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Reciprocating Piston Expanders for Small-Scale ORC Systems

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NB: Some information from the original presentation has been omitted for confidentiality reasons.

Background and Motivation

- Reciprocating machines/processes:
  - Thermofluidic oscillators – “two-phase Stirling” engines
  - Pumped Thermal Electricity Storage (PTES; Isentropic UK) – forward/reverse Joule cycle
- Expander maps?
- Isentropic efficiency (heat transfer + irreversibility = isentropic)?

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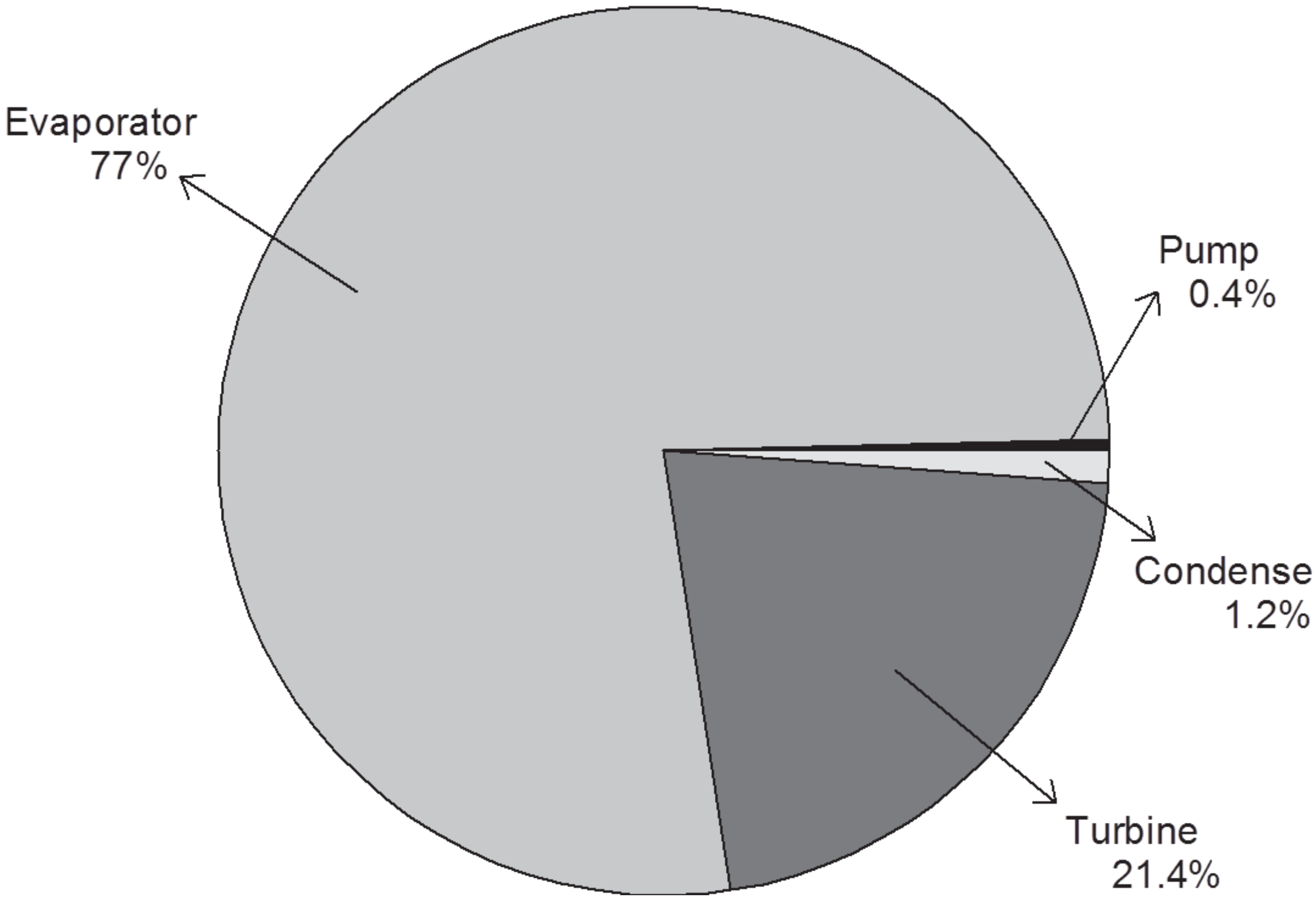
Exergy Destruction in a Typical ORC System



Mago, et al., *International Journal of Energy Research* 31(1), 2008

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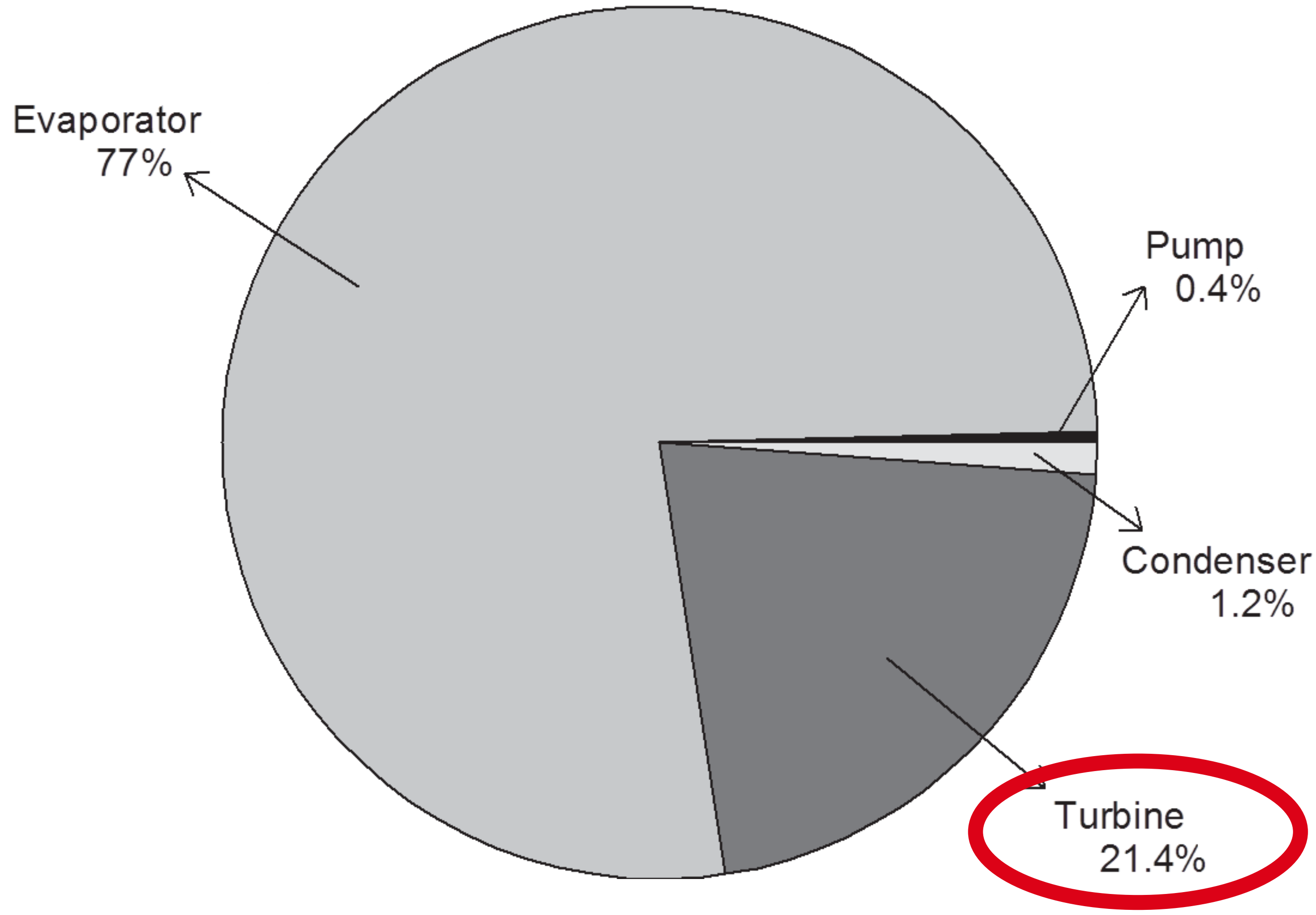
Exergy Destruction in a Typical ORC System



Dimensionless Performance Parameters

$$N_s = \frac{N\dot{V}^{1/2}}{(\Delta h)_s{}^{3/4}}$$

$$D_s = \frac{D(\Delta h)_s{}^{3/4}}{\dot{V}^{1/2}}$$

- Specific diameter proportional to diameter of engine (measure of machine's size)
- Specific speed proportional to rotational speed and to power output

