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EUROPEAN FORUM
for RECIPROCATING
COMPRESSORS

EFRC Training Workshop

Basic Training of Reciprocating Compressor Systems

Gas Compression and Thermodynamics

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HOERBIGER

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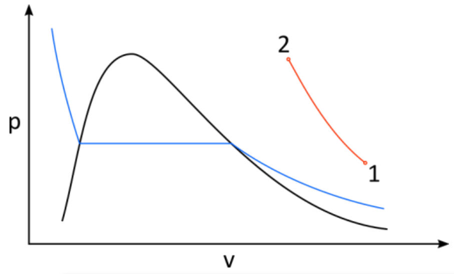
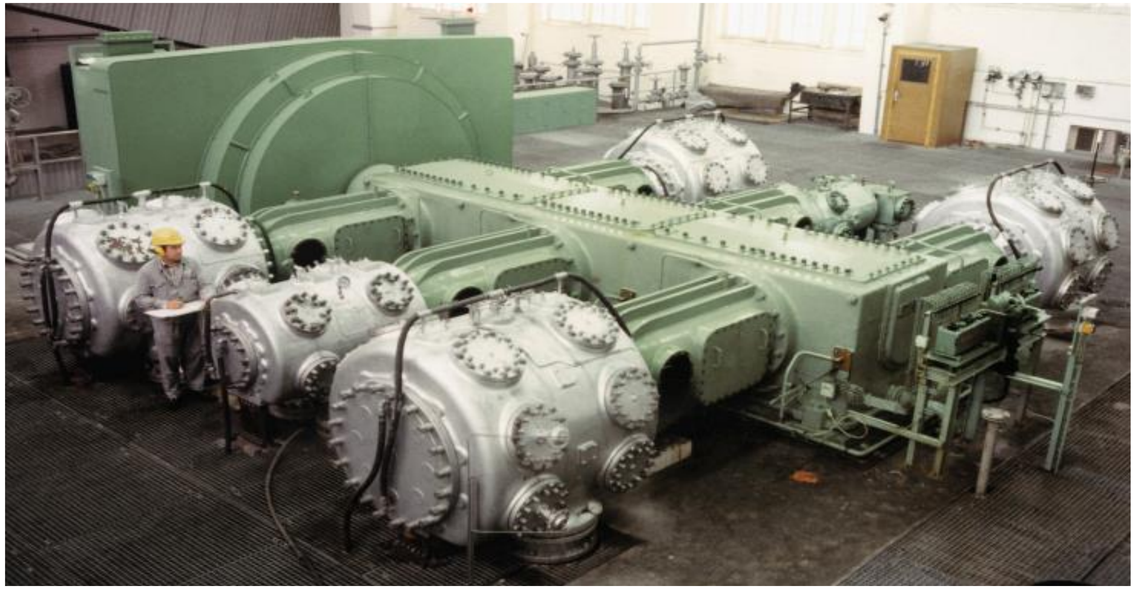
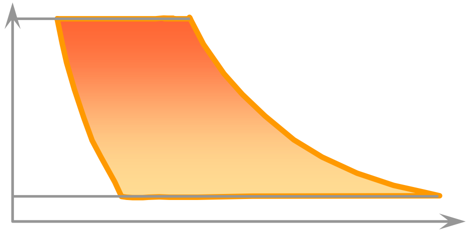
Outline

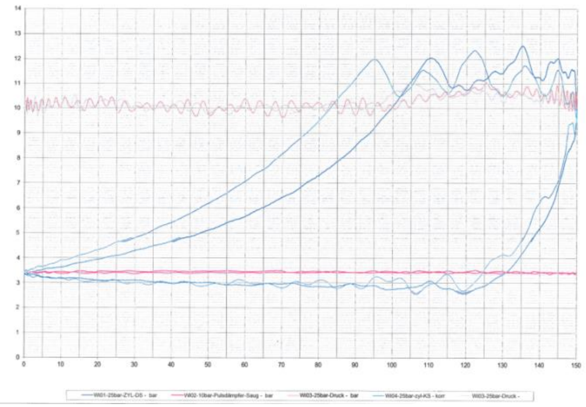


Thermodynamic fundamentals
- p, T, EoS, Processes, Balances





Compression cycle
- p(t) curve, p-V diagram
- Mass-flow rate & power consumption



Losses
- Valve losses
- Blow-by leakage
- Packing leakage

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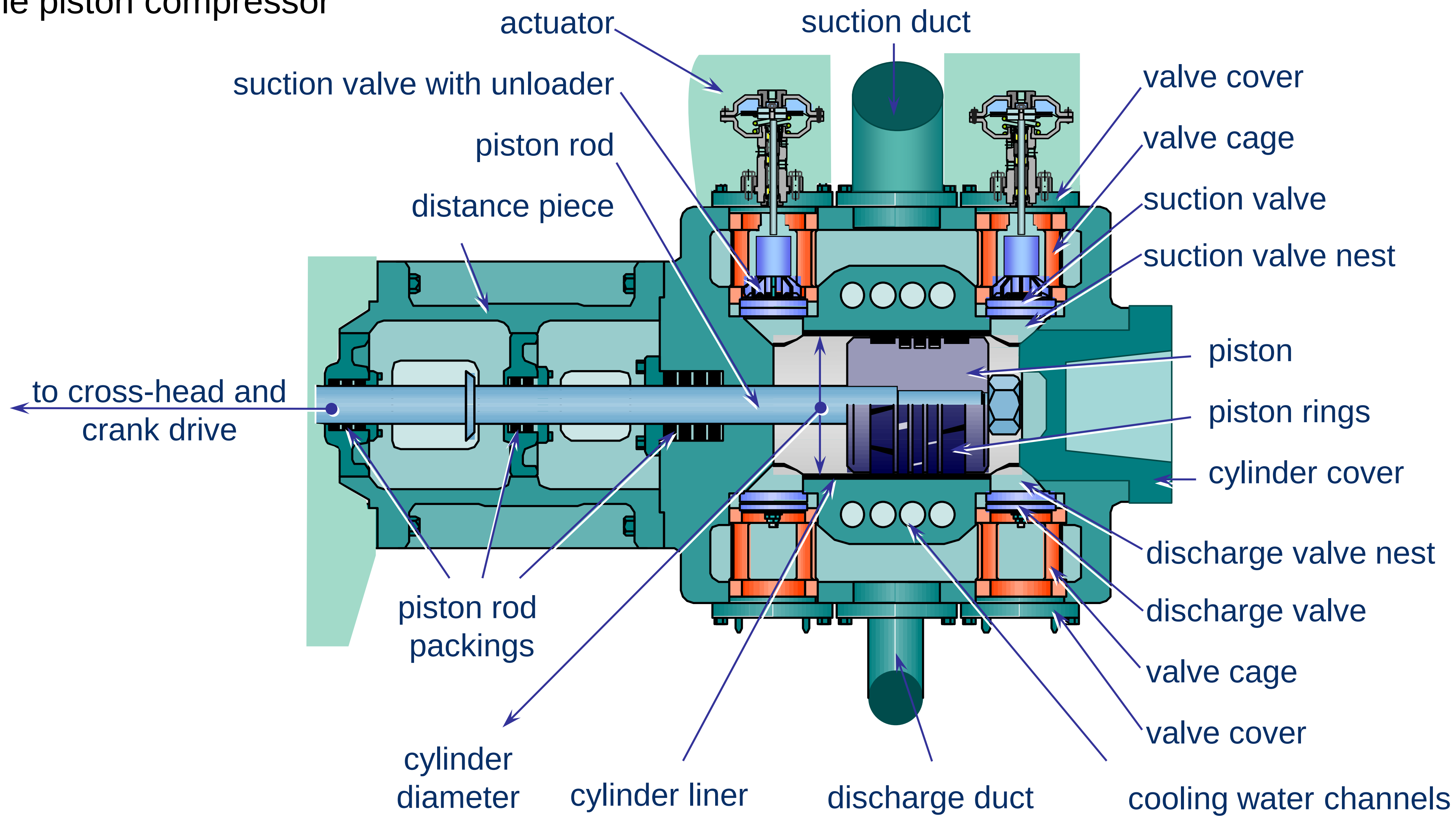
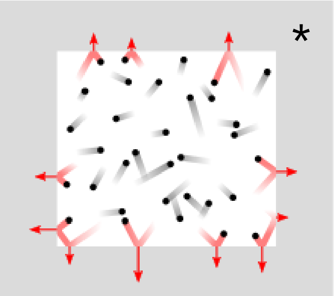
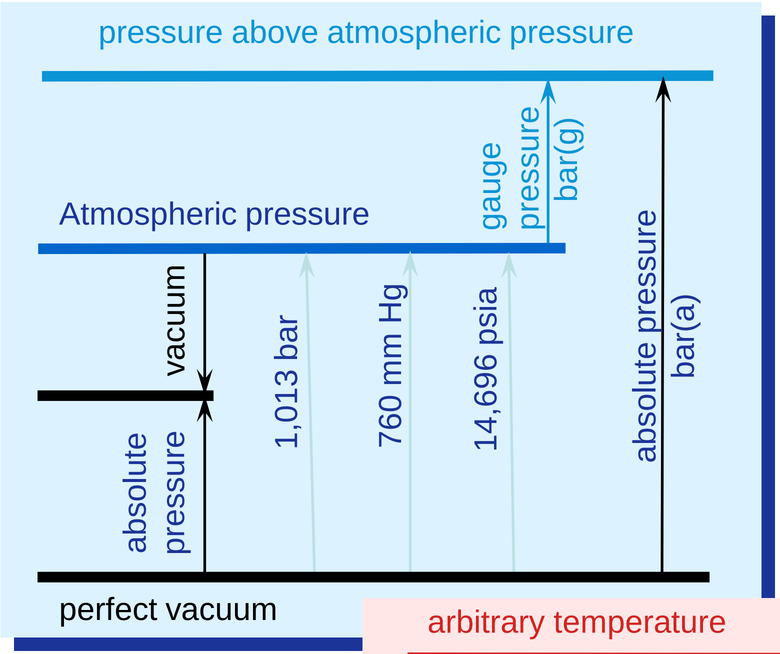
The piston compressor

