h_1)$$

$$0 = \dot{m}_2 c_p(T_2 - T_1) + \dot{m}_3 c_p(T_3 - T_1)$$

$$\dot{m}_2 : \dot{m}_3 : \dot{m}_1 = 40 : 60 : 100$$

Example 6.7



$$0 = \dot{m}_1 s_1 - \dot{m}_2 s_2 - \dot{m}_3 s_3 + \dot{\sigma}_{cv}$$

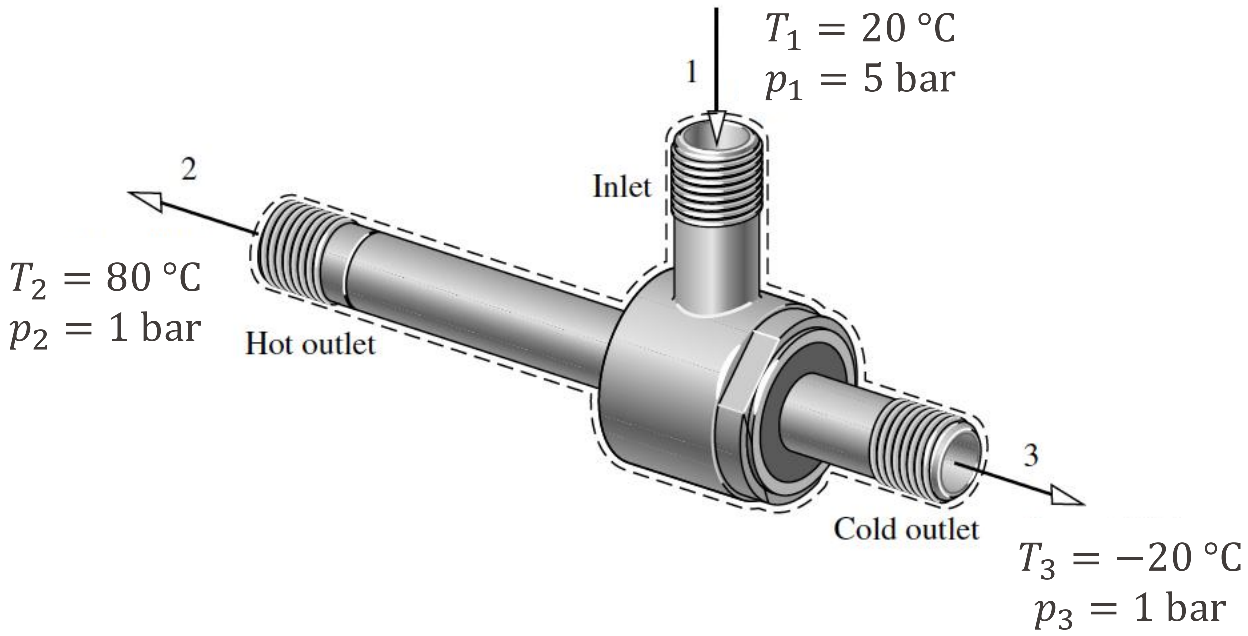
$$\dot{\sigma}_{cv} = \dot{m}_2 s_2 + \dot{m}_3 s_3 - (\dot{m}_2 + \dot{m}_3) s_1$$

$$\frac{\dot{\sigma}_{cv}}{\dot{m}_1} = 0.4(s_2 - s_1) + 0.6(s_3 - s_1)$$

$$= 0.4\left[c_p \ln\left(\frac{T_2}{T_1}\right) - R \ln\left(\frac{p_2}{p_1}\right)\right] + 0.6\left[c_p \ln\left(\frac{T_3}{T_1}\right) - R \ln\left(\frac{p_3}{p_1}\right)\right]$$

$$= 0.4R\left[3.5 \ln\frac{353.15}{293.15} - \ln\frac{1}{5}\right] + 0.6R\left[3.5\ln\frac{253.15}{293.15} - \ln\frac{1}{5}\right] \approx 1.56R > 0$$