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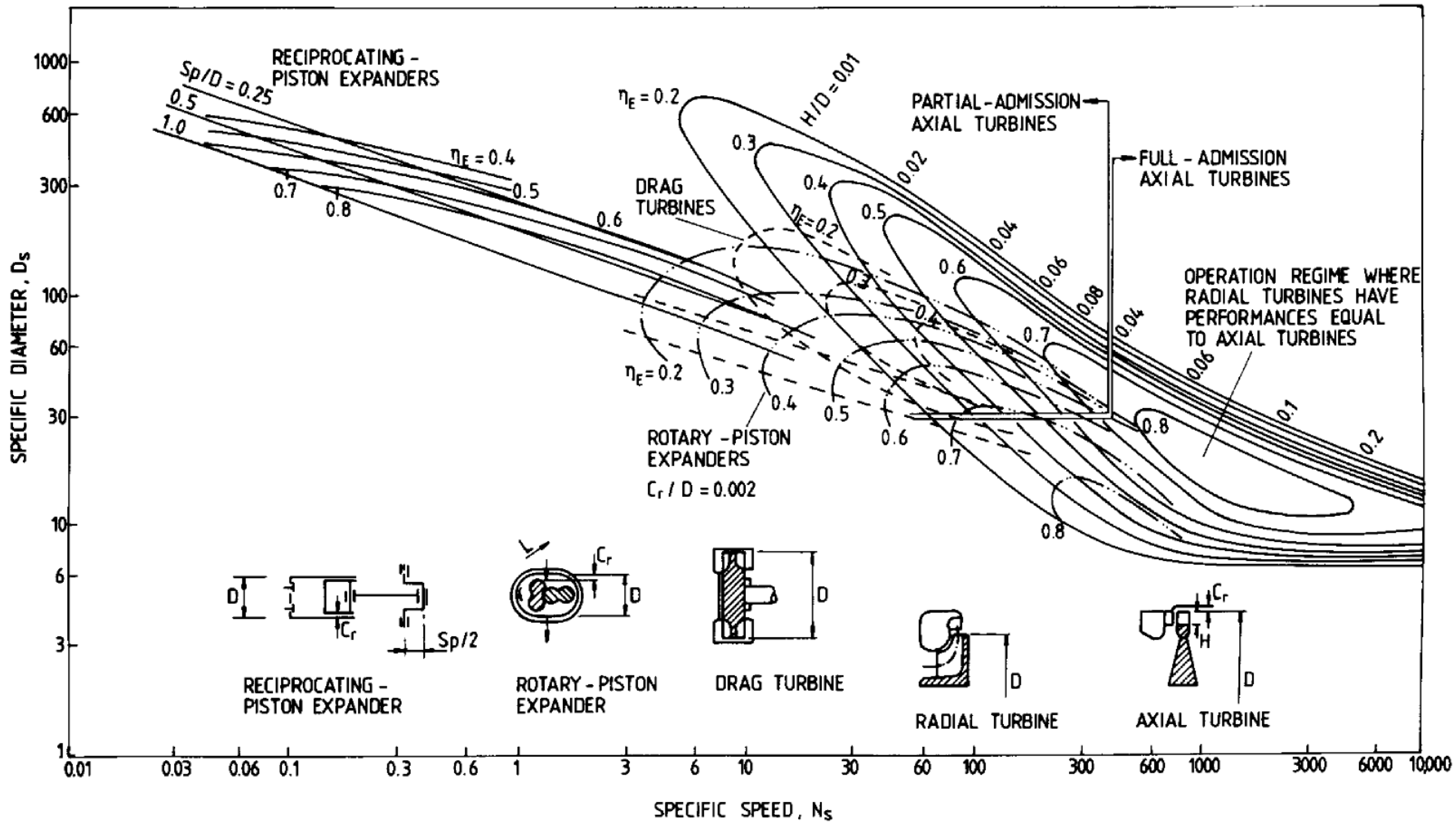
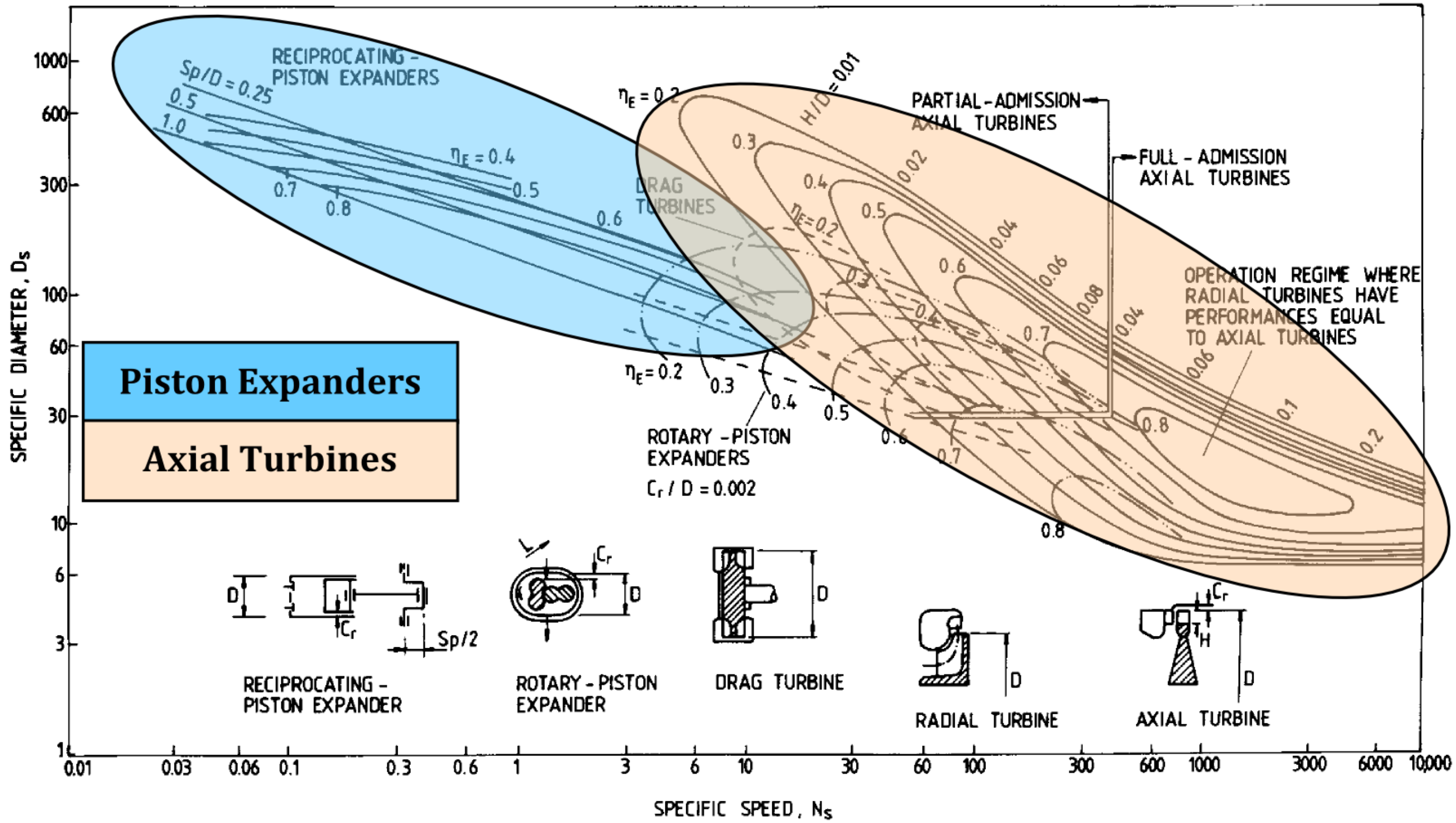
Expander Performance Maps