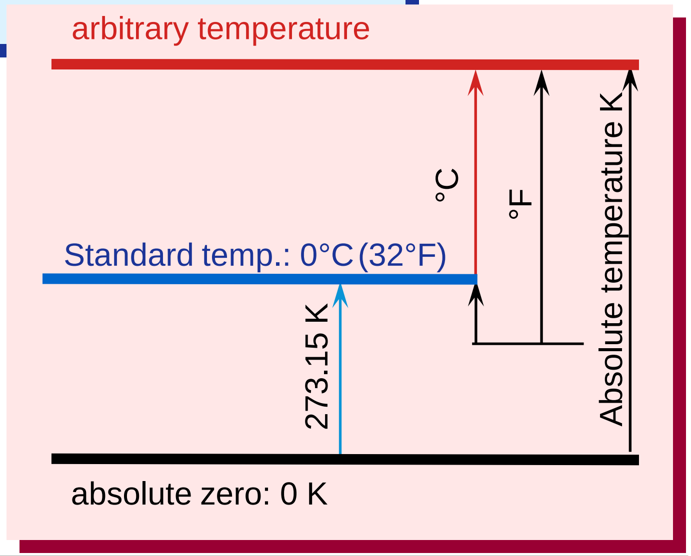


Pressure and temperature

- Pressure: acts in every direction
  ~ kinetic energy of the gas molecules bouncing on the containers walls
- Temperature: related to kinetic energy of the gas molecules (including rotational & vibrational components)
- Are well-defined thermodynamic/physical quantities (i.e. state variables), with links to kinetic gas theory
- Popular units: p in bar, Pa, psi;
  T in K, °C, °F
- Can be field quantities p = p(x,y,z)







Beware: Thermodynamic/Physical relations are expressed in absolute pressures and temperatures!

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Equation of state (EoS)

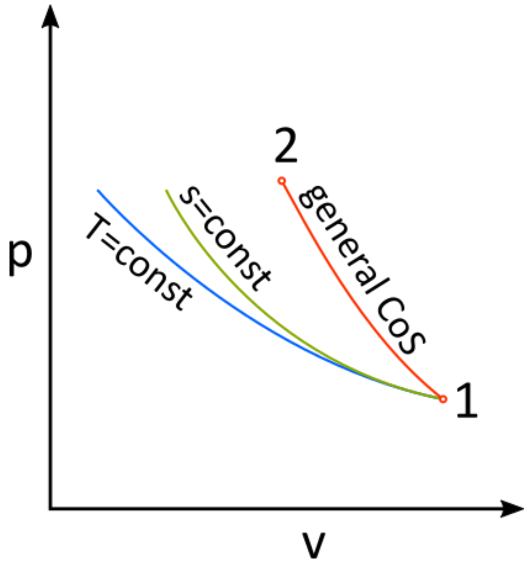
- Relate state variables of a phase to each other,
  e.g. $p \cdot V = m \cdot R \cdot T$ (ideal-gas equation)
- Some EoS allow to calculate phase equilibria (vapour-liquid equilibrium)
- all real gases behave approximately as ideal gases for not too high pressures and temperatures $\Rightarrow$ ideal gas law is asymptotic limiting law for real gases

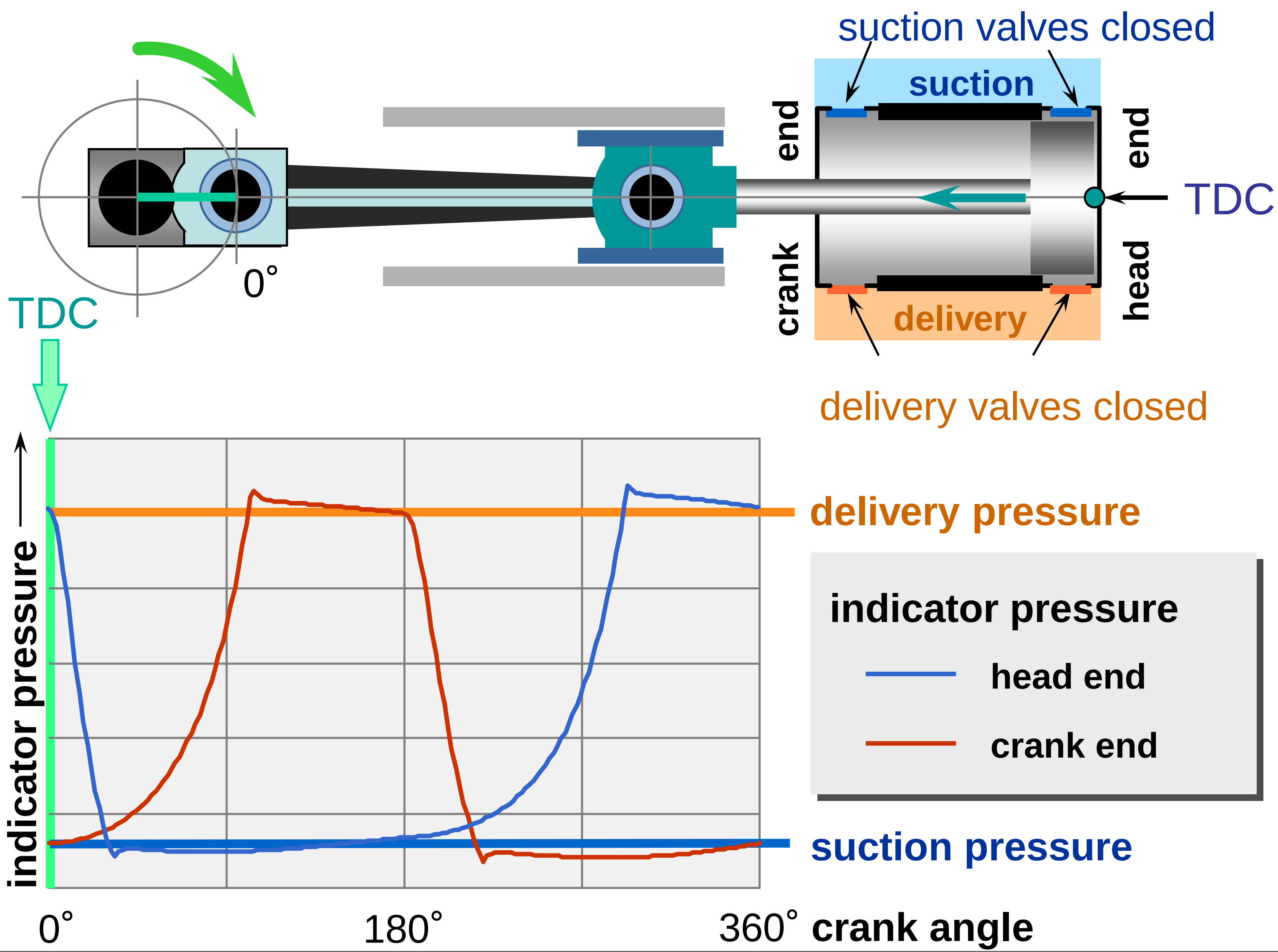
Process

- Change of state, e.g. from state 1 to state 2

Balance equations

- Govern how such a transition can occur
- C.f. first & second law of thermodynamics





Initial state (CE)