Example 6.7

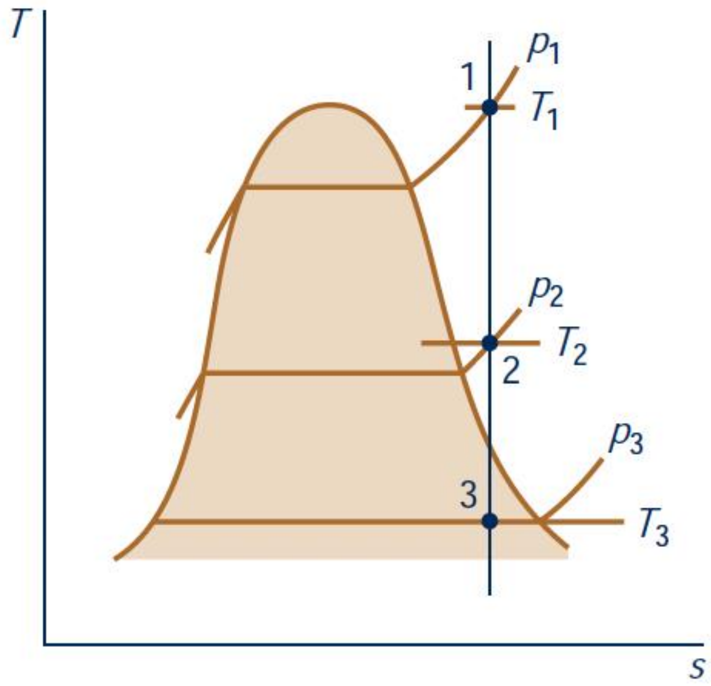


How is this possible for a steady-state device to “de-mix” air flows without additional external heat or work transfer ?

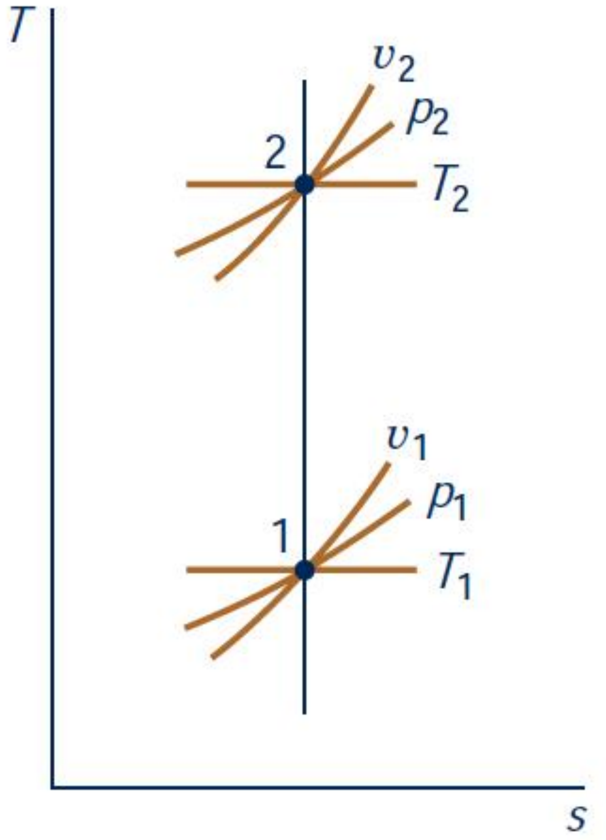
We “sacrificed” the pressure

Isentropic Processes

Isentropic means constant entropy (typically constant specific entropy)



