ME-251: Thermodynamics and energetics I
Second Law V

Zhengmao Lu

Energy Transport Advances Laboratory

EPFL Mechanical Engineering

2025 Fall Semester

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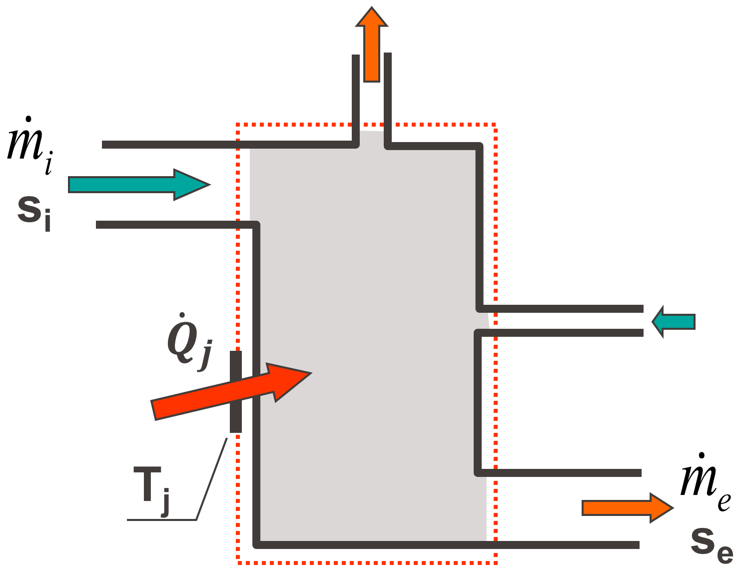
ETA-Lab
Energy Transport Advances

This Monday

- Open system entropy rate balance
- Isentropic process

Open System Rate Balance



Mass balance

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

Energy balance

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

Entropy balance

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

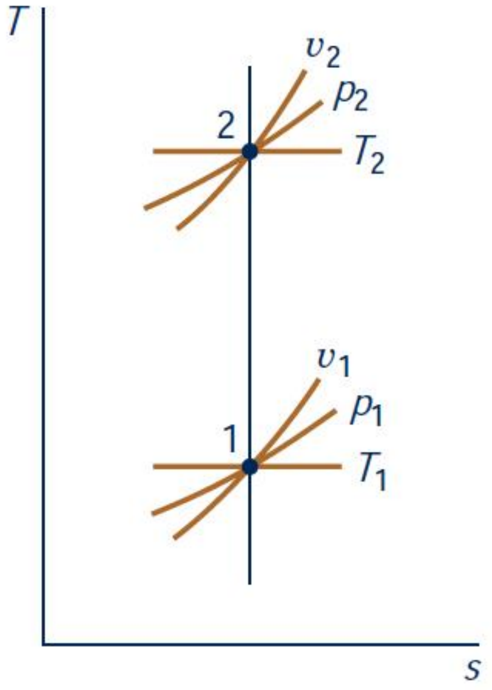
Entropy change

Entropy transfer

Entropy generation

Isentropic Processes

Isentropic means constant entropy (typically constant specific entropy)