- Intake event finished
- Chamber filled with gas at p1
- Valves closed

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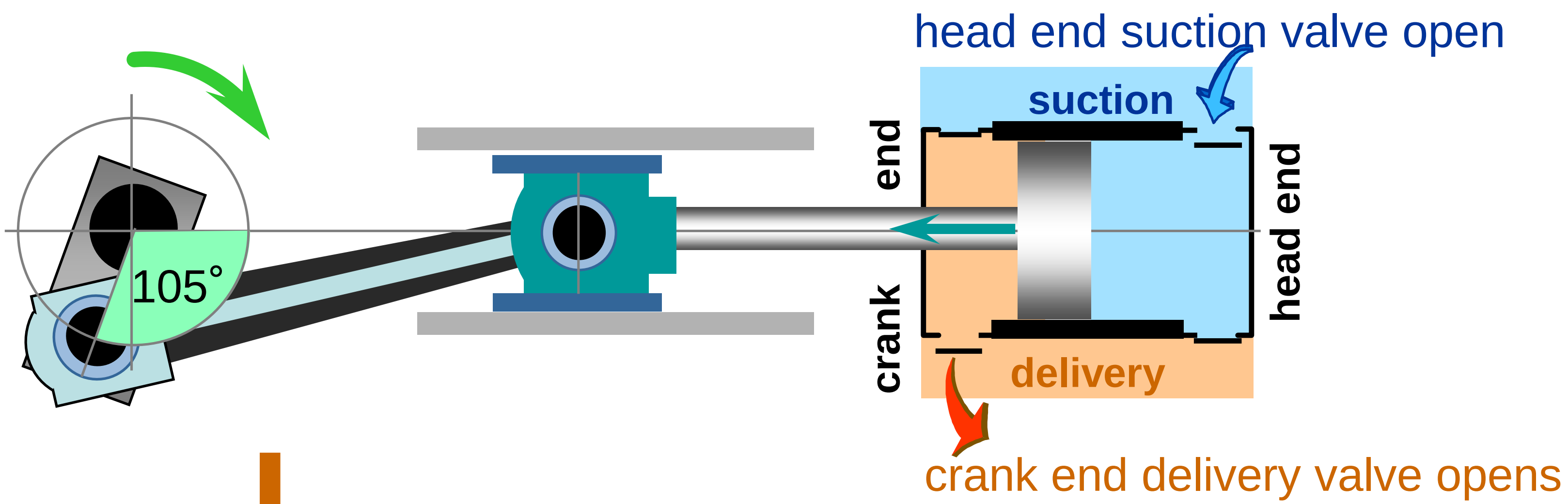
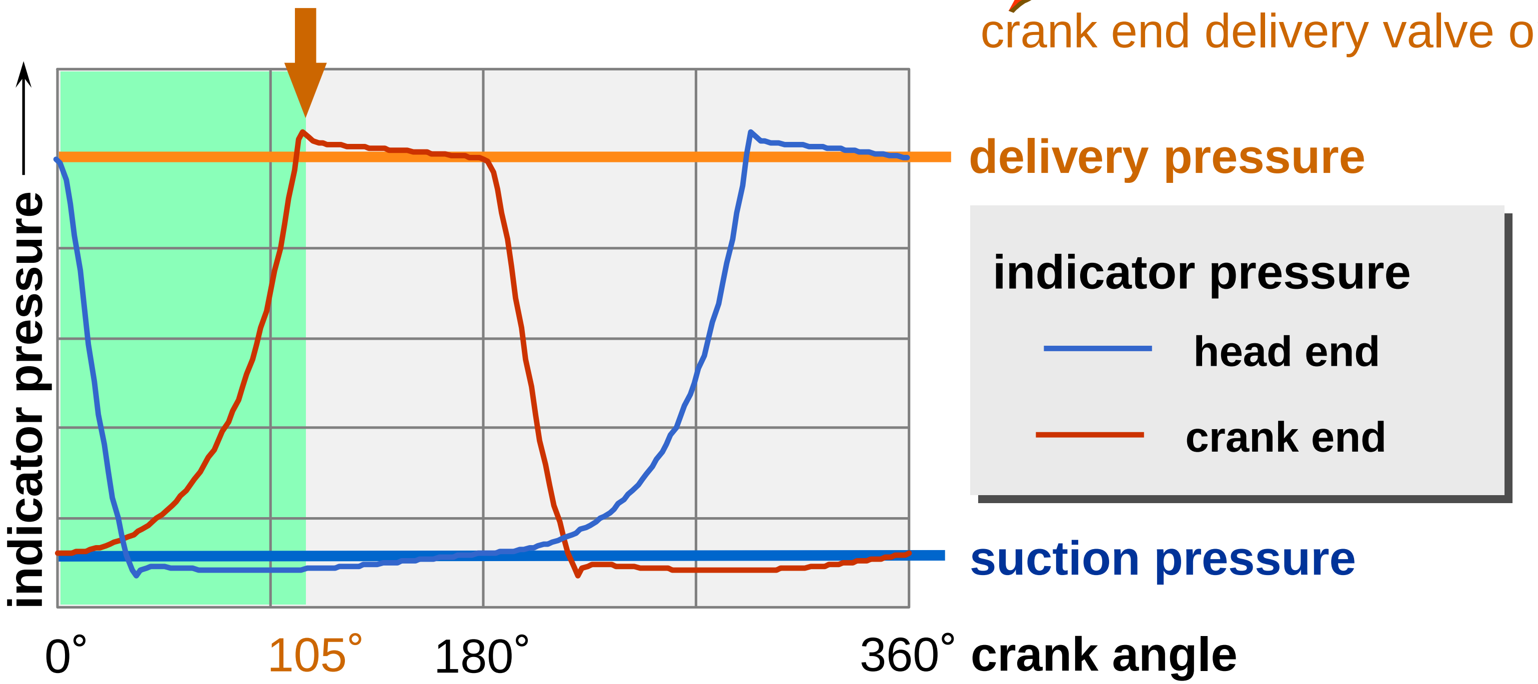




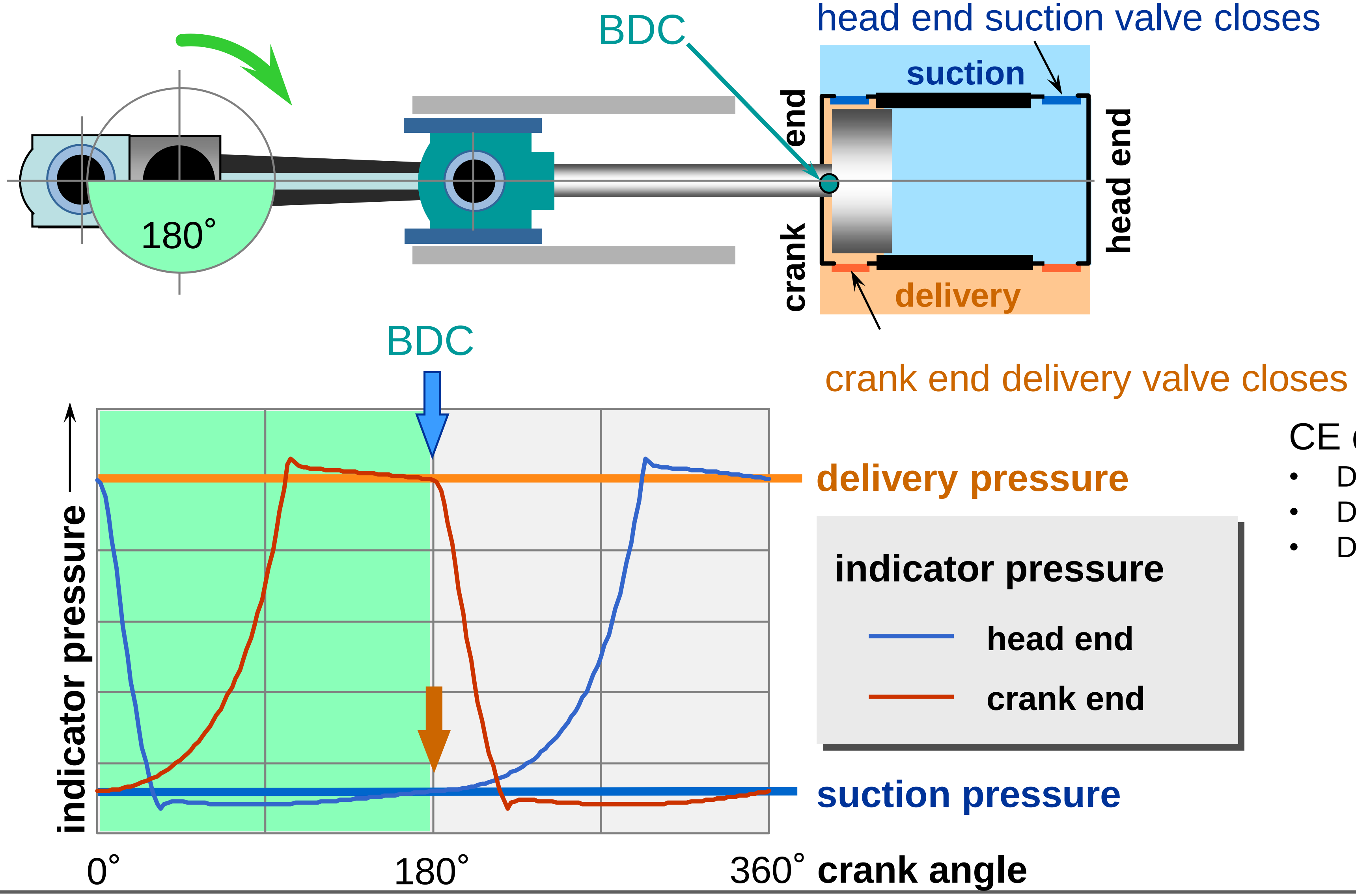
CE compression phase

- Discharge valve closed when p<p2
- DV opens when p=p2
- The change of state is „isentropic“