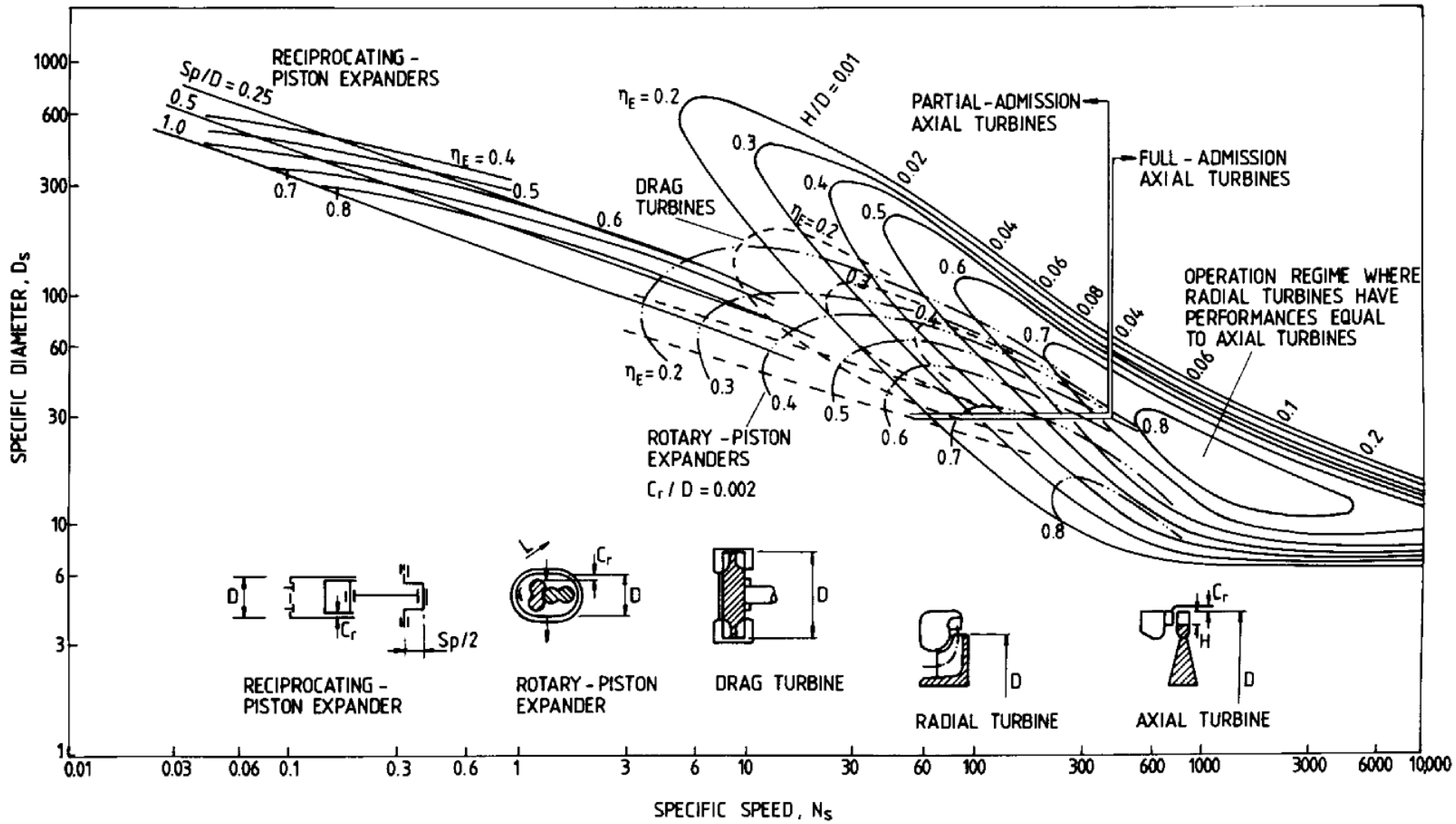


Badr, et al., 1984

Expander Performance Maps

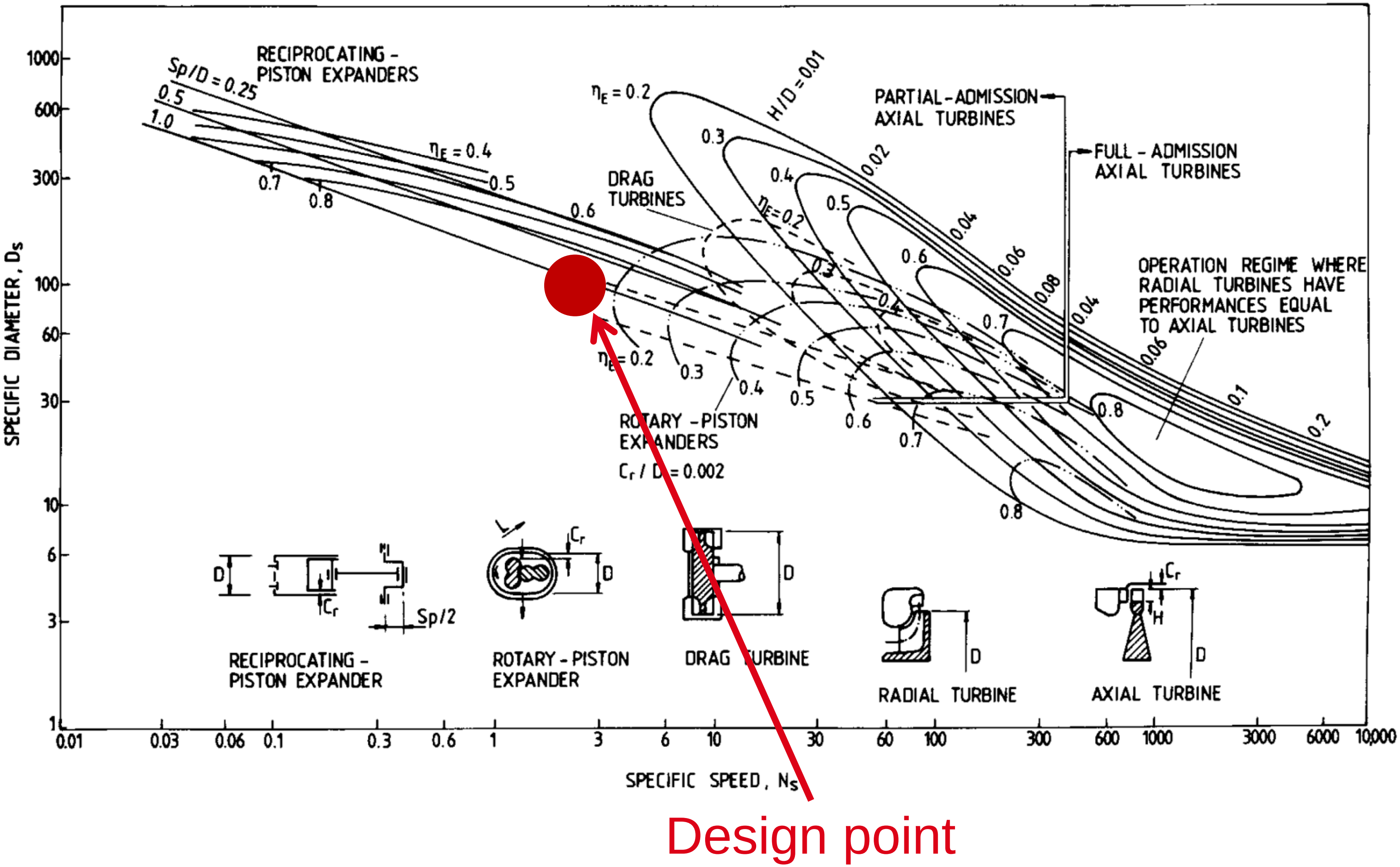


Expander Performance Maps

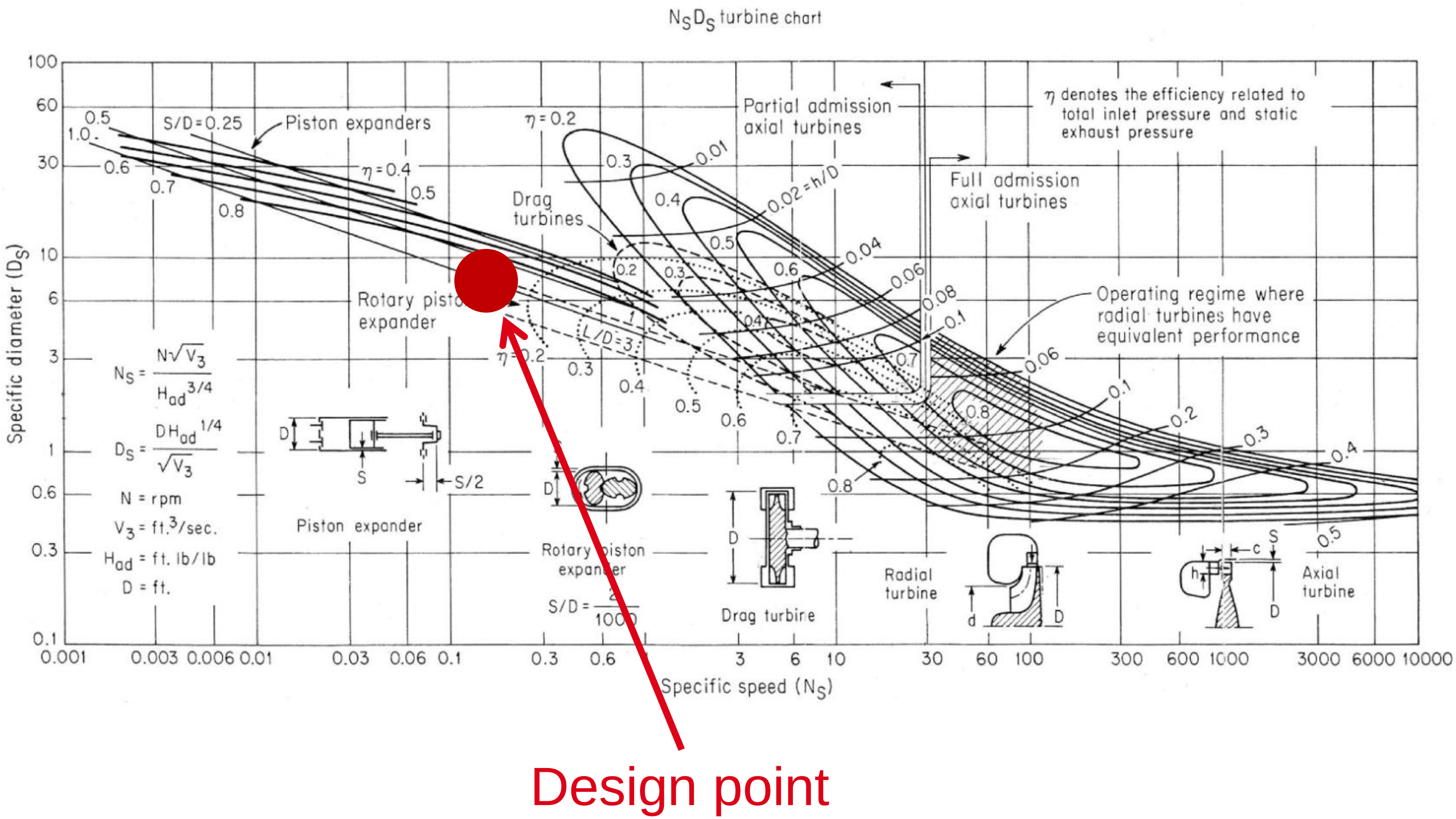


For low power outputs (< 50 kW, < 10 000 rpm) positive displacement expanders more efficient than turbines

Expander Performance Maps



Expander Performance Maps



Balje, et al., 1962

Positive Displacement Expanders vs. Turbomachines

- Higher efficiencies, lower rotational speed (hence friction, vibration, balancing), lower costs than turbines at low power outputs/smaller sizes
- No gear-box required as they can retain high efficiency at smaller operational frequencies
- Liquid phase in vapour possible
- Turbines inefficient in part load

Reciprocating Piston vs. Other Displacement Expanders

- More robust, higher efficiencies than scroll expanders in kW-range
- Less sensitive to leakage → low-cost manufacturing

