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12th International Physicists' Tournament

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Problem no.2 – Precious energy

IPT 2020

Team Slovenia

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Problem statement

- Shaking a bottle of carbonated liquid (soda, beer, champagne, etc.) will lead to a fountain of liquid coming out. **Design and optimize** a setup to **extract electrical energy** from opening such a bottle.

Chemical equilibrium

- Champagne = $H_2O + \overset{\text{IDEAL GAS}}{CO_2}$
- Henry‘s law $k_H = \frac{p_{co_2}}{[co_2]}$ = 29.76 L atm [4]
- ${k_H}' = 29.71$ L atm with corrections from deprotonation of carbonic acid [4]
- Pressure drops -> bubbles grow

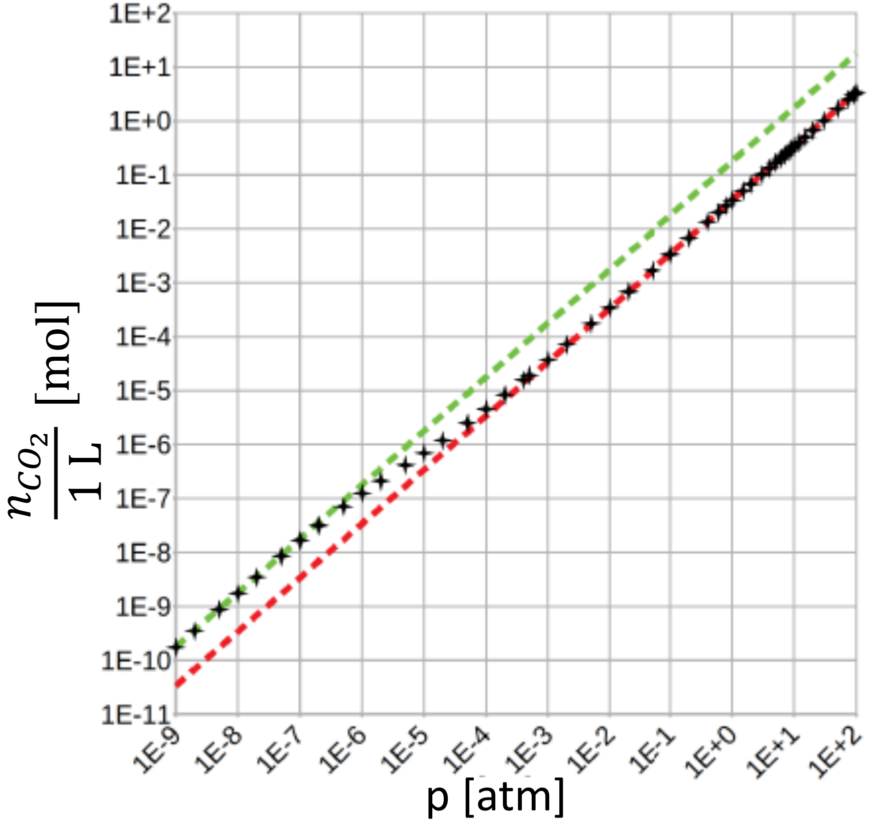


Figure 1: Concentration of dissolved CO_2 as a function of partial CO_2 pressure.

Reversibility and efficiency

- A heat engine does more useful work if it performs reversible processes

$$dF \leq -SdT - dA$$
$$dA \leq -SdT - dF$$

- Foaming liquid fountain is irreversible
- Source of work: $\mathrm{CO_2}$ gas
- Useful work $= \mathrm{Work\ out} - \mathrm{Energy\ in}$