Discussion

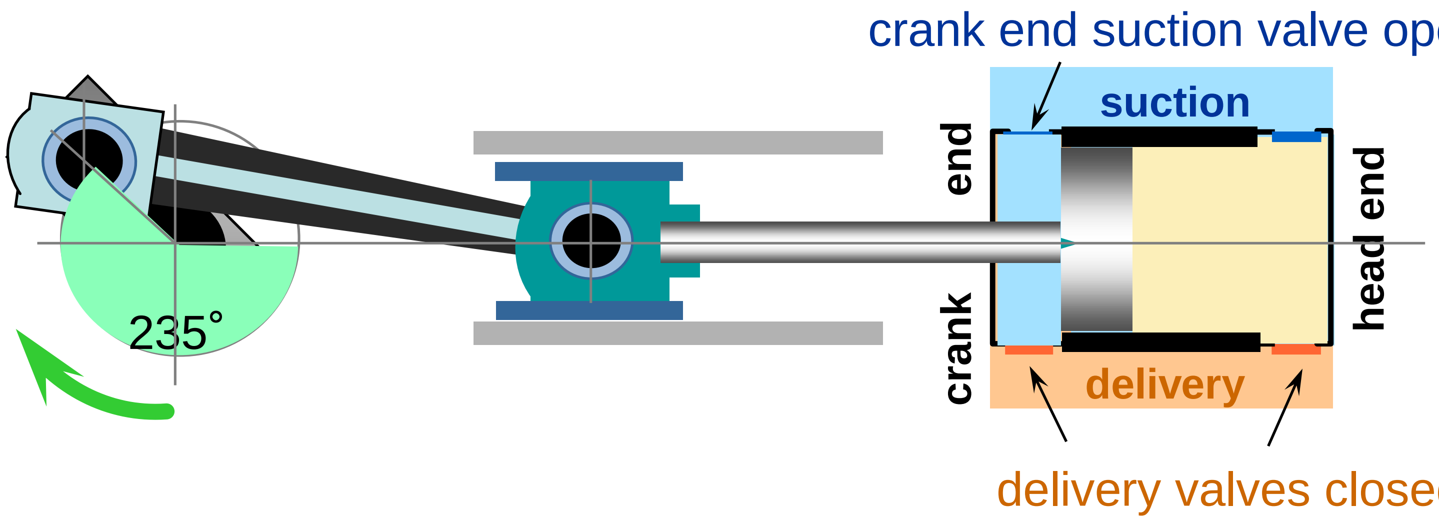
- What does „isentropic“ mean?

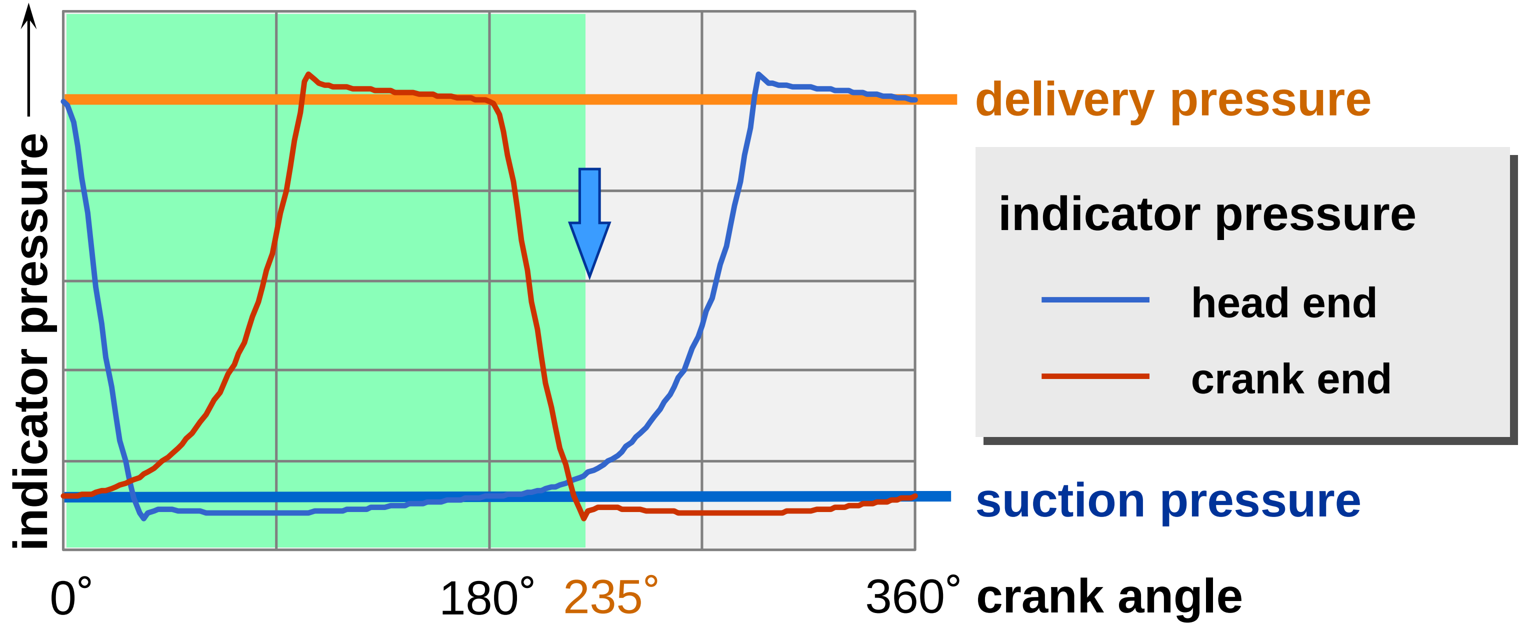
$$\frac{p}{\rho^\gamma} = \mathrm{const}$$



CE delivery phase

- Discharge valve open
- DV closes when the piston is at BDC
- Delivery is also isentropic



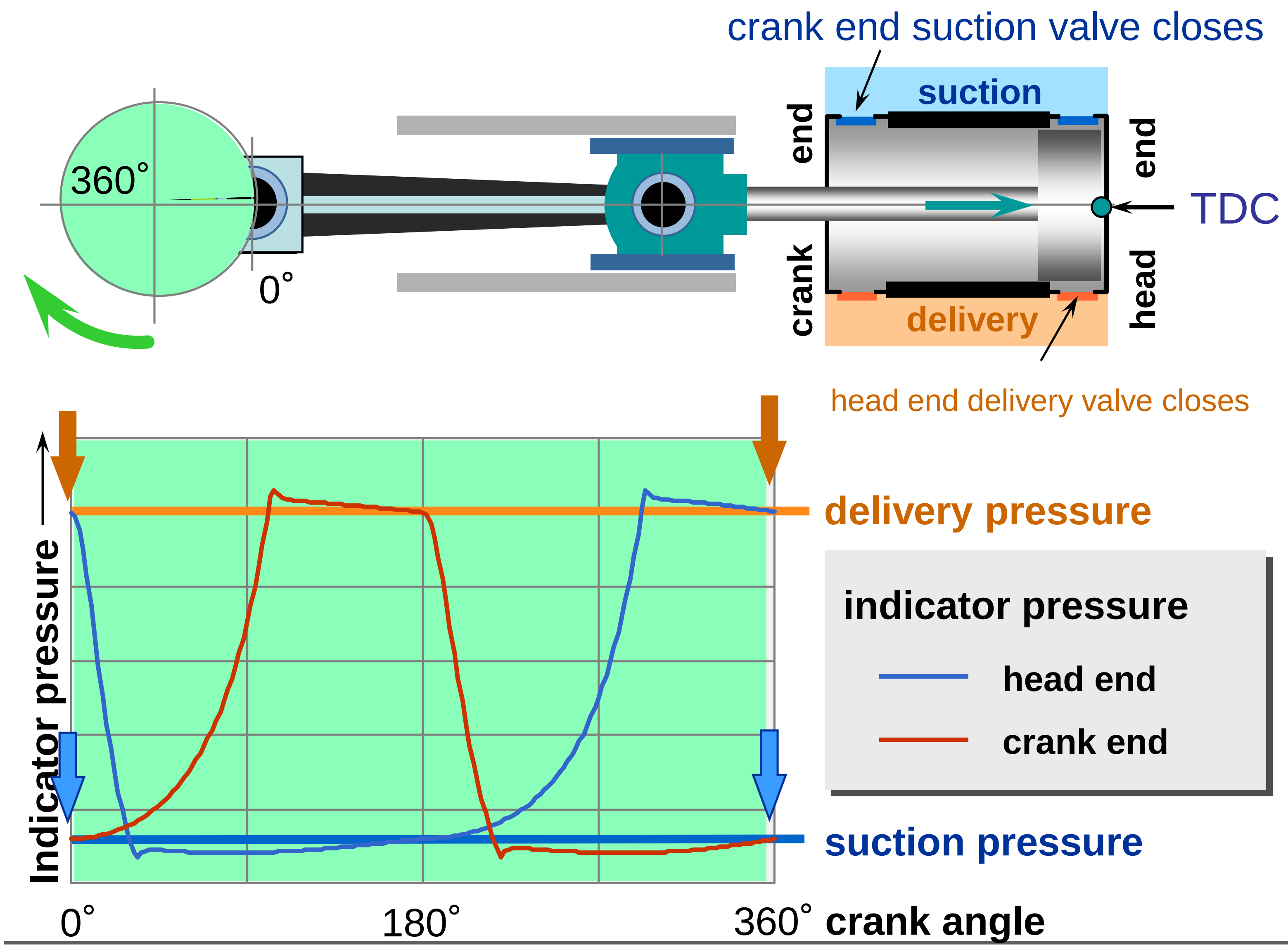


CE re-expansion phase

- Both valves are closed
- Remaining gas (clearance volume!) expands from p2 to p1
- Change of state is isentropic

Discussion

- Why is re-expansion always steeper than compression?