For perfect gas

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

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

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

ILOs Today

- Isentropic efficiency
- Internally reversible, steady-state flow processes

- Reading: 6.12 and 6.13

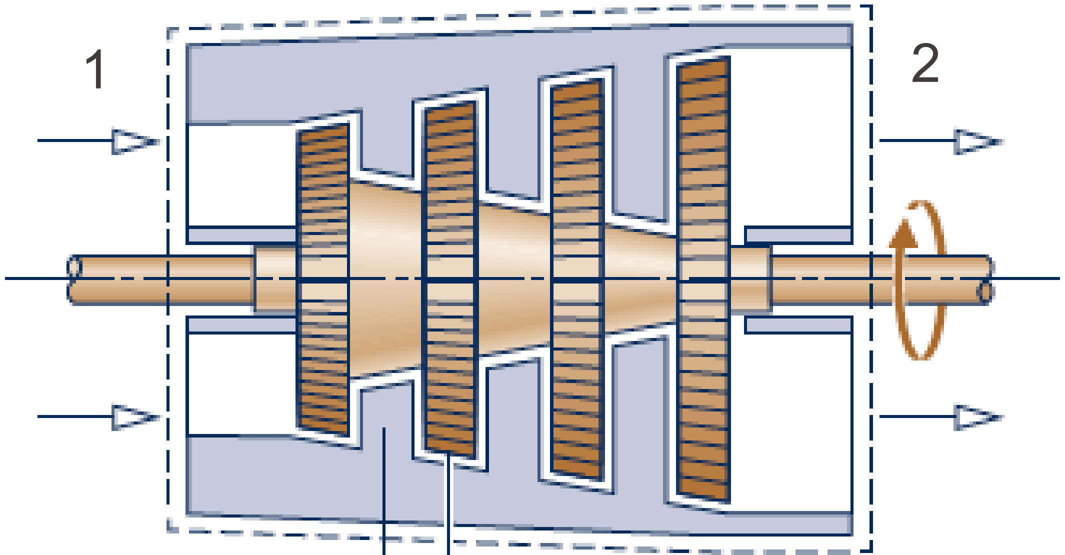
Isentropic Efficiency

For turbines, nozzles, compressors, and pumps at steady states

Isentropic efficiency is to compare the actual performance of a device to the performance that would be achieved under **idealized circumstances** for the **same inlet state** and the **same exit pressure**

What's typically assumed in the ideal case: **adiabaticity** and **internal reversibility**

Isentropic Turbine Efficiency



- Ignore kinetic and potential energy change
- Assume no heat exchange with the surrounding