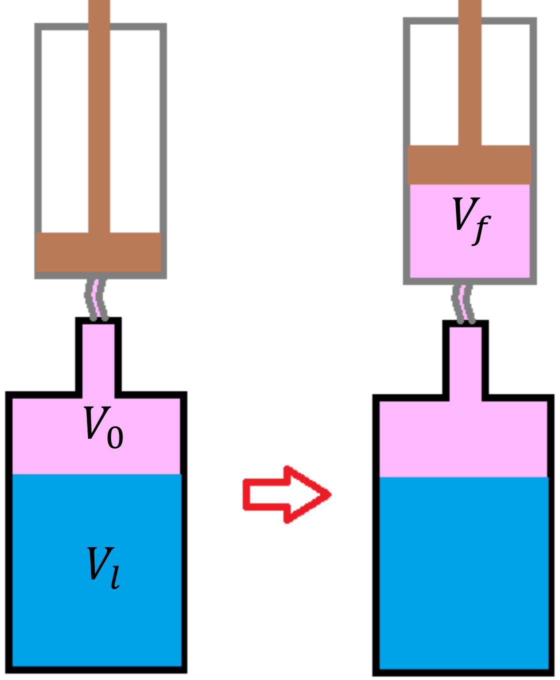
General gas changes

$$pV_{gas} = \frac{m_{\mathrm{co_2}}RT}{M_{\mathrm{co_2}}} \quad \text{and} \quad k_H = \frac{p/1\mathrm{atm}}{[\mathrm{co_2}]}$$

- Begin with an open champagne bottle connected to a piston
- Assumptions:
    1. No gas is lost upon connecting
    2. $\mathrm{CO_2}$ is the only gas in the bottle
    3. 100% efficient transfer mechanical work -> electrical work

- ~~Isobaric~~

Isothermal expansion



- Equillibrium between gaseous and dissolved CO_2
- Ideal isothermal reversible process

Equation of state : $p(V,T=T_R)=p_0\frac{V_0+J}{V+J}$ $\quad J=\frac{RT_RV_l}{k_H}$

$$A=p_0(V_0+\mathrm{J})\ln\left(\frac{J+V_{final}}{J+V_0}\right)-p_{atm}\left(V_{final}-V_0\right)$$

$$=F_{(p_0,T_R,V_0)}-F_{(p_{atm},T_R,V_{final})}-p_{atm}\left(V_{final}-V_0\right)$$

$V_0=0.05\ \mathrm{L},\ V_l=0.75\ \mathrm{L},\ p_0=5\ \mathrm{bar},\ T_R$=296 K

$V_f=2.7\ \mathrm{L}$ and $A=270\ \mathrm{J}$

Adiabatic expansion

- Iterate smaller adiabatic expansion
- Easier to perform in practice than isothermal
- Irreversible!
- $A = 136\,\mathrm{J} < 270\,\mathrm{J}$

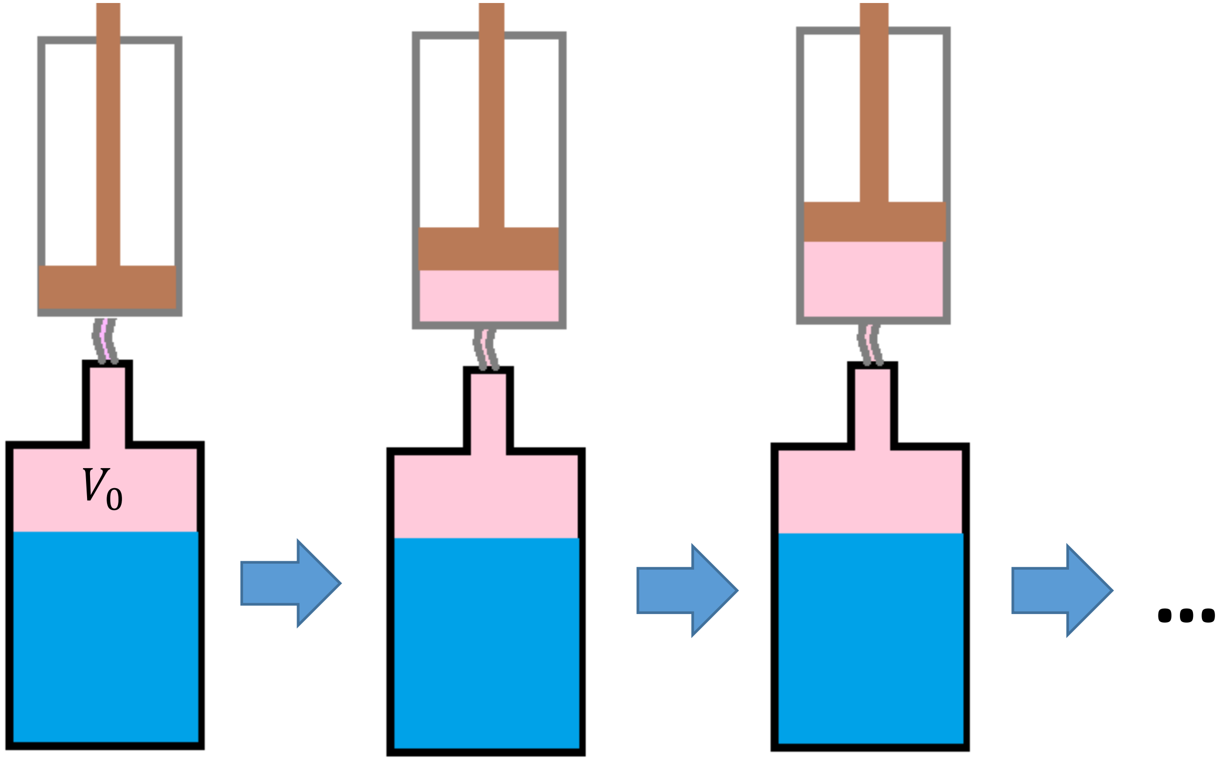
$$A_n = \frac{1}{\kappa - 1}(p_{n-1}V_{n-1} - p_{atm}V_n) - p_{atm}(V_n - V_{n-1})$$