Perfect Gas Isentropic Process



$$s_2 - s_1 = c_v \ln\frac{T_2}{T_1} + R\ln\frac{v_2}{v_1} = 0$$

$$k = \frac{c_p}{c_v} = \frac{c_v + R}{c_v}$$

$$\Rightarrow \frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{k-1}$$

$$s_2 - s_1 = c_p \ln\frac{T_2}{T_1} - R\ln\frac{p_2}{p_1} = 0$$

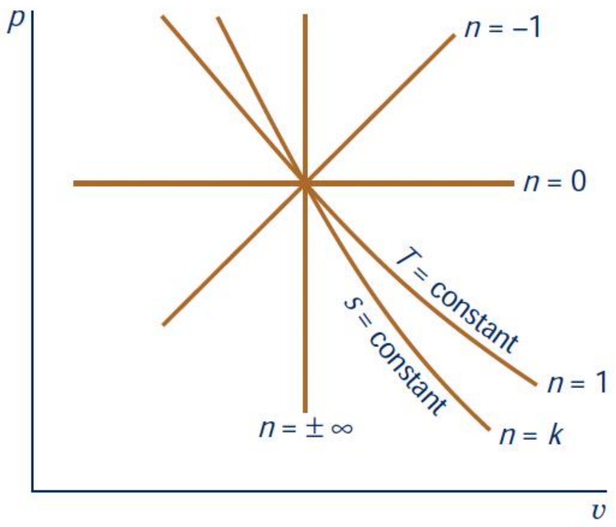
$$\Rightarrow \frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}}$$