$$0 = -\dot{W}_{cv} + \dot{m}(h_1 - h_2)$$

Idealized process $(1 \rightarrow 2s)$

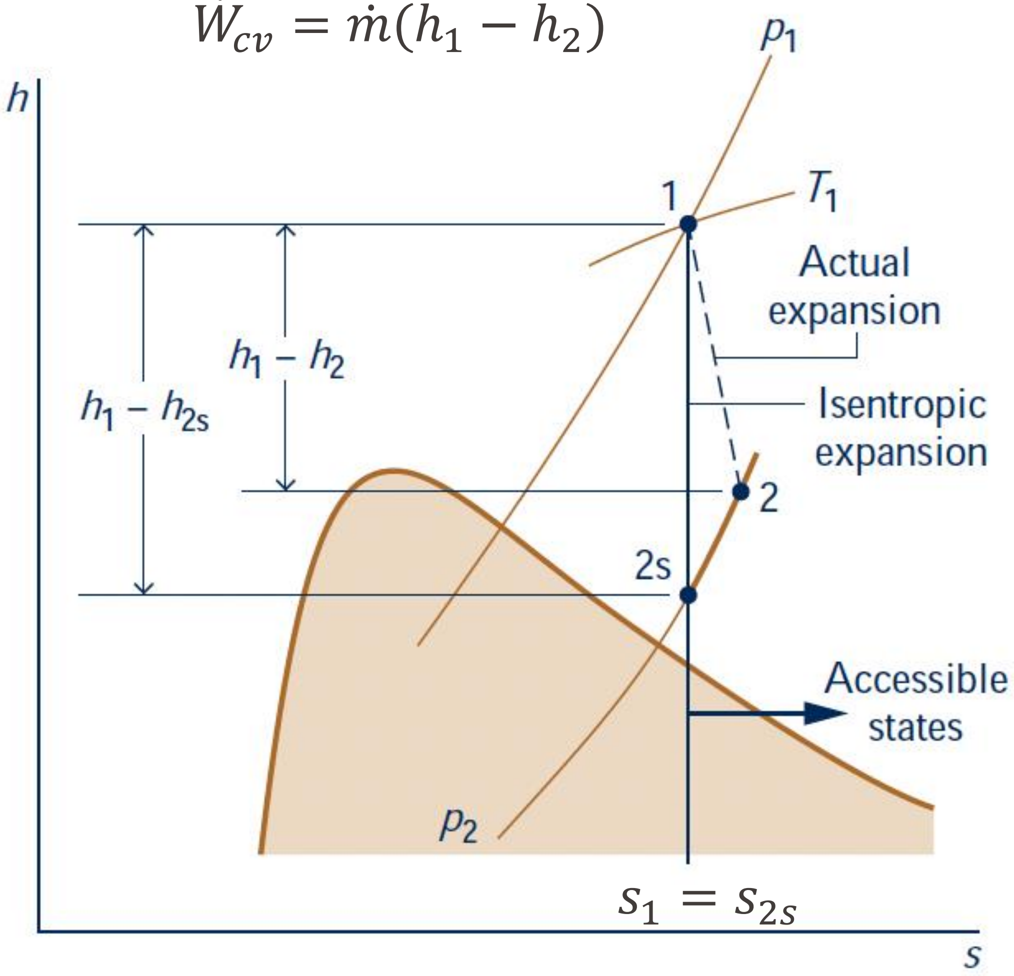
with no internal irreversibility

$$0 = \dot{m}(s_1 - s_{2s}) + \dot{\sigma}_{cv}$$

The ideal process is isentropic

Isentropic Turbine Efficiency

$$\dot{W}_{cv} = \dot{m}(h_1 - h_2)$$



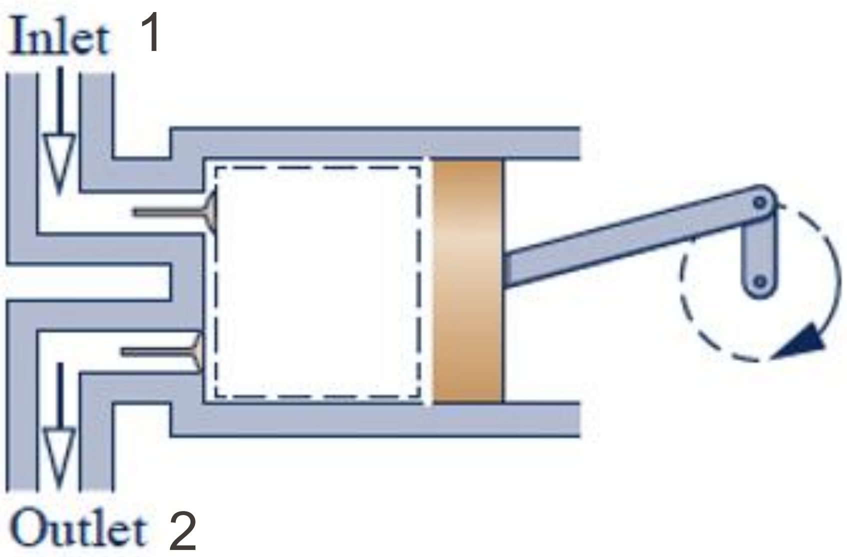
Actual process: same inlet state and exit pressure, with internal irreversibility

$$0 = \dot{m}(s_1 - s_2) + \dot{\sigma}_{cv}$$
$$\dot{\sigma}_{cv} > 0 \;\Rightarrow s_2 > s_1$$

Isentropic efficiency for turbine

$$\eta_t = \frac{\dot{W}_{cv}/\dot{m}}{\left(\dot{W}_{cv}/\dot{m}\right)_s} = \frac{h_1 - h_2}{h_1 - h_{2s}}$$