$$p_{atm}V_n^{\kappa} = p_{n-1}V_{n-1}^{\kappa}$$

$$\kappa = 1.40$$

$$p_n = \frac{m_0}{V_n\frac{M}{RT_R} + \frac{V_l}{k_H}}$$

Sum over *n*



Adiabatic vs. isothermal

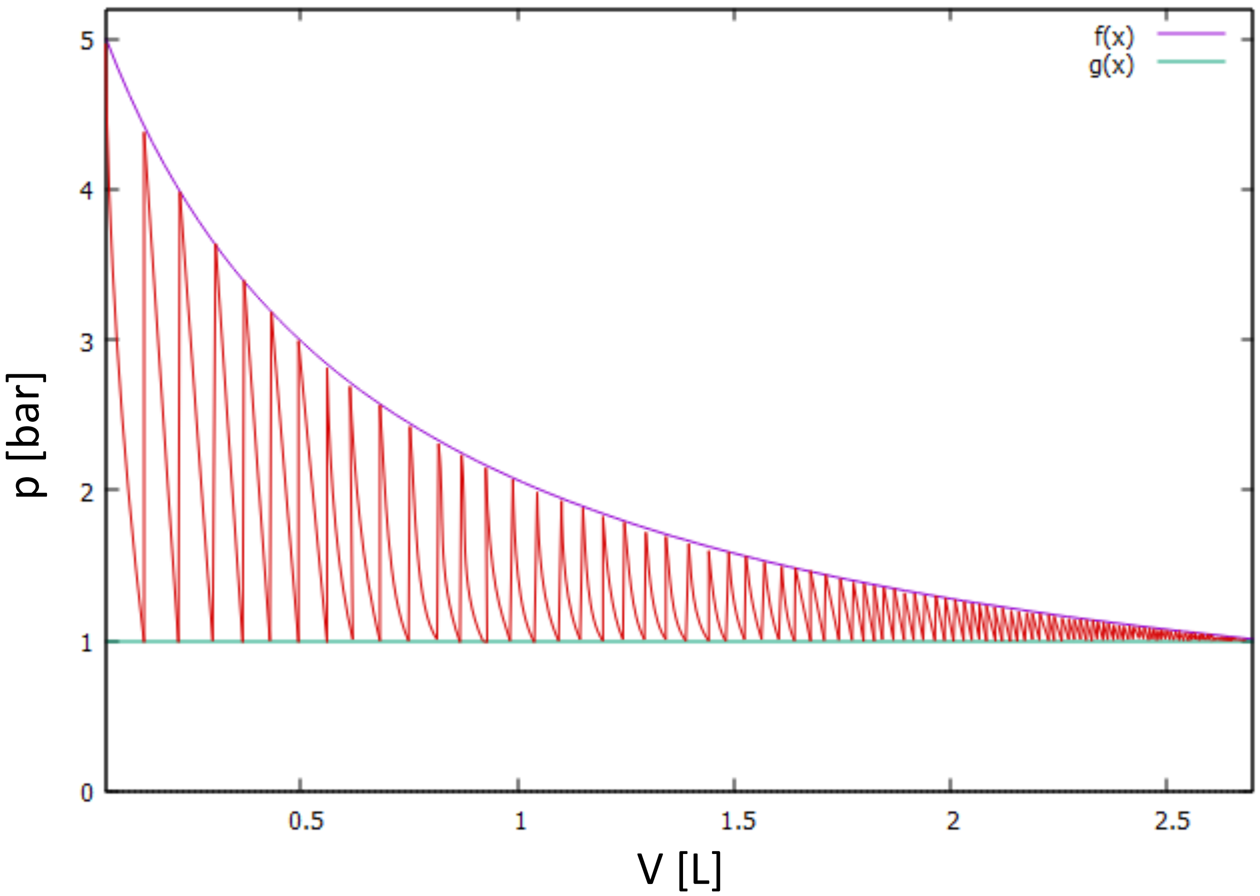
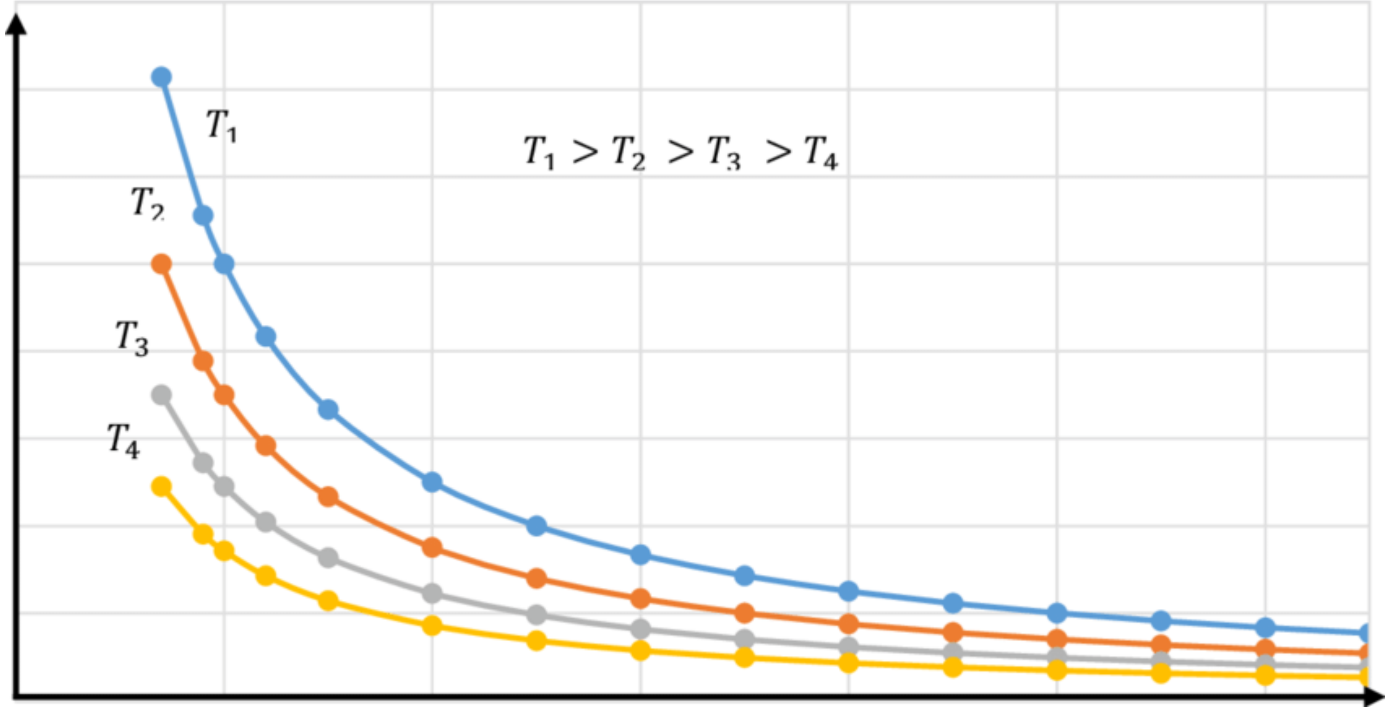


Figure 2: p(V) graph for a isothermal expansion (violet) and for a series of adiabatic expansions (red)

Is that all?

