AKADEMIA GÓRNICZO-HUTNICZA
IM. STANISŁAWA STASZICA W KRAKOWIE
AGH UNIVERSITY OF SCIENCE
AND TECHNOLOGY

Effects of Very Low Piston Speed Regimes on Near-Isothermal Behaviour of Piston Expanders for Micro-CAES Systems

Dominik Gryboś, Jan Markowski, and Jacek Leszczyński

Department of Thermal and Fluid Flow Machines, Faculty of Energy and Fuels, AGH University of Science and Technology,
Al. Mickiewicza 30, 30-059 Krakow, Poland

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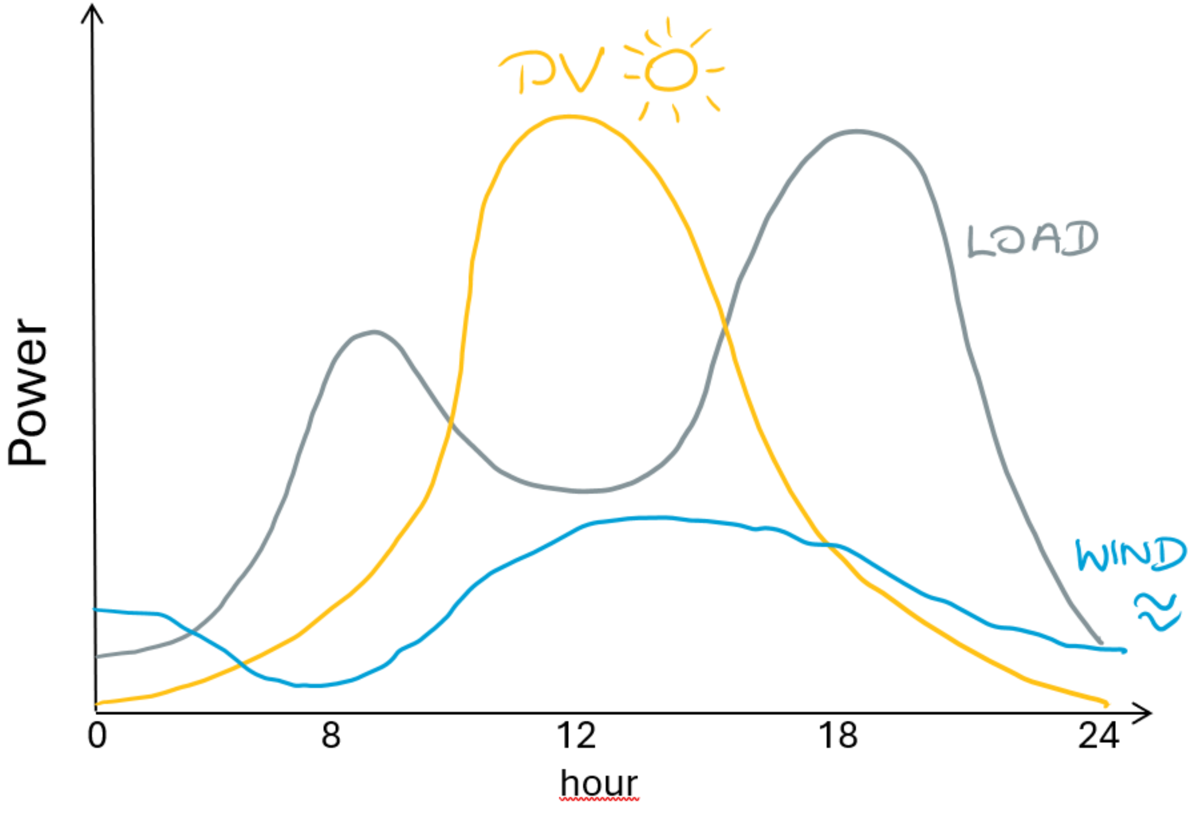
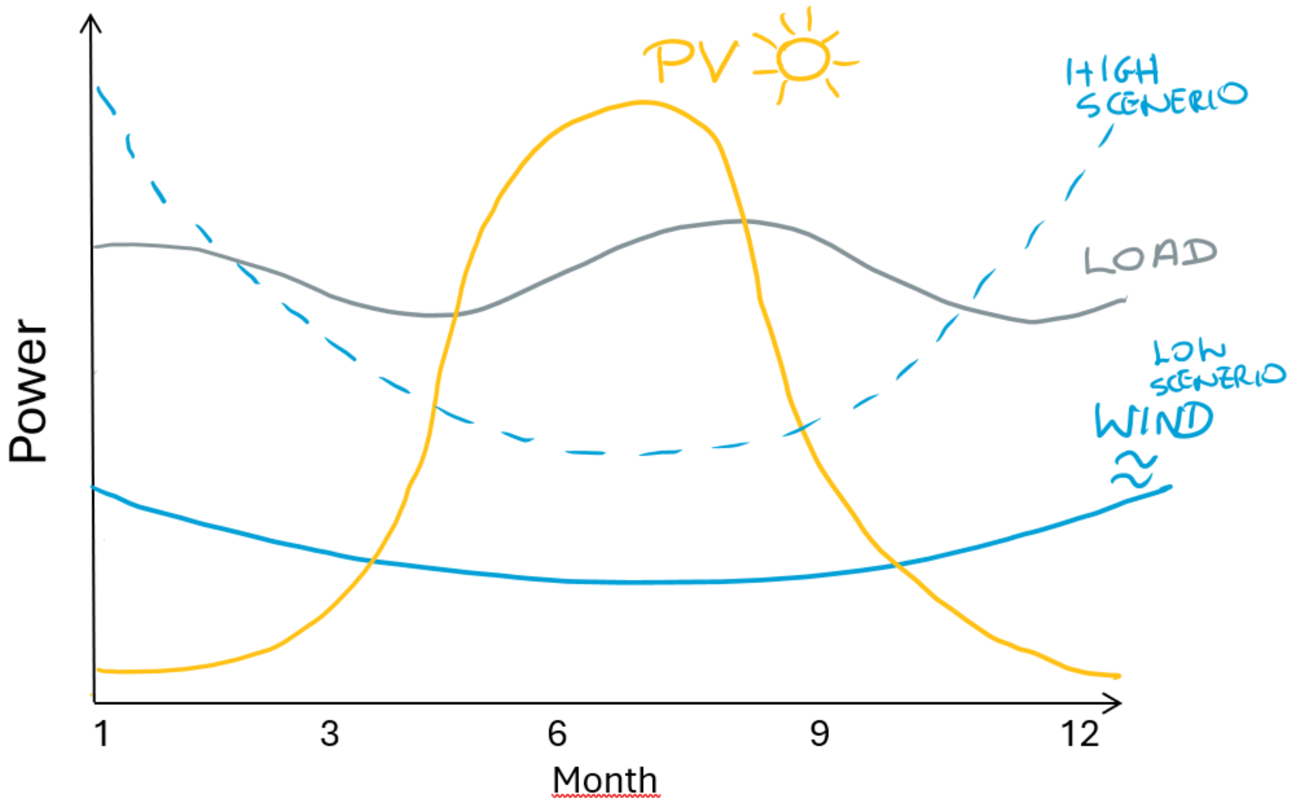
Motivation