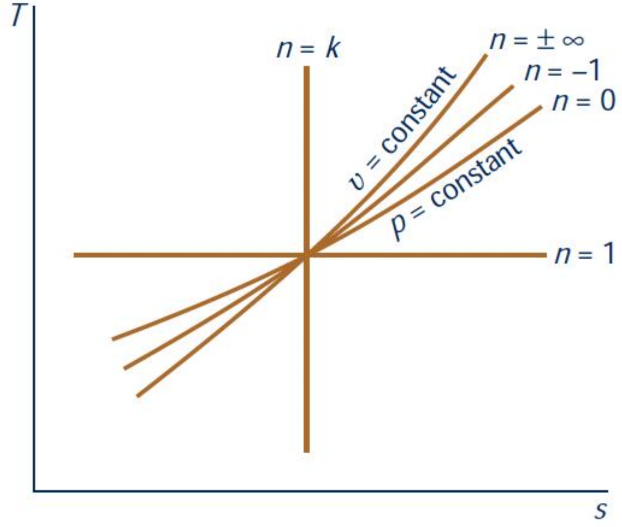
$$p_1 v_1^k = p_2 v_2^k$$

$$pv^k = \text{const}$$

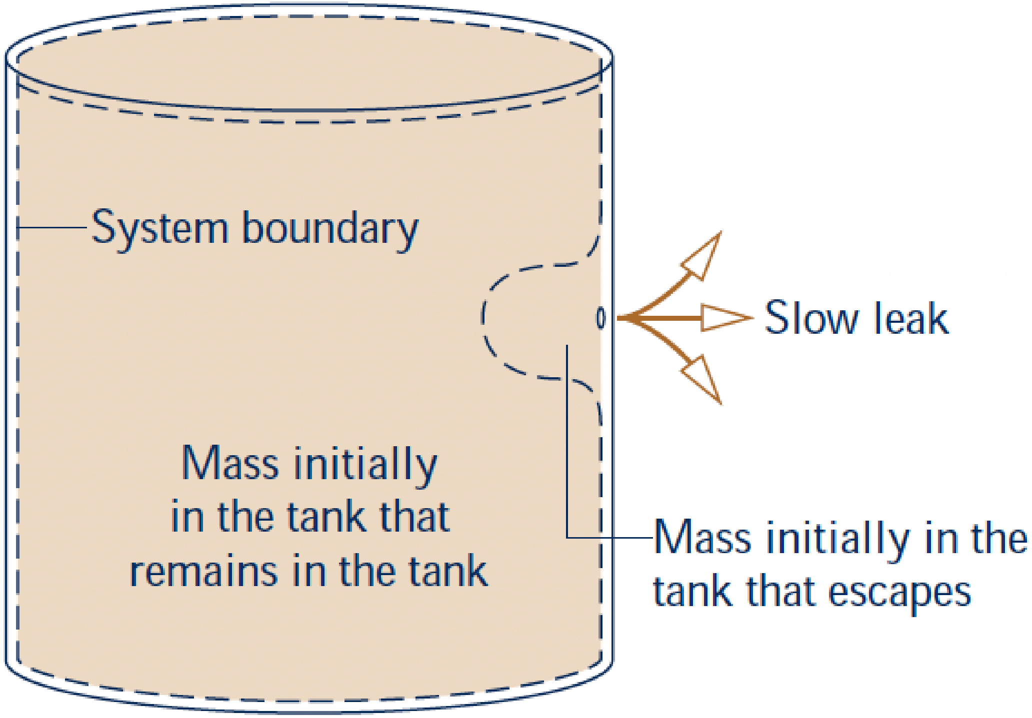
Review of Polytropic Process

- A process where $pv^n = \text{const}$
  - Isobaric process: $p = \text{const} \Rightarrow n = 0$
  - Isothermal process: $pv = RT = \text{const} \Rightarrow n = 1$
  - Isochoric processes: $v = \text{const} \Rightarrow n = +\infty \quad (p^{1/n}v = \text{const})$
  - Isentropic process: $pv^k = \text{const} \Rightarrow n = k = c_p/c_v$





Example 6.10



Initial condition of tank

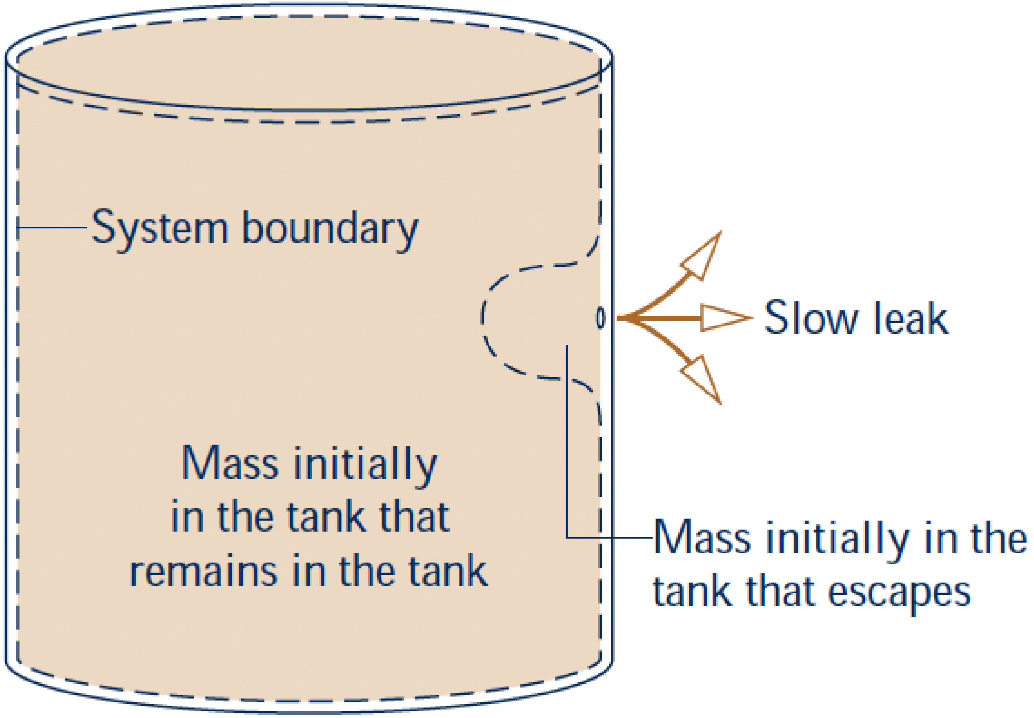
Air leaking from a rigid tank insulated from the surrounding (initially 5 kg, 5 bar, 500 K)

Air slowly escapes with **no internal irreversibility** inside the tank, until reaching 1 bar

Assume perfect gas behavior, $c_p = 3.5R$

Determine the mass of the remaining air in the tank and its temperature

Example 6.10



Initial condition of tank

$$\frac{dS}{dt} = \sum_j \frac{\dot{Q}_j}{T_j} + \dot{\sigma}$$

$$k = \frac{c_p}{c_v} = \frac{c_p}{c_p - R} = 1.4$$

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} \Rightarrow T_2 = 316\ \text{K}$$

$$p_1 v_1^k = p_2 v_2^k$$

$$\Rightarrow \frac{m_2}{m_1} = \frac{V_{tank}/v_2}{V_{tank}/v_1} = \frac{v_1}{v_2} = \left(\frac{p_2}{p_1}\right)^{\frac{1}{k}} \Rightarrow m_2 = 1.58\ \text{kg}$$