Table C: Expander indicated and isentropic efficiency vs. leakage gap size

	5 μm		10 μm		15 μm	
	η_{ind}	η_{is}	η_{ind}	η_{is}	η_{ind}	η_{is}
Recip. piston	0.90	0.75	0.87	0.72	0.81	0.66
Rotary piston	0.94	0.79	0.84	0.69	0.78	0.63
Scroll	0.93	0.78	0.75	0.60	0.47	0.32

Huff and Radermacher, 2003

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Loss Mechanisms in Reciprocating Expanders

- Valve (pressure, friction) losses
- Leakage losses
- Thermal losses

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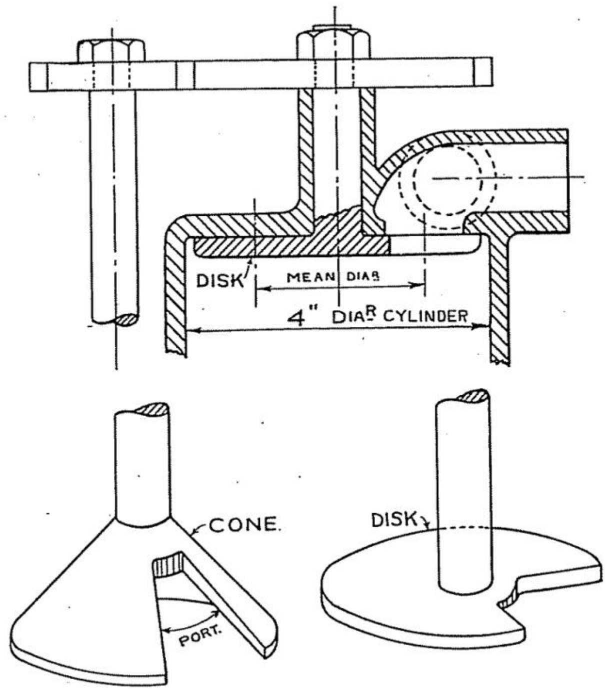
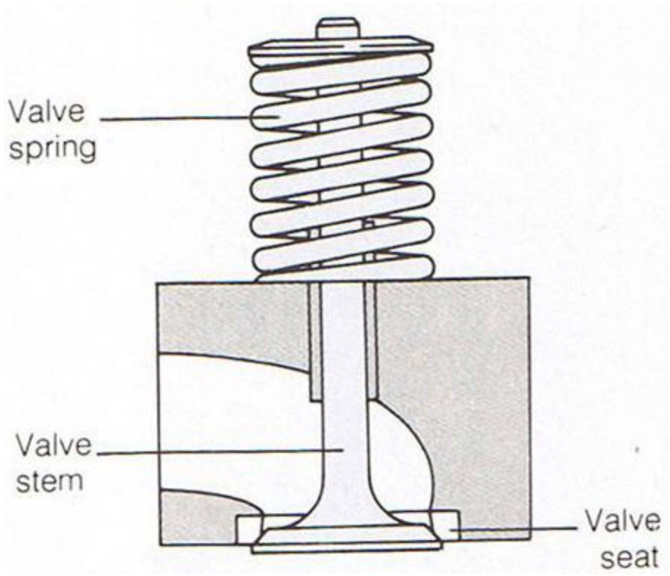
Valve Types



Rotary Valve



Poppet Valve

Leakage Losses

- Flow through a rotary valve is a combination of Couette, Poiseuille and Taylor flow
- Pressure loss:

$$\Delta P = \frac{1}{2}\rho U^2 \left(\frac{fl}{2s}\right),\ s\text{: gap/clearance}$$

$$f = \frac{48}{Re} \text{ for laminar flow}$$

$$f = \frac{0.26}{Re^{0.24}}\left[1 + \left(\frac{7}{8}\right)^2 \left(\frac{\omega R}{U}\right)^2\right]^{0.38} \text{ for turbulent flow}$$

Yamada, *Bulletin of the Japanese Society Mechanical Engineers* 5(18), 1962

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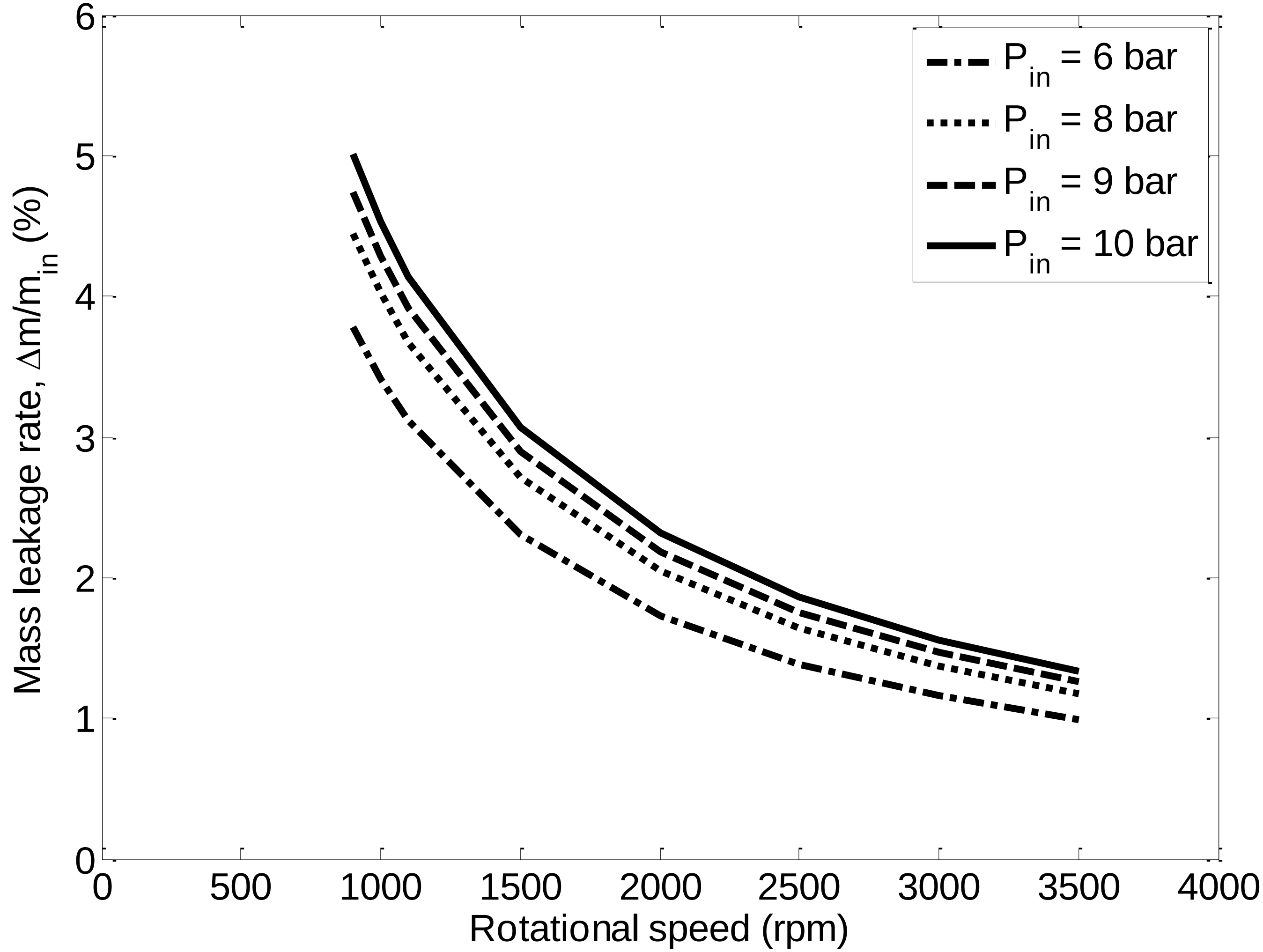
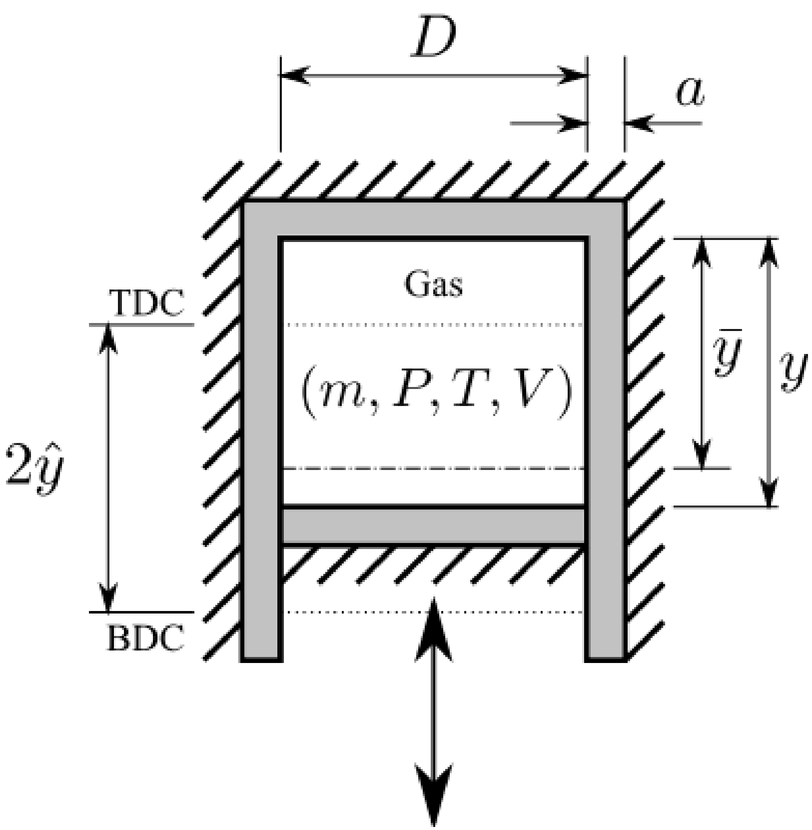
Leakage Losses