Heating the liquid by 1 K takes 3000 J >> 270 J



Cooling the gas decreases the work area

Room temperature isothermal expansion is optimal!

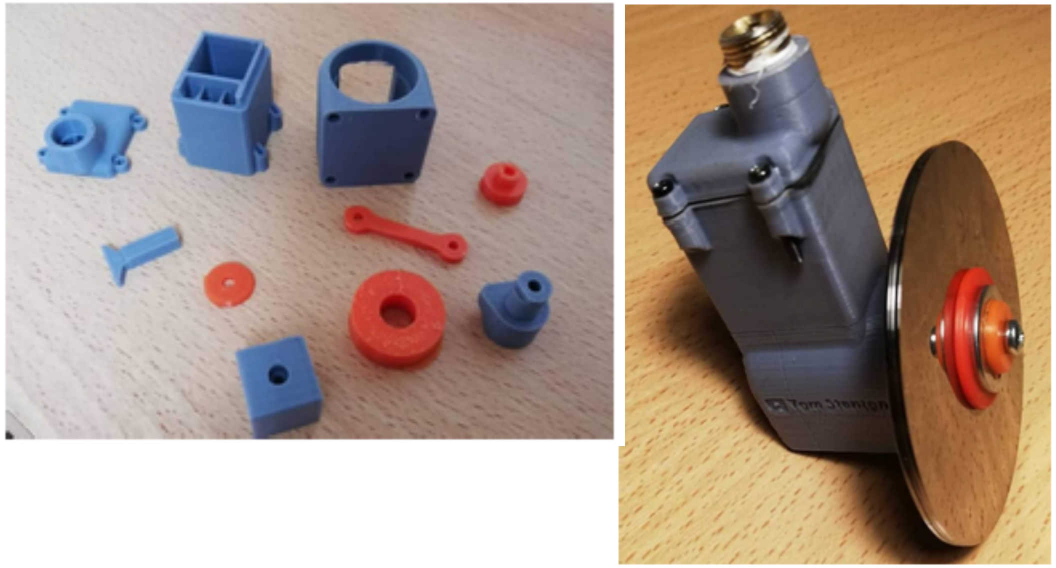
First experimental attempts

Rack and pinion setup

Figure 2: Experimental setup. Left and centre: expansion tube. Top right: container with valve. Bottom right: electric generator and pinion

3D printed air motor

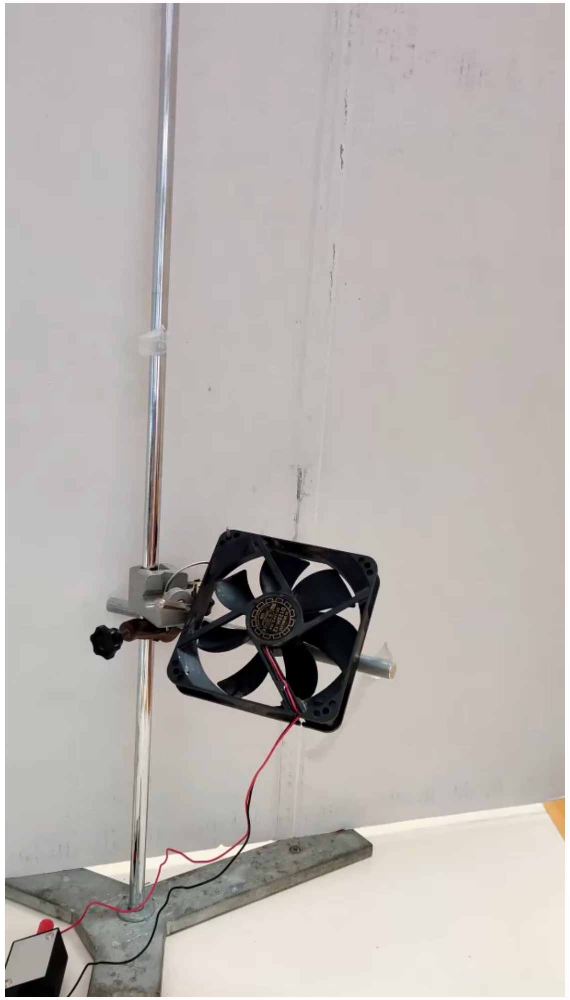
Online designs [6] to print a compressed air motor.