Isentropic Compressor and Pump Efficiencies



Idealized process $(1 \rightarrow 2s)$

with no internal irreversibility

$$0 = \dot{m}(s_1 - s_{2s}) + \dot{\sigma}_{cv}$$

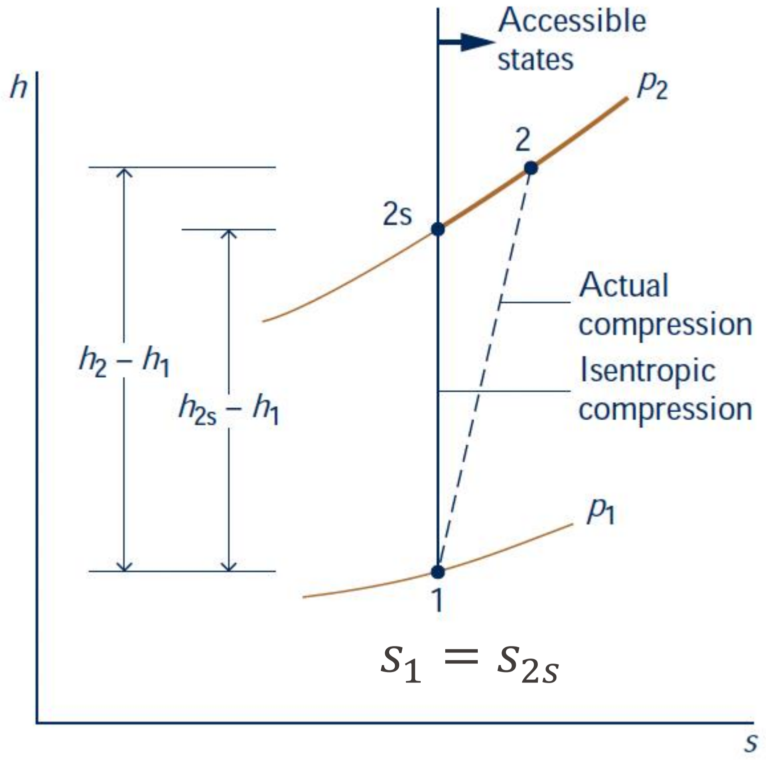
$$s_1 = s_{2s}$$

- Ignore kinetic and potential energy change
- Assume no heat exchange with the surrounding

$$0 = -\dot{W}_{cv} + \dot{m}(h_1 - h_2)$$

Isentropic Compressor and Pump Efficiencies

$$-\dot{W}_{cv} = \dot{m}(h_2 - h_1)$$



$$s_1 = s_{2s}$$

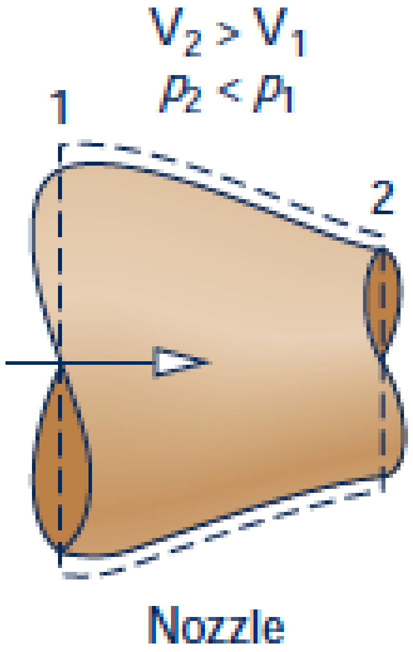
Actual process: same inlet state and exit pressure, with internal irreversibility

$$0 = \dot{m}(s_1 - s_2) + \dot{\sigma}_{cv}$$
$$\dot{\sigma}_{cv} > 0 \Rightarrow s_2 > s_1$$

Isentropic efficiency for compressors and pumps

$$\eta_c = \frac{-\left(\dot{W}_{cv}/\dot{m}\right)_s}{-\dot{W}_{cv}/\dot{m}} = \frac{h_{2s} - h_1}{h_2 - h_1} = \frac{\text{Min. work needed}}{\text{Actual work}}$$