Thermal Losses



- Piston inside a cylinder enclosing a fixed mass of gas/vapour
- Oscillation in cylinder position:
  1. Fixed displacement/swept volume, OR
  2. Fixed applied force (pressure) variation
- As piston moves upwards: Pressure and temperature of the enclosed gas increase
- Temperature changes can drive heat transfer
- Heat transfer across finite temperature difference → exergy loss

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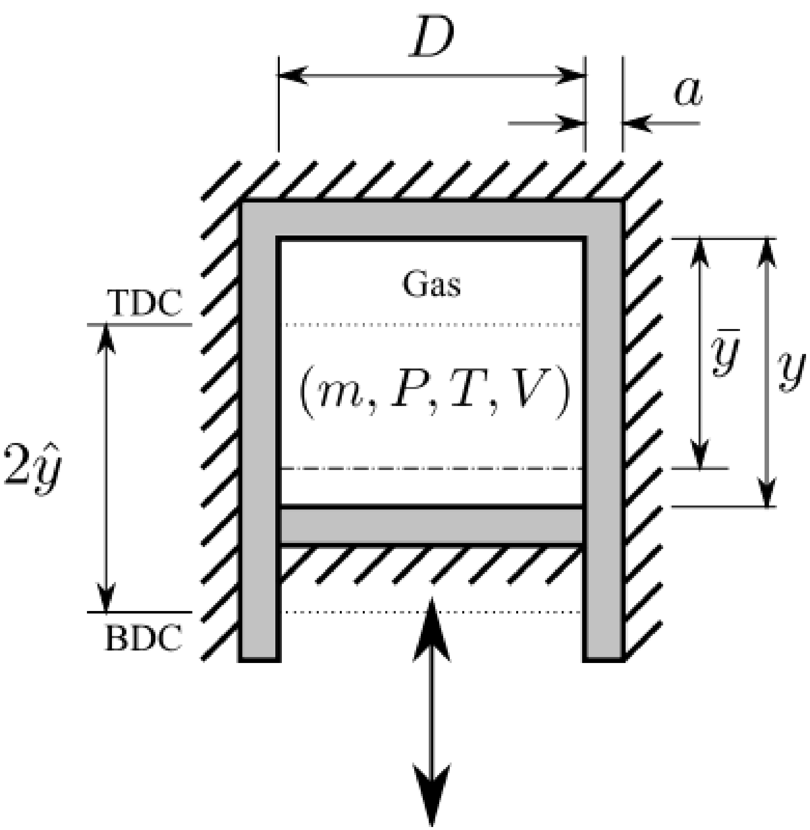
Thermal Losses



- Previous models (Lee, Lékic) assume an isothermal inside wall boundary condition
- Consider a layer of insulation of thickness a on the inside cylinder wall
- Surrounding metallic cylinder effectively isothermal
- Use 1D thermal conduction model for the insulation

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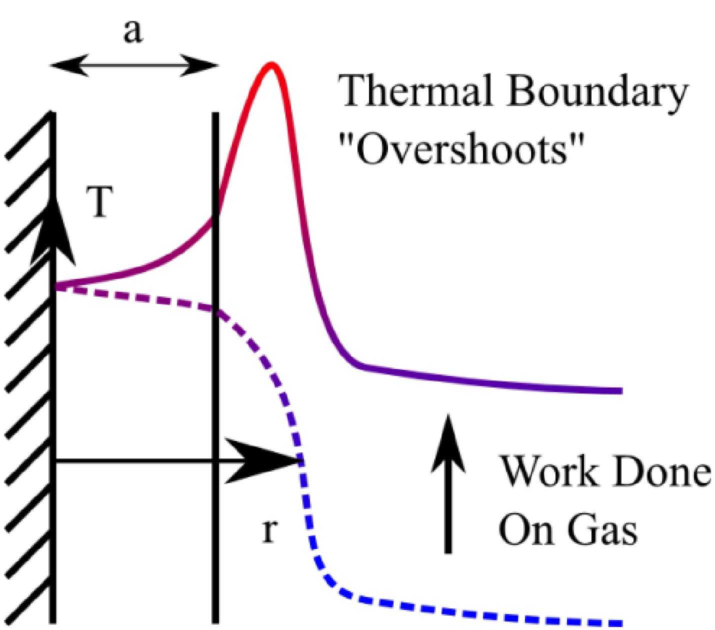
Thermal Losses



- Work done on gas generates an inversion of the temperature profile at the wall
- Heat can be transferred into the fluid, despite the bulk fluid temperature being higher than the wall
- “Traditional” heat transfer coefficient inadequate
- Use a complex Nusselt number (Lee, Kornhauser and Smith, Lekic, and Kok)

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Thermal Losses

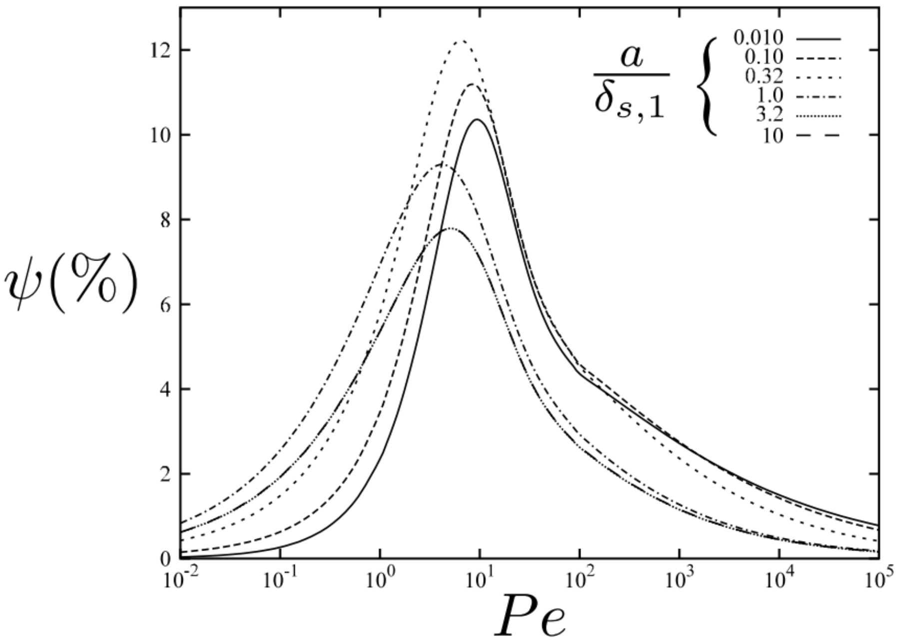

Figure: Loss Factor, current model, $\kappa_r = 1$, $\rho_r = 1$, $c_r = 1$, $y_a = 0.5$.

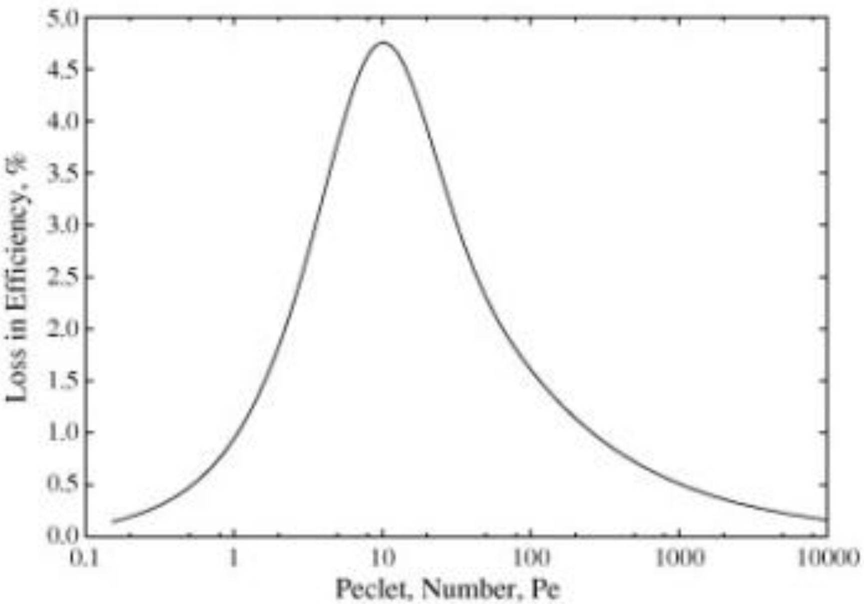

Figure: Loss Factor, K.P. Lee, isothermal cylinder, $P_r = 2$.