Too much friction and leaking for champagne

Storing pressurized air in a baloon

BALOON FILLS UP



AIR IS RELEASED TO THE FAN THAT GENERATES POWER

$$R = 40\ \Omega$$

$$A = UIt = R\frac{q^2}{t}$$

$$A = 80 \pm 30\ \text{mJ} << 270\text{J}$$

Drawbacks:

- Baloon turbolence
- Air flow direction
- Not all CO_2 was utilised

PROOF OF CONCEPT

Discussion

- Champagne gives most from carbonated liquids
- 1 bottle $\leq 270\ \mathrm{J}$
- Experimental proof of concept
- Caloric energy stored in champagne:
  - 20 g of sugar -> 0.34 MJ [2]
  - 90 ml of ethanol -> 2 MJ [1] [3]

- Comparison with standard electricity sources (no caloric work):

Energy source	**Price of kWh**	**CO_2 emitted per kWh**
Coal	0.07 € (Slovenia)	1.1 kg
Champagne (10€ per bottle)	134 000 €	73 kg

[7]

References

[1] Green, A. 2015. How many glasses of champagne equals one shot of liquor? ANDYGREEN. Link: https://www.andygreenlaw.com/dui/how-many-glasses-of-champagne-equals-one-shot-of-liquor/

[2] Karson, P. 2018. Sugar levels in champagne and other sparkling wines. Link: https://www.bkwine.com/features/winemaking-viticulture/sugar-levels-champagne-sparkling-wines-brut-etc/

[3] Food energy. Wikipedia. Link: https://en.wikipedia.org/wiki/Food_energy

[4] Greenwood, Norman N.; Earnshaw, Alan (1997). Chemistry of the Elements (2nd ed.). Butterworth-Heinemann. p. 310. ISBN 978-0-08-037941-8.

[5] Hui P. The physics factbook: pressure in a champagne bottle. 2003. Link: https://hypertextbook.com/fa cts/2003/PeterHui.shtml

[6] Stanton, T. Compressed air engine. Thingiverse, 1.6.2018. Link: https://www.thingiverse.com/thing:2936786?fbclid=IwAR3uDC6d0sgls6y6Dcn04sl7K3LxwAEzVUSYwmcvcmXR0lo8FtHcC270OoM

[7] Cene in ceniki. Elektro energija. January 2020. Link: https://www.elektro-energija.si/za-dom/dokumenti-in-ceniki

Pictures

- Cyclists spraying champagne. https://www.mylespaul.com/threads/champagne-spray-celebration-for-race-winners-wtf.302292/
- Isotherms of an ideal gas. Waleed Hamanah. https://www.researchgate.net/figure/The-Isotherms-Curve-for-an-Ideal-Gas_fig31_323540295

Adiabatic expansion

$$A_n = \frac{1}{\kappa - 1}(p_{n-1}V_{n-1} - p_{atm}V_n) - p_{atm}(V_n - V_{n-1})$$

$$p_{atm}V_n^{\kappa} = p_{n-1}V_{n-1}^{\kappa}$$

$$\kappa = 1.40$$

$$p_n = \frac{m_0}{V_n \frac{M}{RT_R} + \frac{V_l}{k_H}}$$

Take p_N as p_n-1 for the next expansion

Ideal gas isothermal optimal

$$\int p\mathrm{d}V - \int T\mathrm{d}S = \int [p - T(\frac{\partial p}{\partial T})_V]\,\mathrm{d}V - \int m c_V\mathrm{d}T = - \int m c_V\mathrm{d}T$$