Isentropic Nozzle Efficiency



Ignore PE change and heat transfer

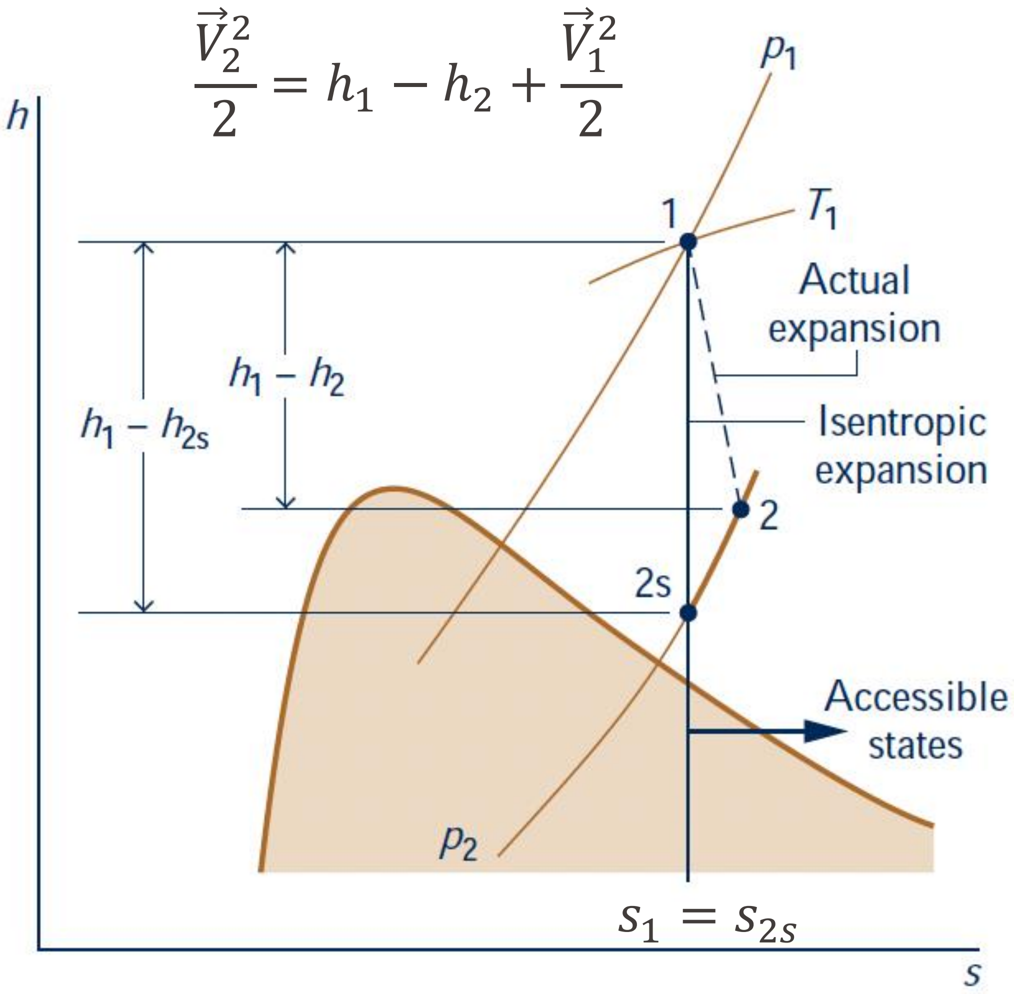
$$h_1 + \frac{\vec{V}_1^2}{2} = h_2 + \frac{\vec{V}_2^2}{2}$$

Idealized situation ($1 \rightarrow 2s$) with no internal irreversibility

$$0 = \dot{m}(s_1 - s_{2s}) + \dot{\sigma}_{cv}$$

$$s_1 = s_{2s}$$

Isentropic Nozzle Efficiency



Actual process: same inlet state and exit pressure, with internal irreversibility

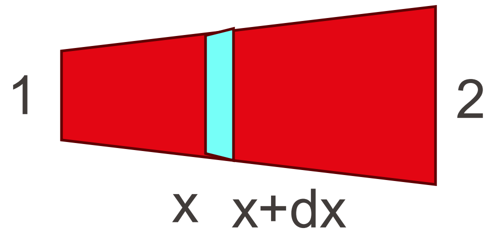
$$0 = \dot{m}(s_1 - s_2) + \dot{\sigma}_{cv}$$
$$\dot{\sigma}_{cv} > 0 \;\Rightarrow s_2 > s_1$$

Isentropic efficiency for nozzles

$$\eta_{nozzle} = \frac{\vec{V}_2^2}{\vec{V}_{2s}^2}$$

Internally Reversible, Steady-State Flow Processes

One-inlet, one-exit control volumes at steady state



Entropy balance

Heat transfer

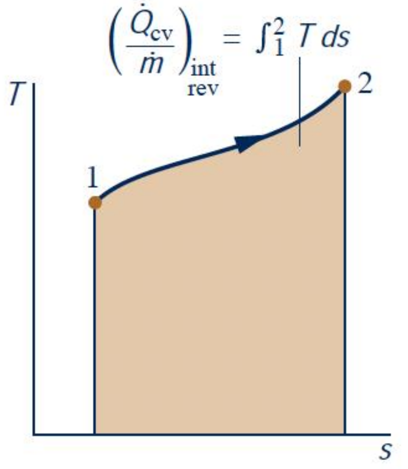


Fig. 6.13 Area representation of heat transfer for an internally reversible flow process.

$$0 = \frac{\delta(\dot{Q}_{cv})_{\substack{int\\rev}}}{T_x} + \dot{m}(s_x - s_{x+dx}) + \delta\dot{\sigma}$$

$$\delta\left(\frac{\dot{Q}_{cv}}{\dot{m}}\right)_{\substack{int\\rev}} = T_x ds$$

$$\left(\frac{\dot{Q}_{cv}}{\dot{m}}\right)_{\substack{int\\rev}} = \int_1^2 T_x ds$$