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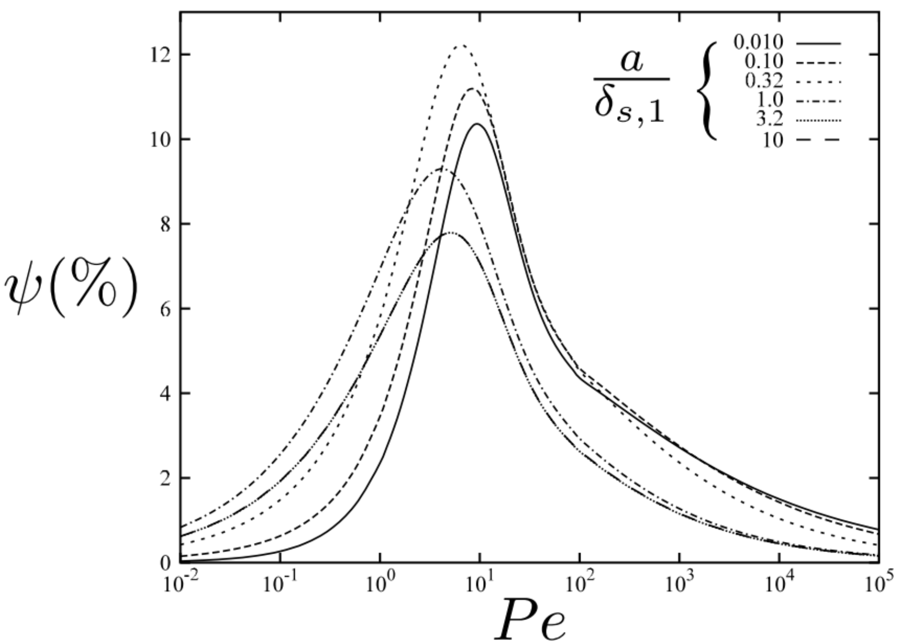
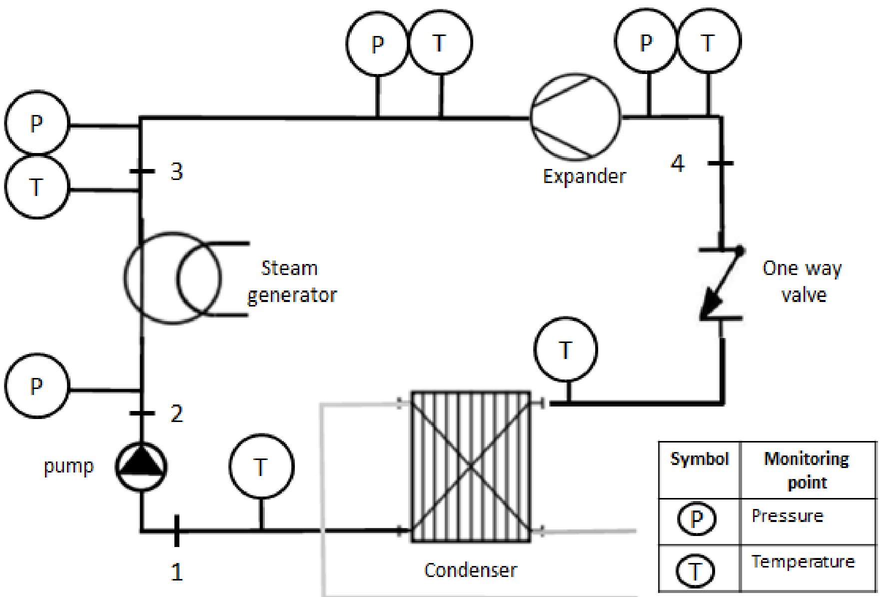
Thermal Losses



- Low Péclet numbers insulation moves the system towards the isothermal ideal
- At high Péclet numbers insulation moves the system away from the adiabatic ideal
- Loss can be up to 20% greater than isothermal gas spring

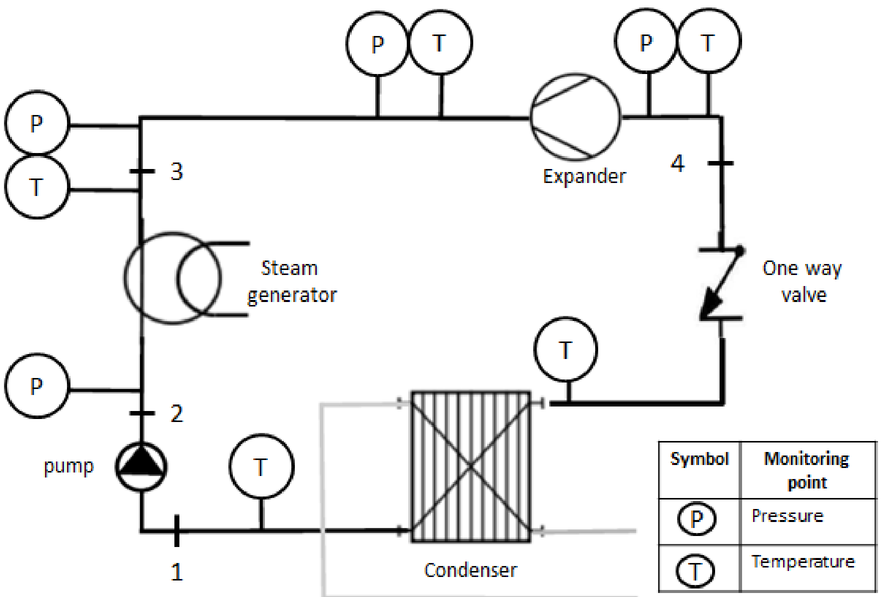
Experimental Setup



Design parameters:

- Assuming solar collector as heat source
- Electric boiler as heater and evaporator
- R245fa working fluid
- Process air heater as superheater
- $T_{3,\max} = 150\ °C$
- $p_{3,\max} = 10$ bar

Experimental Setup



Design parameters:

- $T_4 = 17\ °\mathrm{C}$
- $P_4 = P_{\mathrm{sat}}(17\ °\mathrm{C}) \cong 1\ \mathrm{bar}$
- $P_{\mathrm{out,max}} = 3\ \mathrm{kW}$
- $\dot{m} = 0.07\ \mathrm{kg/s}$
- Cooling medium: water at ambient conditions

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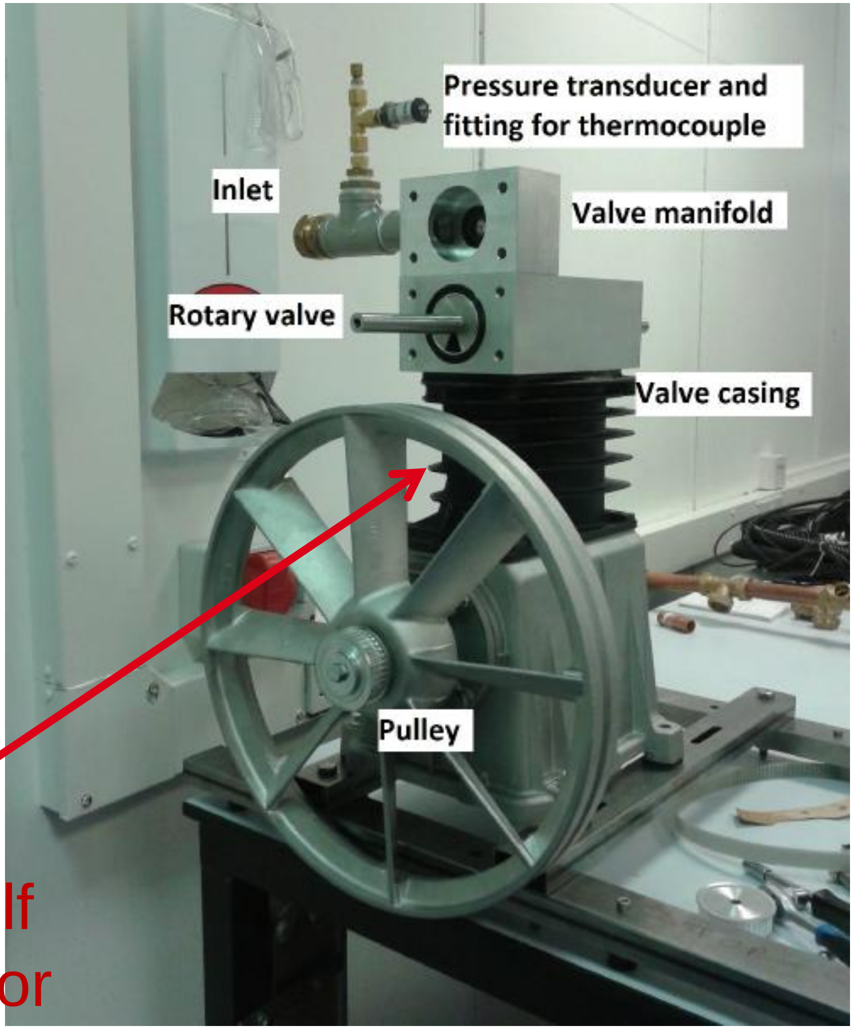
Expander