CE suction phase

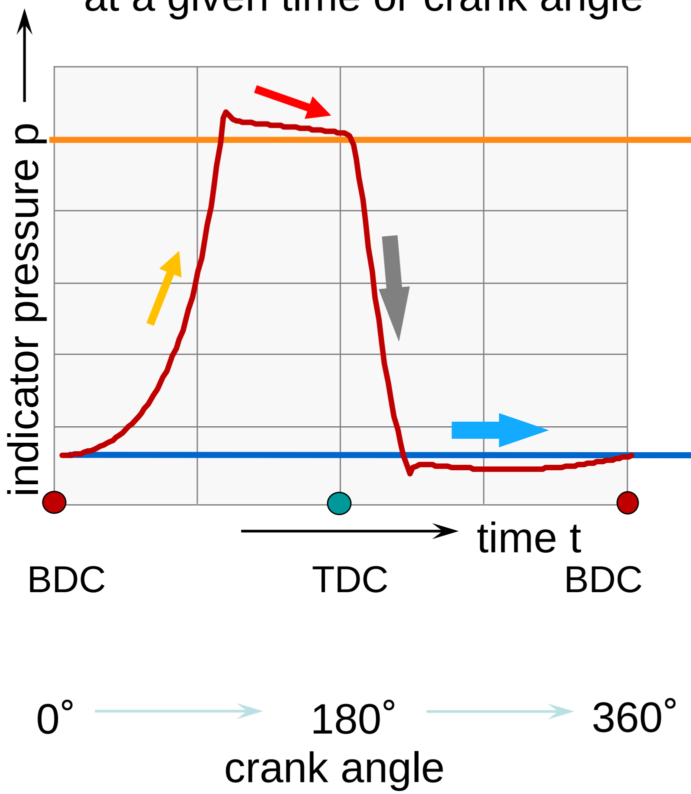
- Suction valve opens when p=p1
- SV closes when the piston is at TDC
- Chamber is being filled with gas at (approximately) T1, p1
- The change of state is <u>not</u> isentropic (only in the limit of infinitely large valves)

Discussion

- What are the main differences between HE and CE?

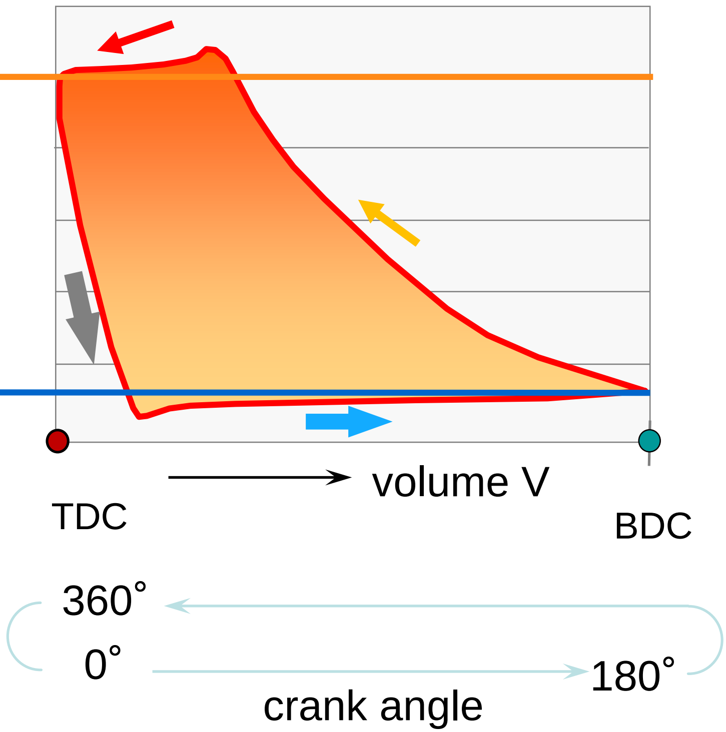
Pressure - Time Diagram
p,t

shows the pressure in the cylinder at a given time or crank angle



Pressure - Volume Diagram
p,V

shows the pressure in the cylinder at a given volume or piston position



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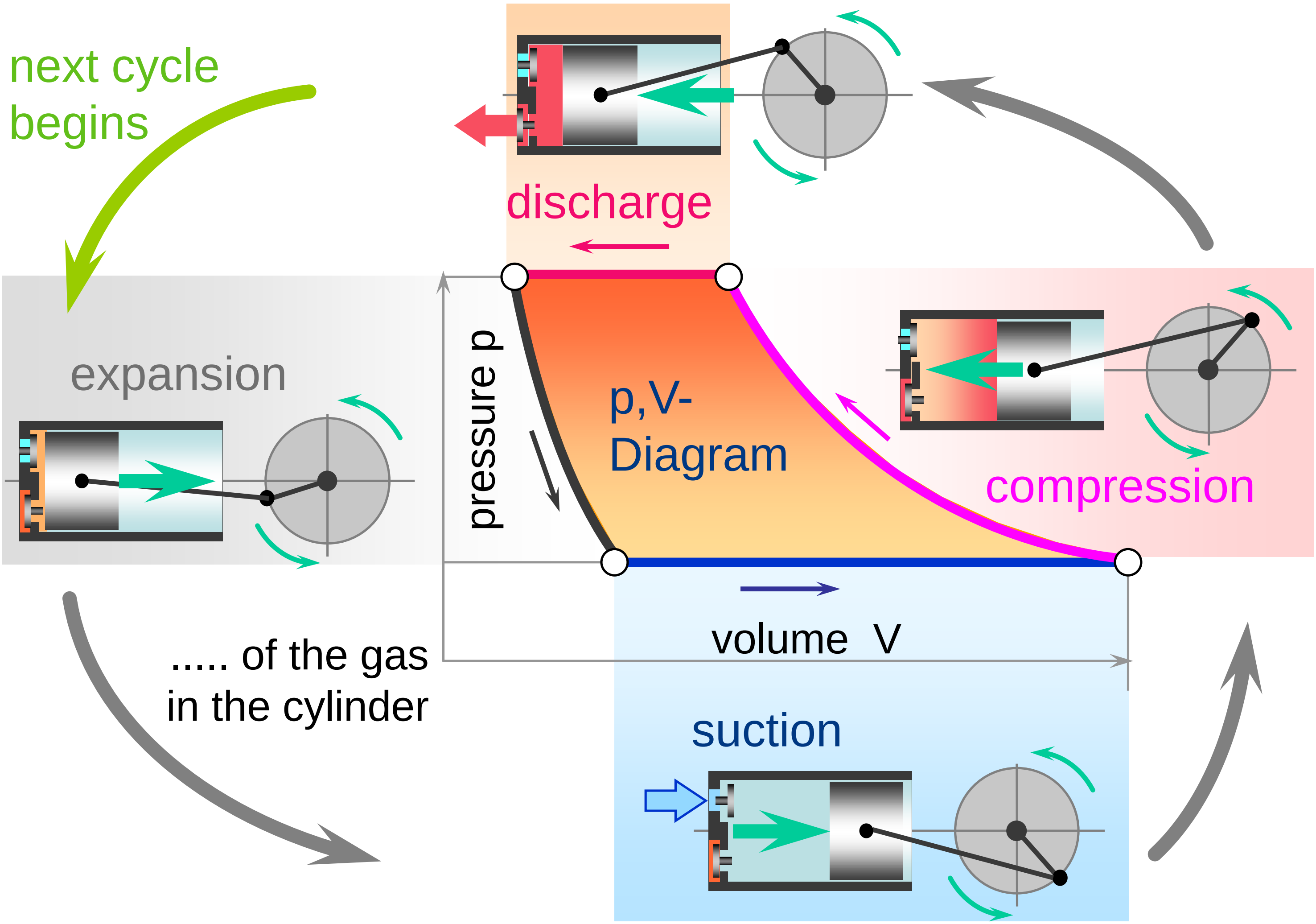
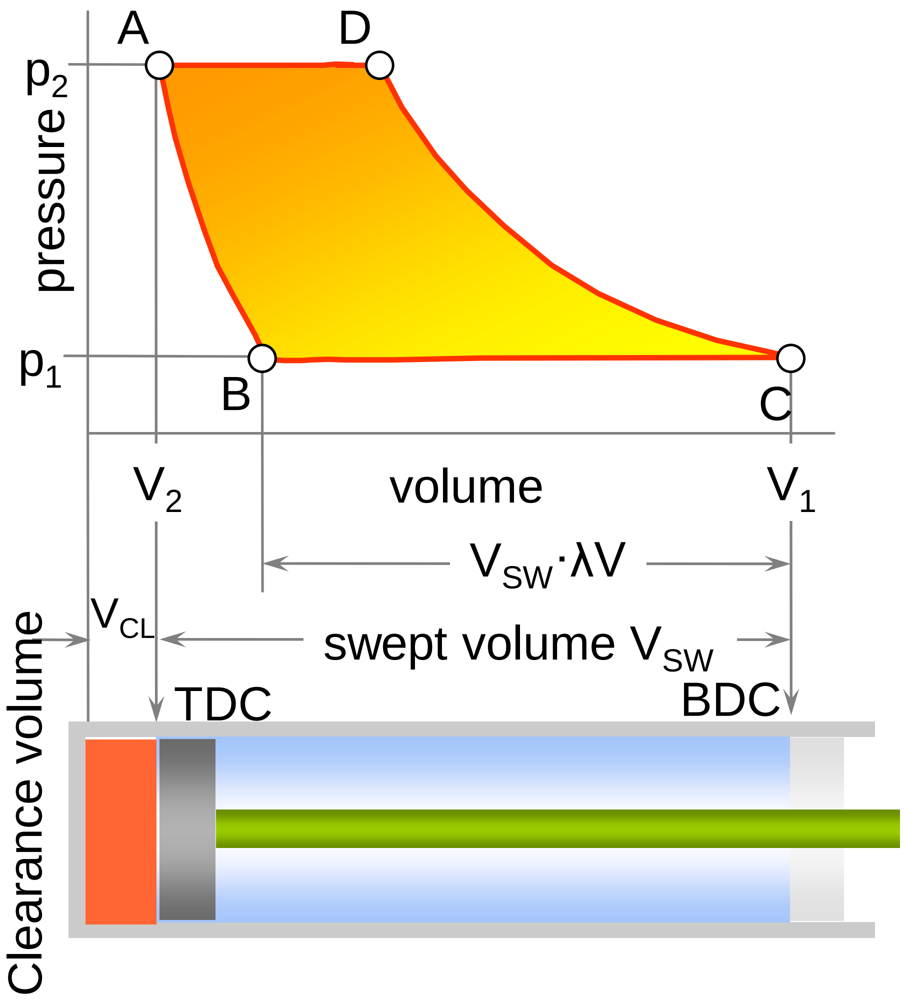