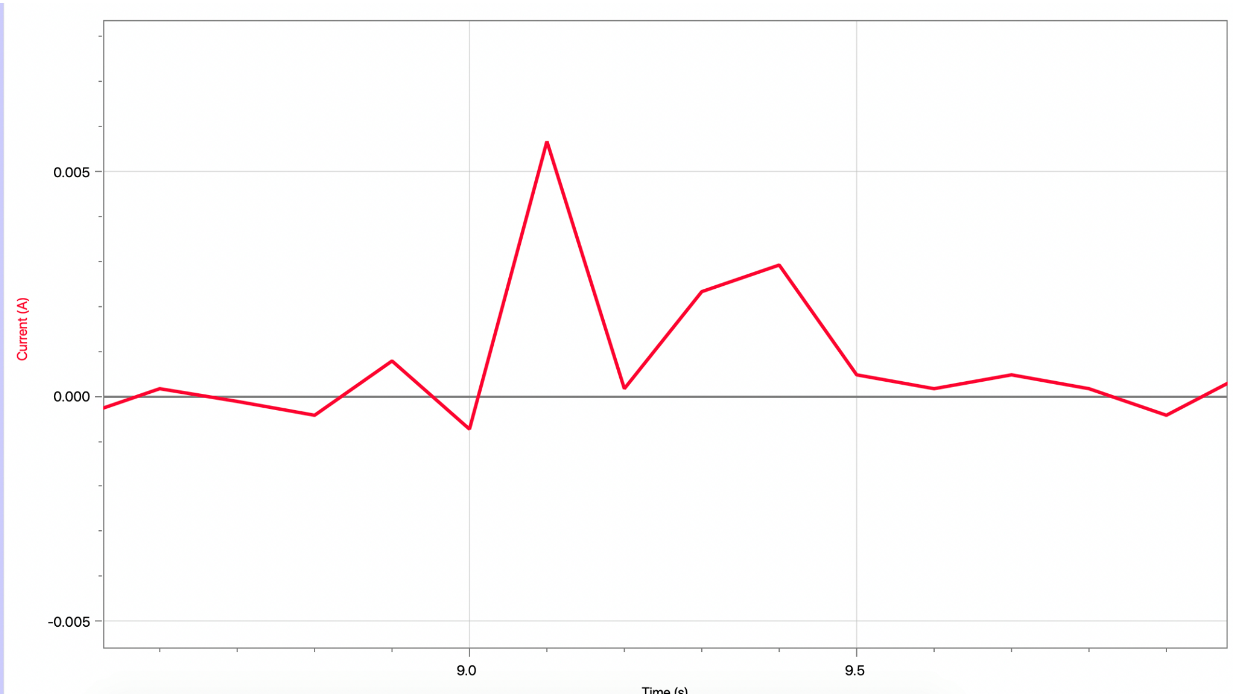
$$\mathrm{d}S = (\frac{\partial S}{\partial V})_T\,\mathrm{d}V + (\frac{\partial S}{\partial T})_T\,\mathrm{d}T$$

$$(\frac{\partial p}{\partial T})_V = \frac{\beta}{\chi_T} = \frac{p}{T}$$

We care only for the input heat, the output flows spontaneously

Experimental baloon data

- Champagne Suha Radgonska $q = 1.14 \pm 1\ \mathrm{mAs}$
- Champagne Srebrna Radgonska $q = 3.80 \pm 1\ \mathrm{mAs}$ $\mathrm{t} = 1.9 \pm 0.3\ \mathrm{s}$
- $R = 40\ \Omega$
- $A = UIt = R\frac{q^2}{t}$



Current vs time for Srebrna radgonska, measured with LoggerPro

Rack and pinion setup with pressurized air

Plastic cylinder 2 m long, 15 mm in diameter
0.35 L of expansion volume
Too much friction and leaking for champagne
5 bar with an air compressor
$R = 2\ \mathrm{M\Omega}$

$$A_e \approx \sum_{i=0}^{N-1} \frac{U_i^2}{R}(t_{i+1} - t_i) \ = \ 29 \ \pm 5 \text{ mJ}$$