Reversed Off-the-Shelf
Two-Stage Compressor

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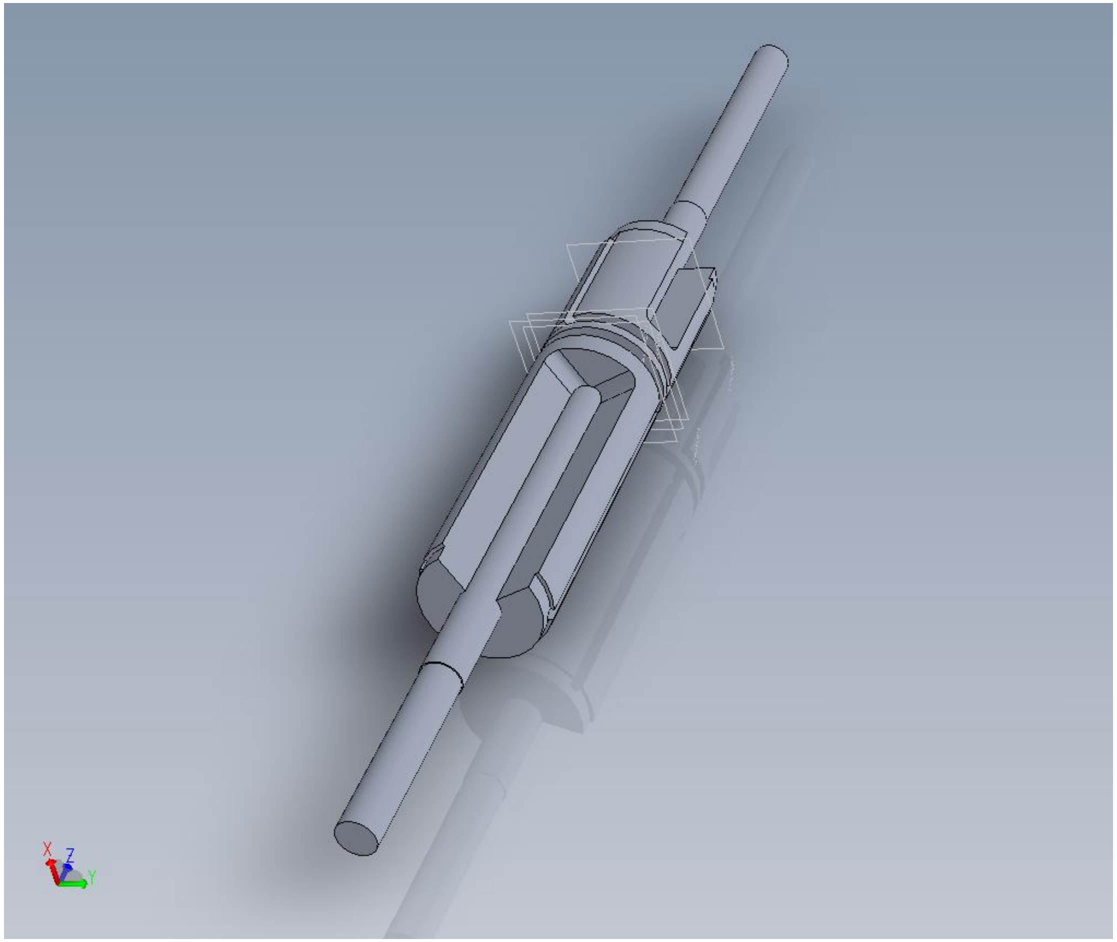
Rotary Valve Design



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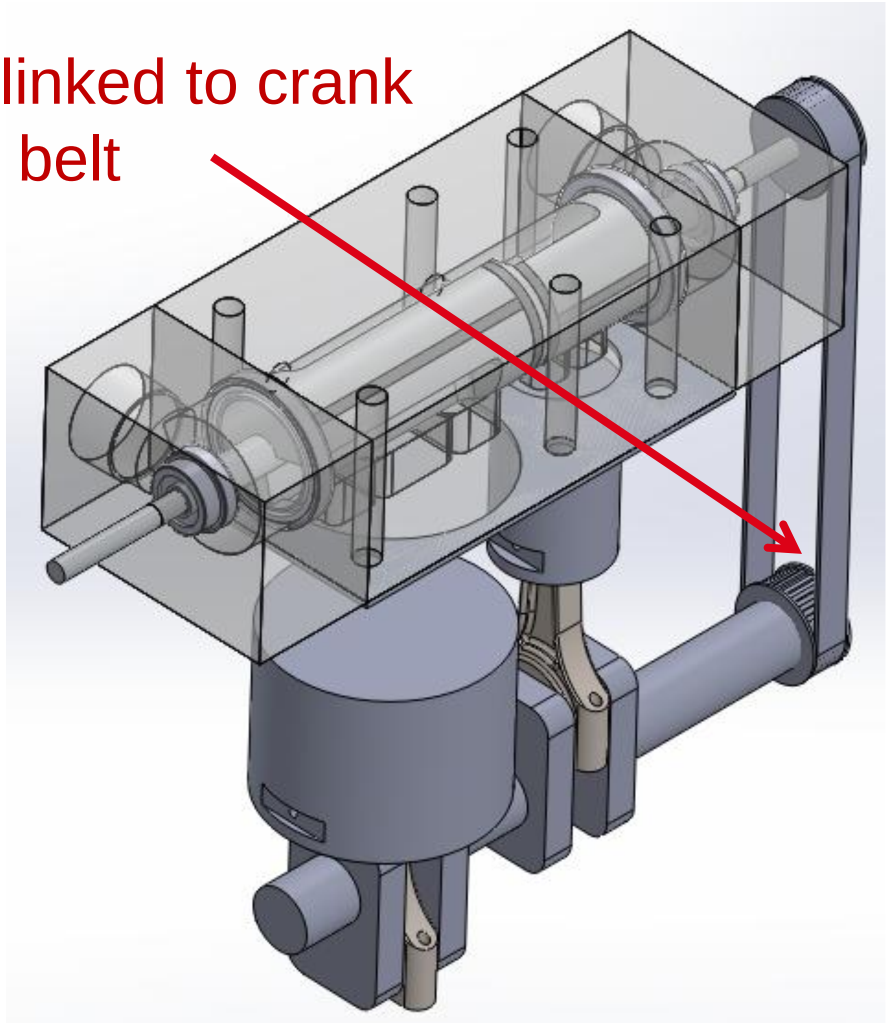
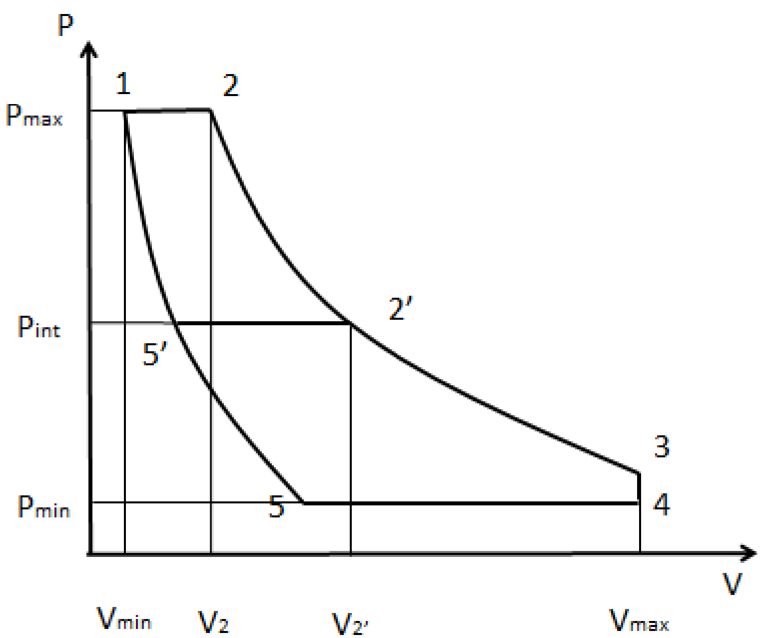
Rotary Valve Design

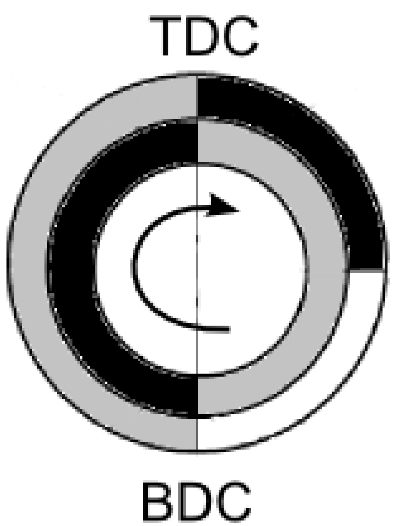
Rotary valve linked to crank shaft through belt