Delivered mass-flow rate



Mass flow rate

$$M_{\mathrm{ad}} = V_{\mathrm{SW}} \rho_1 \cdot \lambda_{\mathrm{V}} \cdot \frac{rpm}{60}$$

M_{ad} adiabatic mass flow (kg/s)
rpm compressor speed
V_{SW} swept volume (m³)
λ_V volumetric filling efficiency (-)

Volumetric filling efficiency

$$\lambda_{\mathrm{V}} = 1 - \sigma \left(\left(\frac{p_2}{p_1} \right)^{1/\gamma} - 1 \right)$$

γ isentropic exponent
σ clearance volume referred to swept volume

Generalised filling efficiency

$$\lambda = \lambda_{\mathrm{V}} \cdot \lambda_{\mathrm{p}} \cdot \lambda_{\mathrm{H}} \cdot \lambda_{\mathrm{L}}$$

- Volumetric filling efficiency
- Pressure loss (SV)
- Heating
- Leakages

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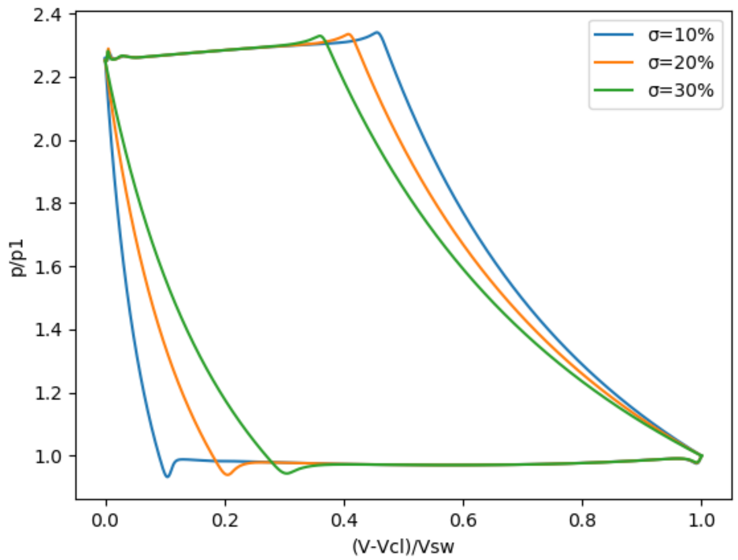
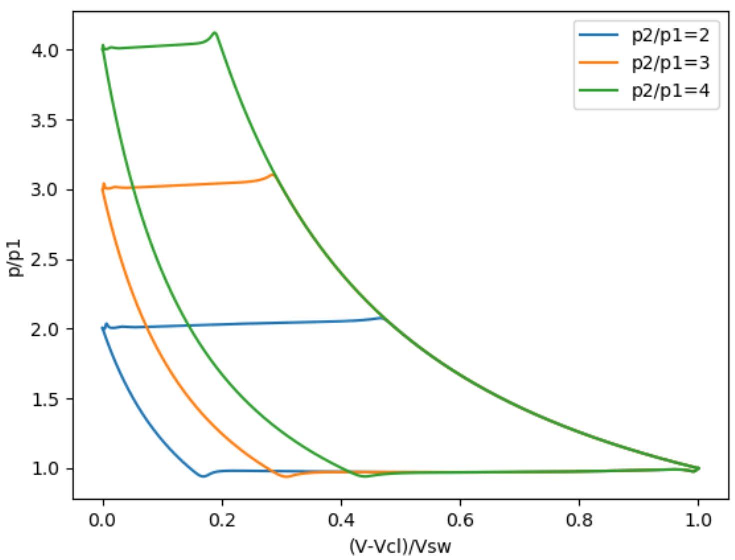
Dependence of the filling efficiency on σ and p_2/p_1





Increasing σ, p_2/p_1:

- •Longer re-expansion phase
- •Longer compression phase
- •Shorter suction and delivery phases

There‘s a p_2/p_1— σ combination where $\lambda \rightarrow 0$!

Discussion:

- •How does the p-V diagram look like when $\lambda \rightarrow 0$?
- •Practical limits of p_2/p_1 (upper), σ (lower)

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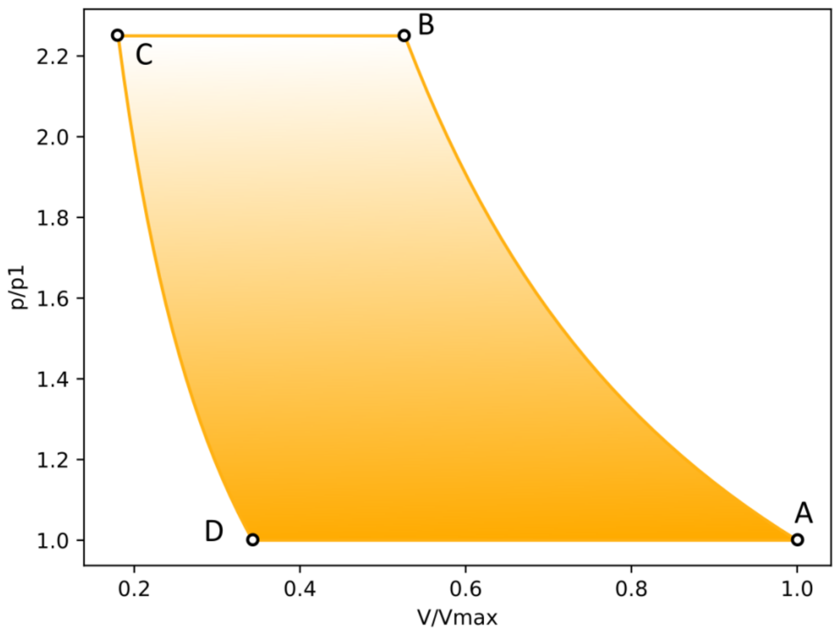
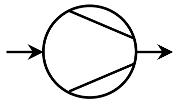
Required driver power





By the first law of thermodynamics:

- State 1 → 2:

$$U_2 - U_1 = \int_1^2 \left(- p\dot{V} + \sum_i \dot{m}_i \underbrace{\left(u_i + \frac{p_i}{\rho_i} \right)}_{h} \right) \mathrm{d}t$$

- H: „Enthalpy“ = internal energy + p/ρ, H = H(T, p)
- Cycle:

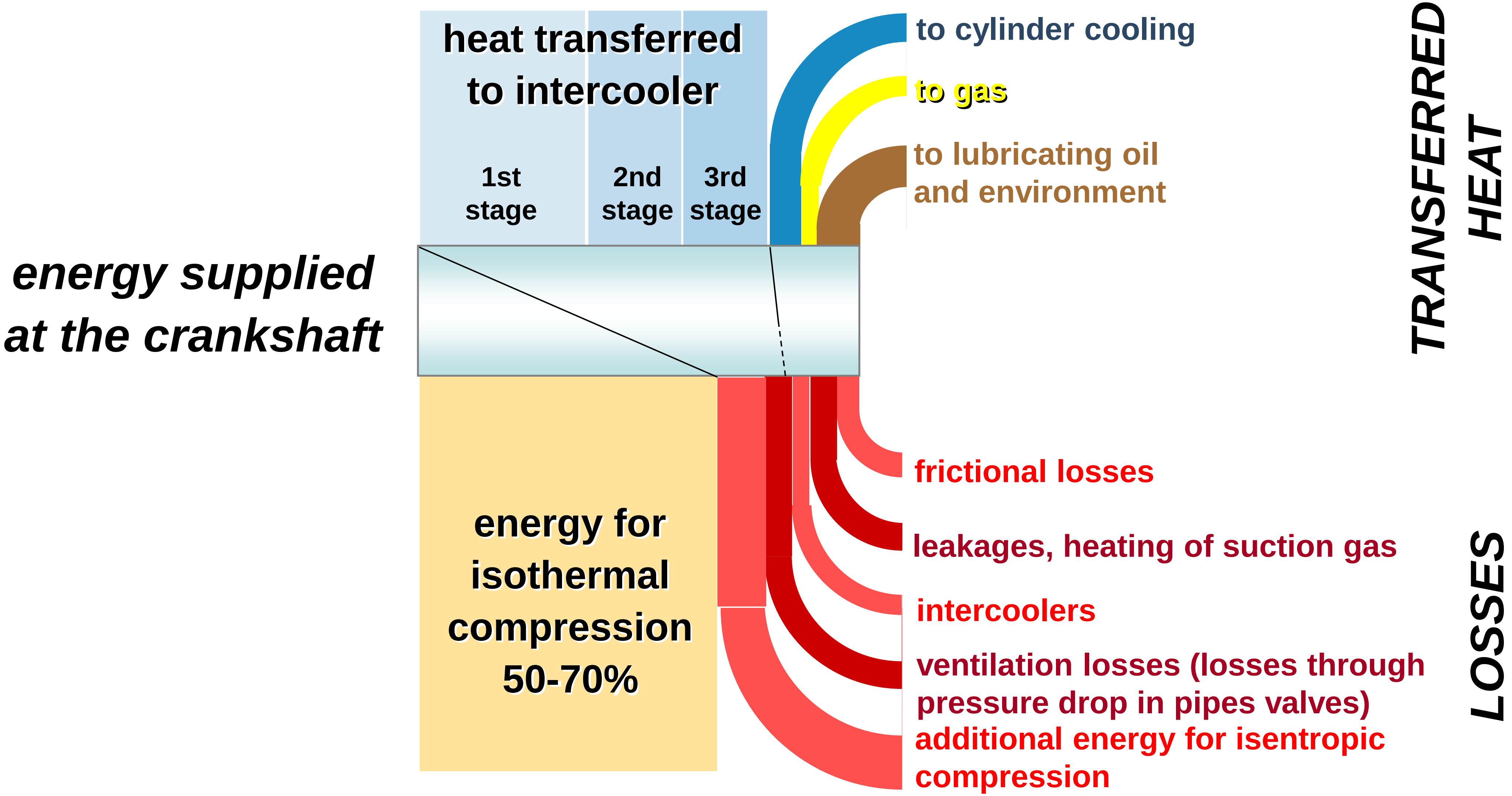
$$W = H_o - H_i = - \oint p\mathrm{d}V$$

- Enclosed area of the pV diagram equals the work done in the cycle (ABCDA, isentropic compression)

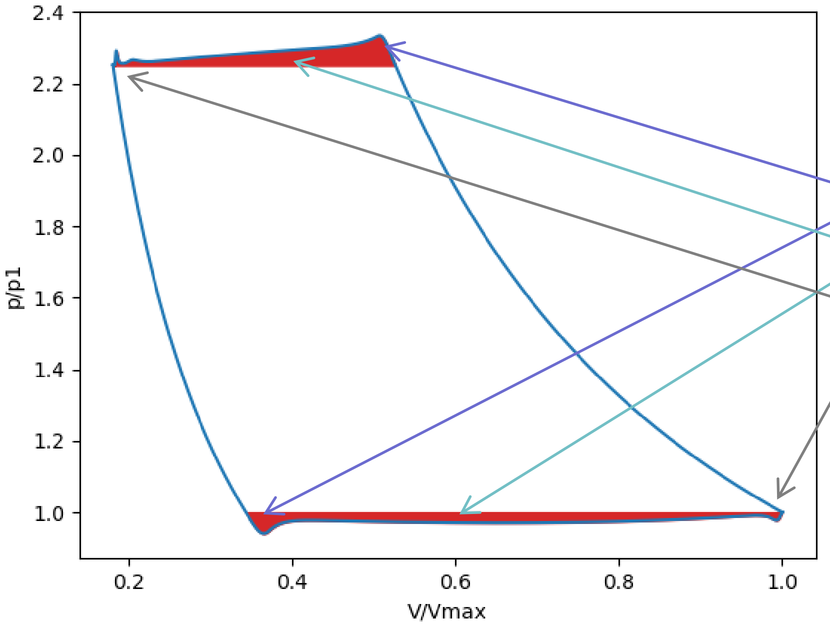
Adiabatic power (ideal gas, no losses, no heat transfer)

$$P_{\mathrm{ad}} = \frac{\gamma}{\gamma - 1} \frac{p_1}{\rho_1} M_{\mathrm{ad}} \left(\left(\frac{p_2}{p_1} \right)^{(\gamma-1)/\gamma} - 1 \right)$$

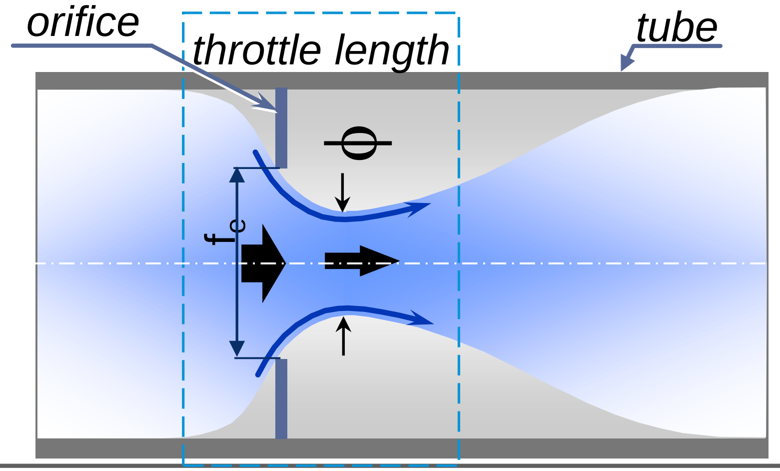
Global compressor energy balance



Valve losses



- Peak due to slow valve opening
- Loss when the valve is fully open
- Fluctuations due to closing valve

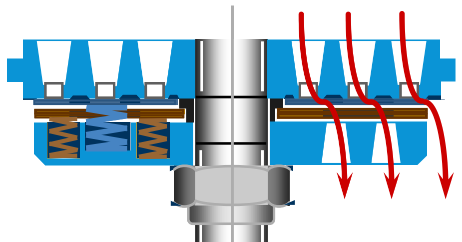


Pressure loss when the valve is fully open:

•in the valve
•in the valve pocket
•in the pipe

Valve losses:

•Increase the indicated power (red area)
SV losses:
•Decrease the mass-flow rate (λ_p!)



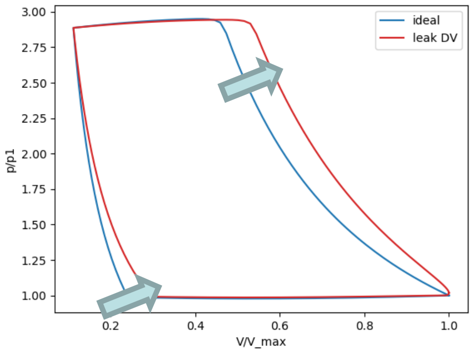
Loss model

•Nozzle with ideal acceleration and full loss of kinetic energy (*isenthalpic* change of state)

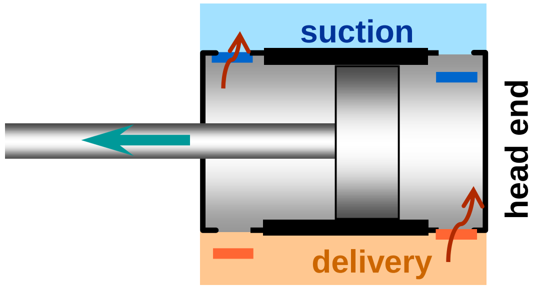
Gas Compression and Thermodynamics

Leaking DV valve

Hot, compressed gas flows into the compression chamber

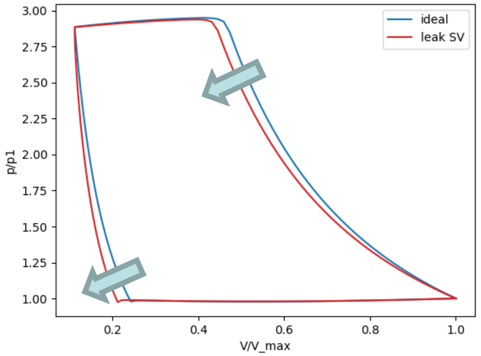


- Faster compression, slower re-expansion
- Suction gas is heated up (in the compression chamber)
- Discharge temperature increases