For isothermal processes: $\left(\frac{\dot{Q}_{cv}}{\dot{m}}\right)_{\substack{int\\rev}} = T(s_2 - s_1)$

Internally Reversible, Steady-State Flow Processes

Work transfer

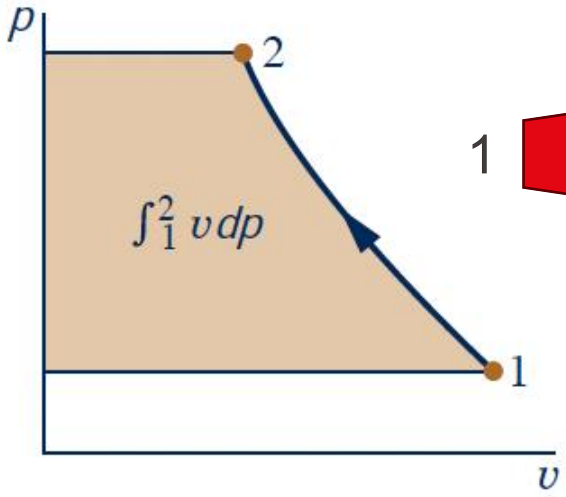
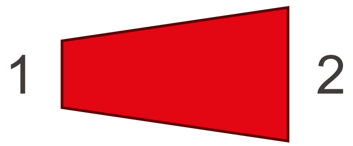


Fig. 6.14 Area representation of $\int_1^2 v\,dp$.



$$\left(\frac{\dot{W}_{cv}}{\dot{m}}\right)_{\substack{int\\rev}} = \left(\frac{\dot{Q}_{cv}}{\dot{m}}\right)_{\substack{int\\rev}} + h_1 - h_2 + \frac{\vec{V}_1^2 - \vec{V}_2^2}{2} + g(z_1 - z_2)$$

$$\left(\frac{\dot{Q}_{cv}}{\dot{m}}\right)_{\substack{int\\rev}} + h_1 - h_2 = \int_1^2 (T\,ds - dh) = -\int_1^2 v dp$$

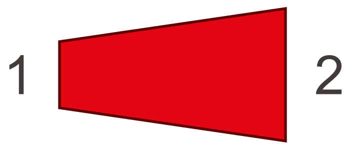
Ignoring KE and PE change $\left(\frac{\dot{W}_{cv}}{\dot{m}}\right)_{\substack{int\\rev}} = -\int_1^2 v dp$

For incompressible fluids $\left(\frac{\dot{W}_{cv}}{\dot{m}}\right)_{\substack{int\\rev}} = -v(p_2 - p_1)$

When $\dot{W}_{cv} = 0$, keeping PE and KE terms $\int_1^2 v dp + \frac{\vec{V}_2^2 - \vec{V}_1^2}{2} + g(z_2 - z_1) = 0$

Bernoulli's Principle Rewritten

$$\int_1^2 v\,dp + \frac{\vec{V}_2^2 - \vec{V}_1^2}{2} + g(z_2 - z_1) = 0$$



Incompressible fluids

$$v(p_2 - p_1) + \frac{\vec{V}_2^2 - \vec{V}_1^2}{2} + g(z_2 - z_1) = 0$$

Perfect gas (adiabatic)

$$\int_1^2 p_1^{\frac{1}{k}} v_1 \cdot p^{-\frac{1}{k}} dp + \frac{\vec{V}_2^2 - \vec{V}_1^2}{2} + g(z_2 - z_1) = 0$$

$$\frac{k}{k-1}(p_2 v_2 - p_1 v_1) + \frac{\vec{V}_2^2 - \vec{V}_1^2}{2} + g(z_2 - z_1) = 0$$

Pop Quiz


blog.ed.ted.com

Question: This football is going *upward* while spinning *counterclockwise*. Based on your understanding, it will:

A) curve to the left

B) go along a straight line

C) curve to the right

D) I don’t know

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

Enter Code

luepfl

Magnus Effect

Incomplete explanation

Bernoulli's principle cannot fully explain the Magnus effect