Rotary Valve Timing

- Cylindrical rotary valve
- Angles/position of groves determine valve timing

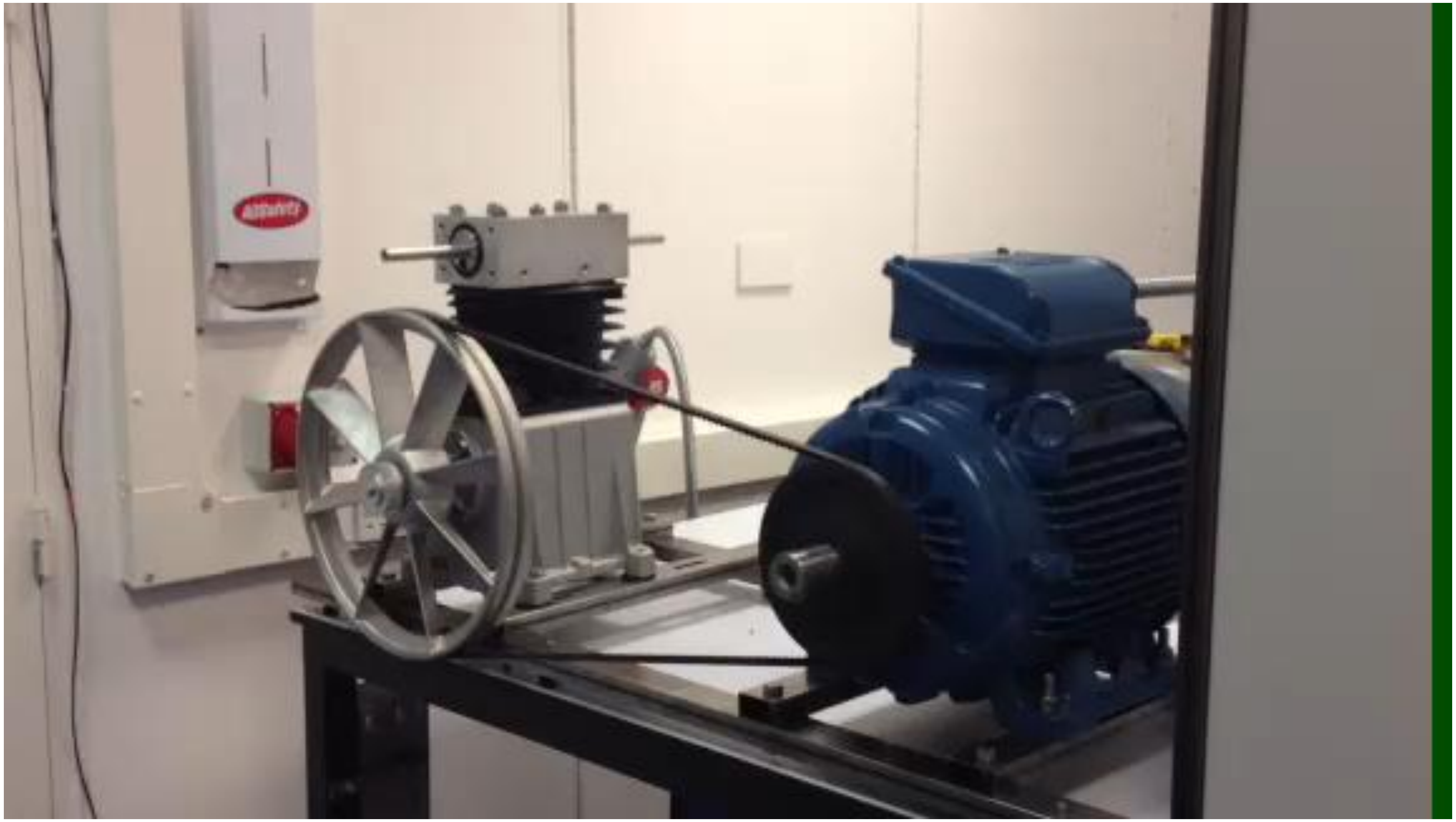




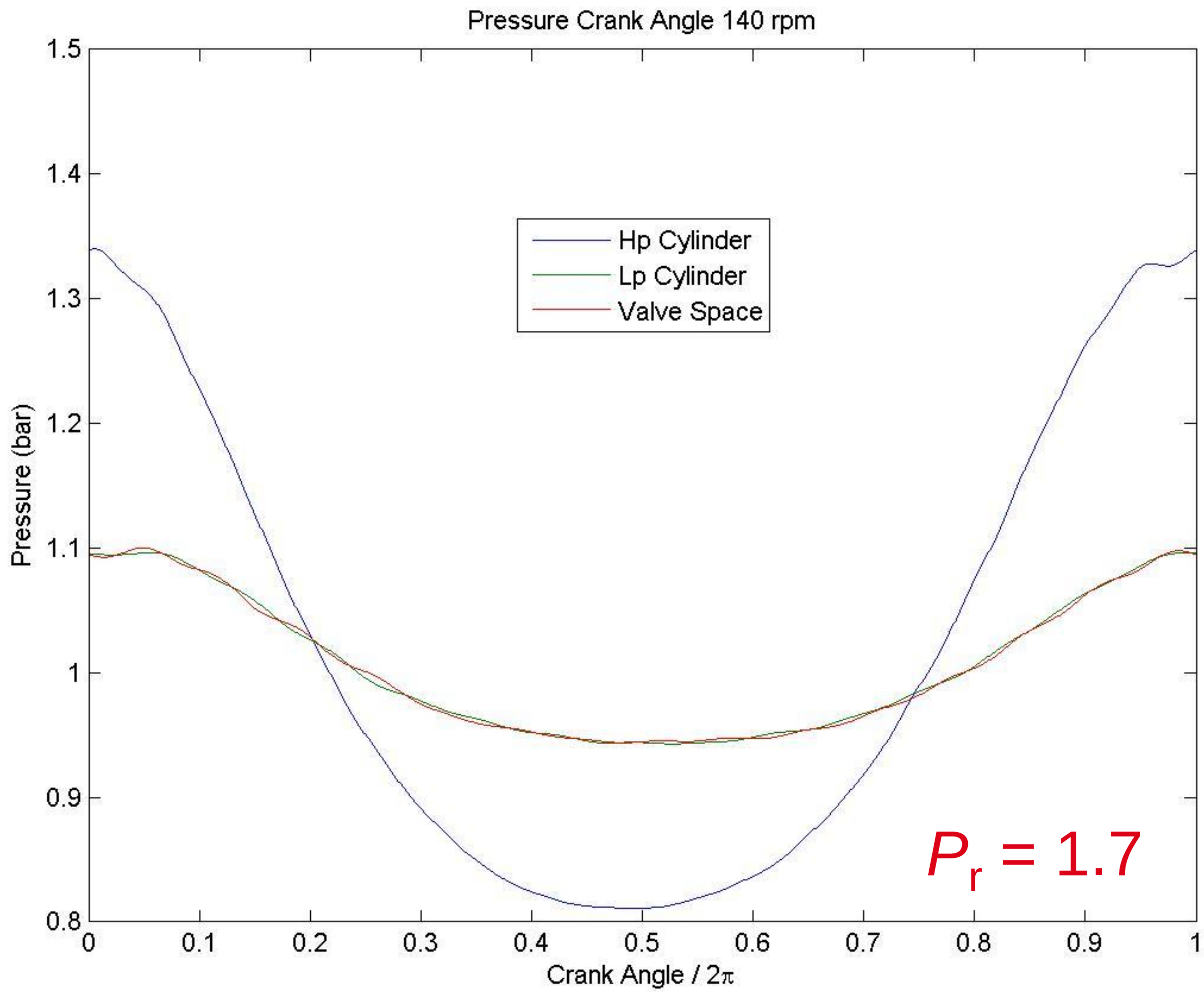
Outer Circle : HP Piston
Inner Circle: LP Piston

Black: inlet valve open
Gray: exhaust valve open
White: both valves closed

Operation



Results (Pressure)



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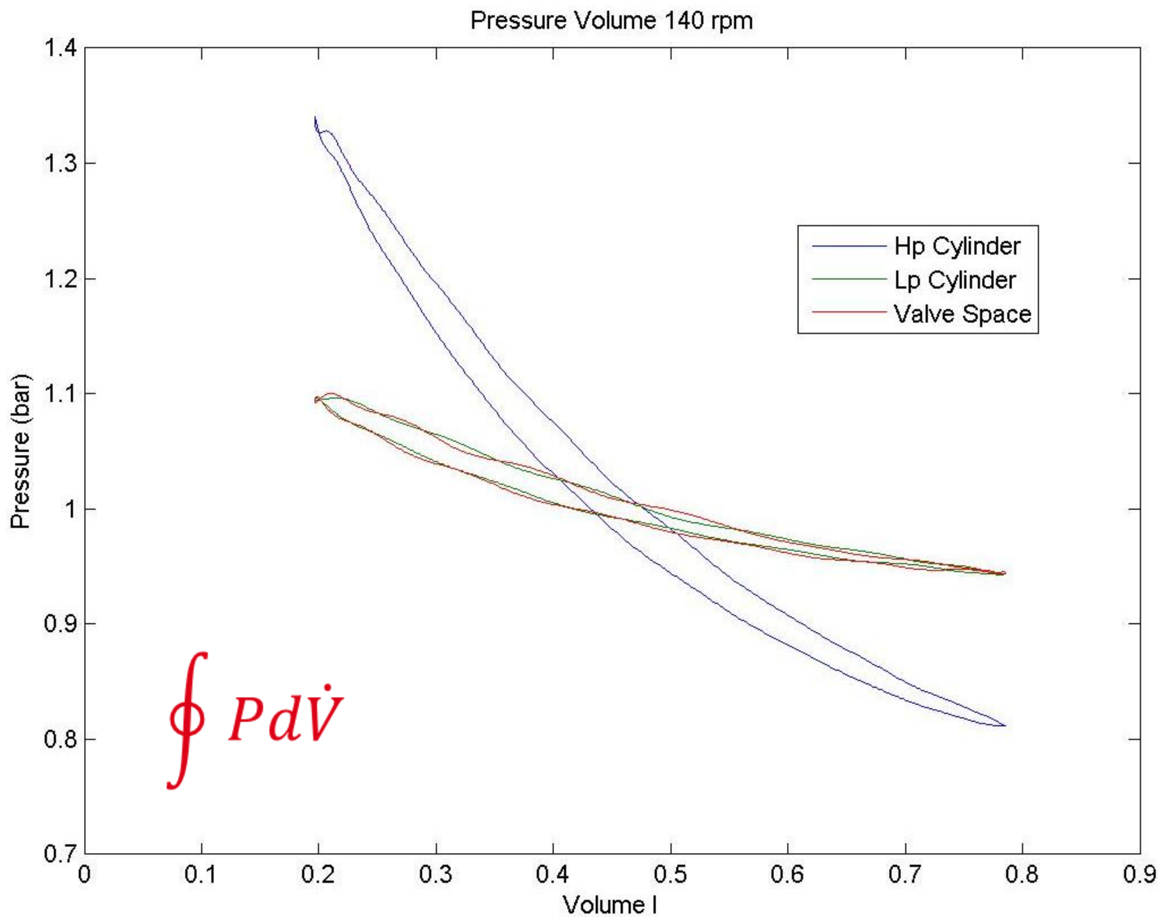
Results (P-V Indicator Diagrams)



HP cylinder loss = 5.9 J / 14 W (1.4%)

LP cylinder loss = 10.3 J / 24 W (2.4%)

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Conclusions

- We are investigating the use of small-scale reciprocating piston expanders with rotary valves
- At the moment we are testing them in “gas spring” mode with R245fa at low pressure ratios
- We have measured ~4% in thermodynamic losses at low-speeds (140 rpm), due to heat transfer and other irreversibilities (e.g. leakage)
- Next steps:
  - Increase the pressure ratio and speed
  - Connect the valves
  - Estimate leakage vs. oil (selected fluids)
  - Test surface materials

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