Leaking SV valve

Hot, compressed gas flows into the intake manifold



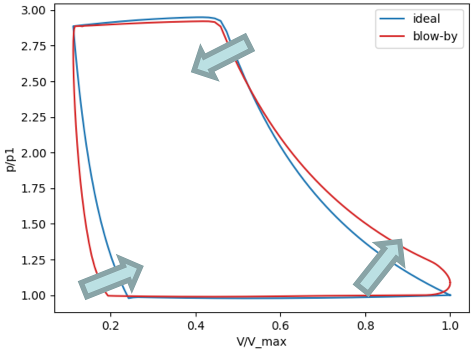
- Slower compression, faster re-expansion
- Suction gas is heated up (in the intake-manifold)
- Discharge temperature increases

Packing leakage

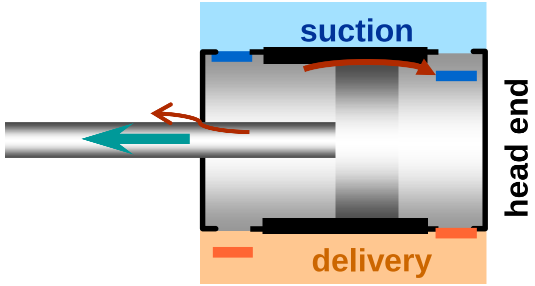
- Similar in appearance, but doesn‘t increase the discharge temperature.
- CE Side only.

Blow-by leakage

Hot, compressed gas flows into the compression chamber



- „S“ curve in the compression line
- Suction gas is heated up (in the compression chamber)
- Discharge temperature increases



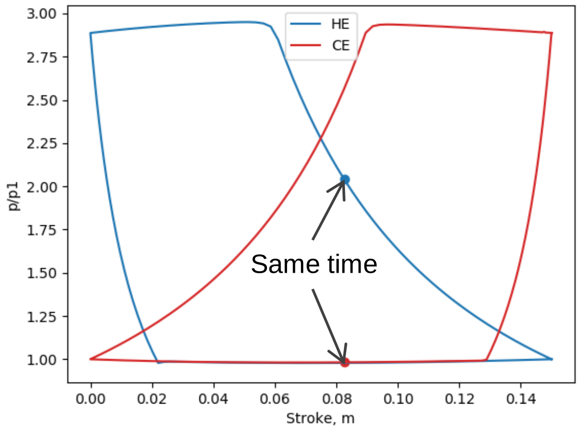
Discussion

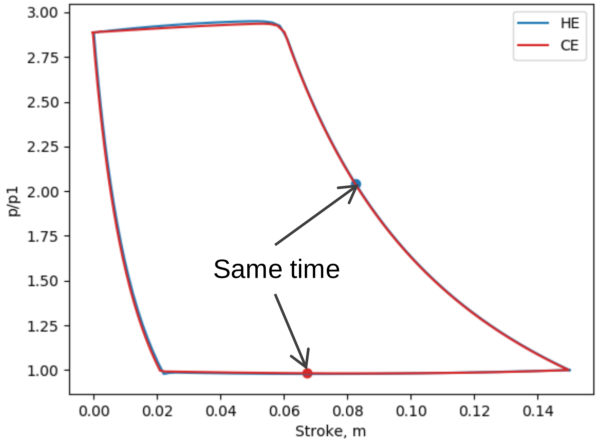
- Which data is available typically?
- Analyzing p-V diagrams from the field

P-V diagrams in the field

Double-acting pistons:

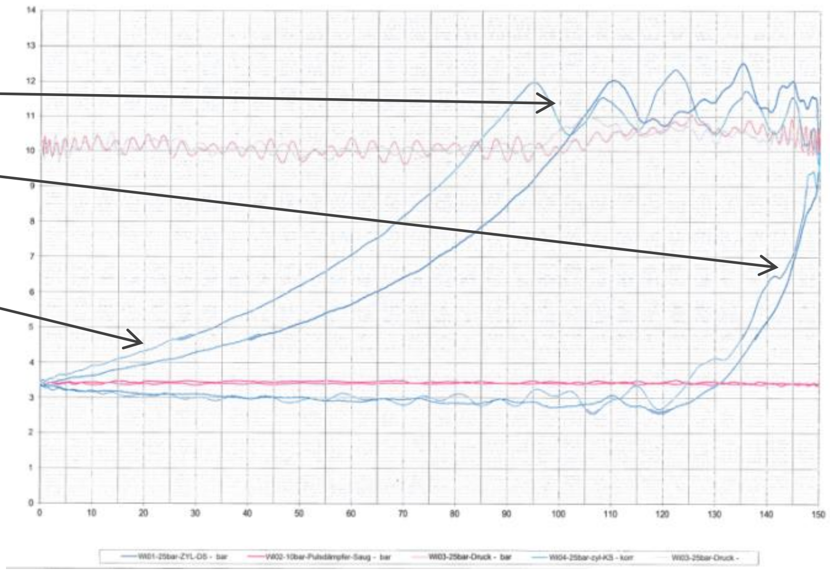
- Over piston position (left)
- Over shifted piston position (right)





Further deviations:

- Pulsations during valve opening (discharge)
- Pulsations after valve closing (re-expansion line)
- HE/CE differences due to losses, etc.



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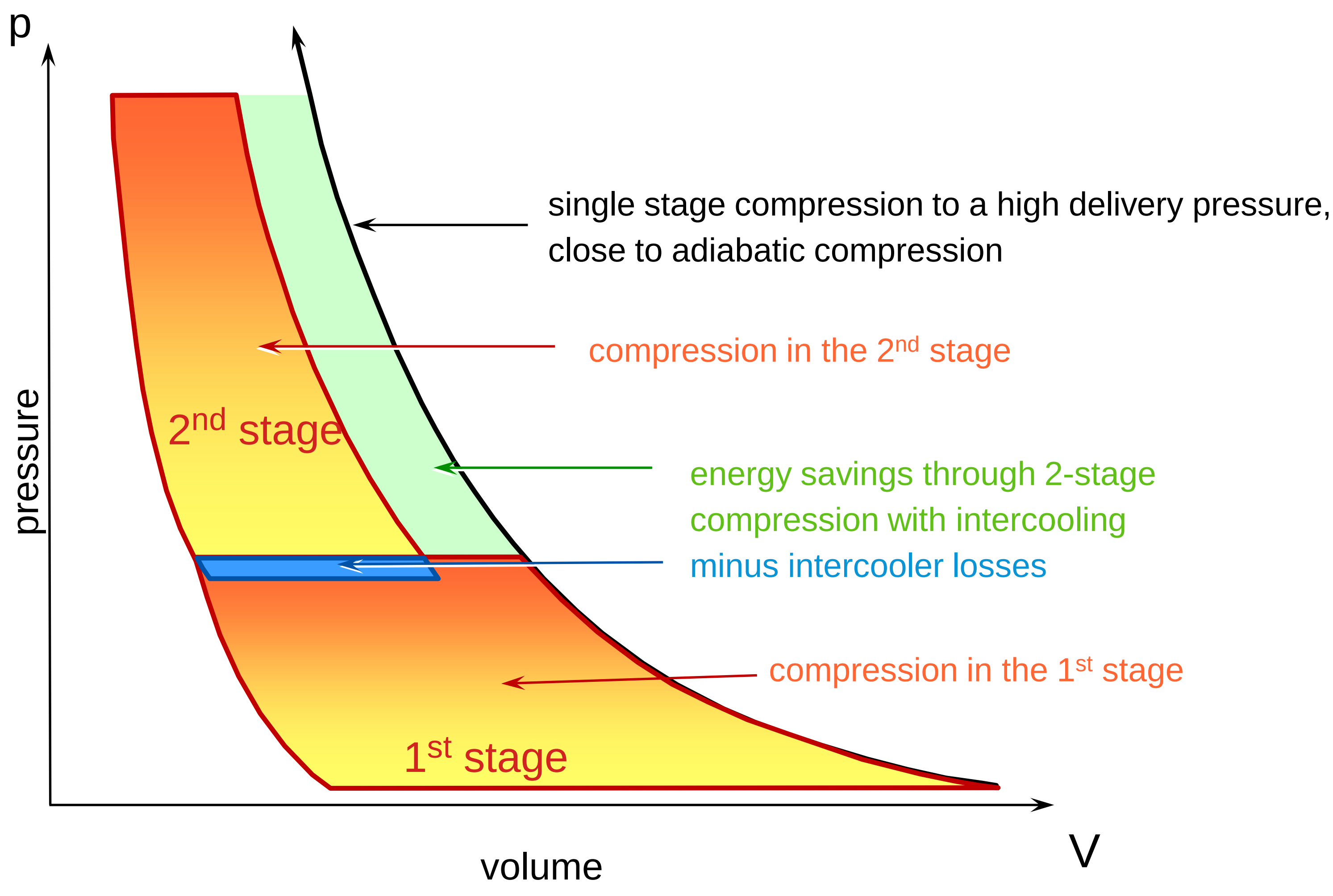
Two-stage compressor



Discussion

- Selecting the number of stages
- Compressor sizing approaches

Thank you for your attention