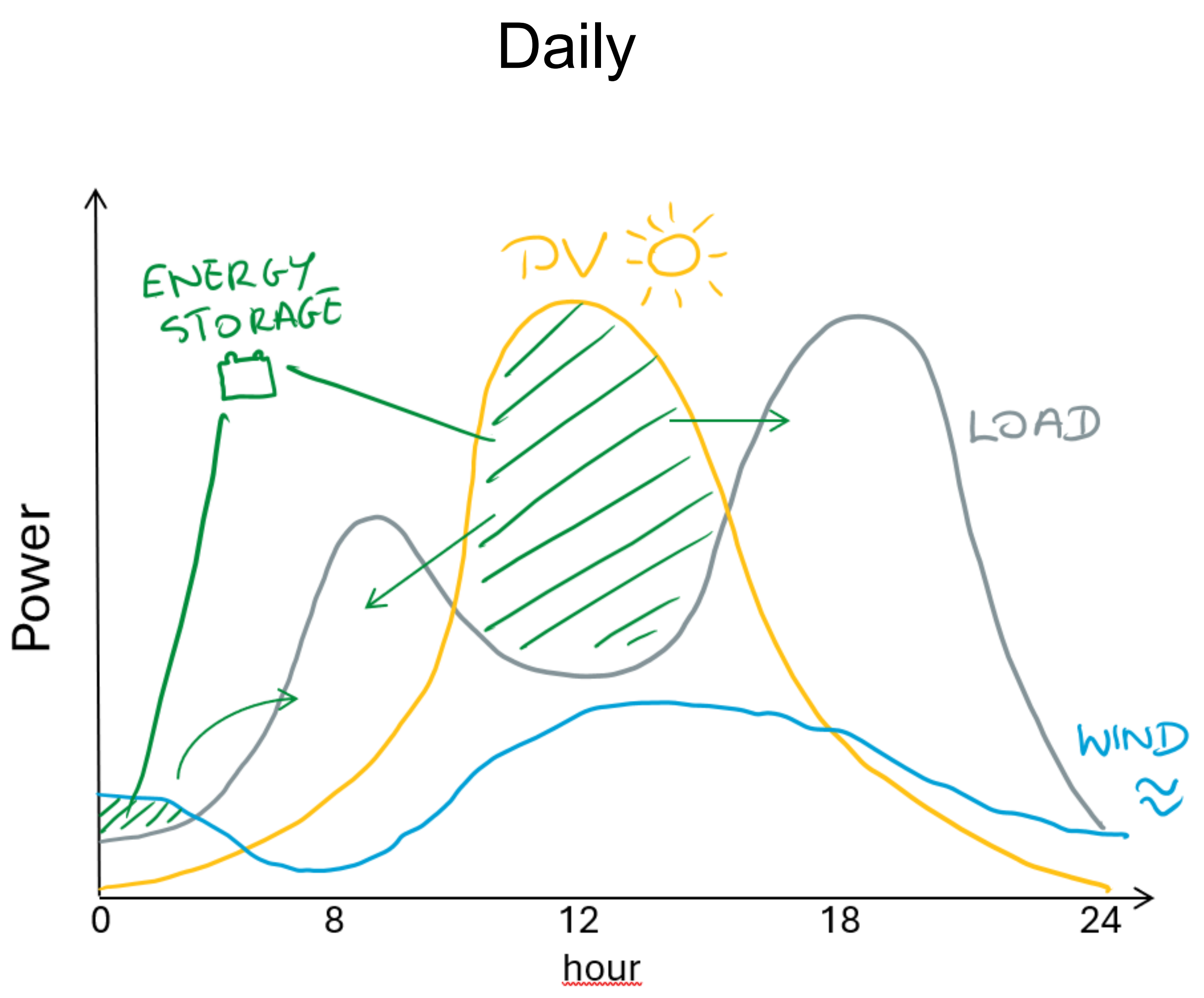
Daily

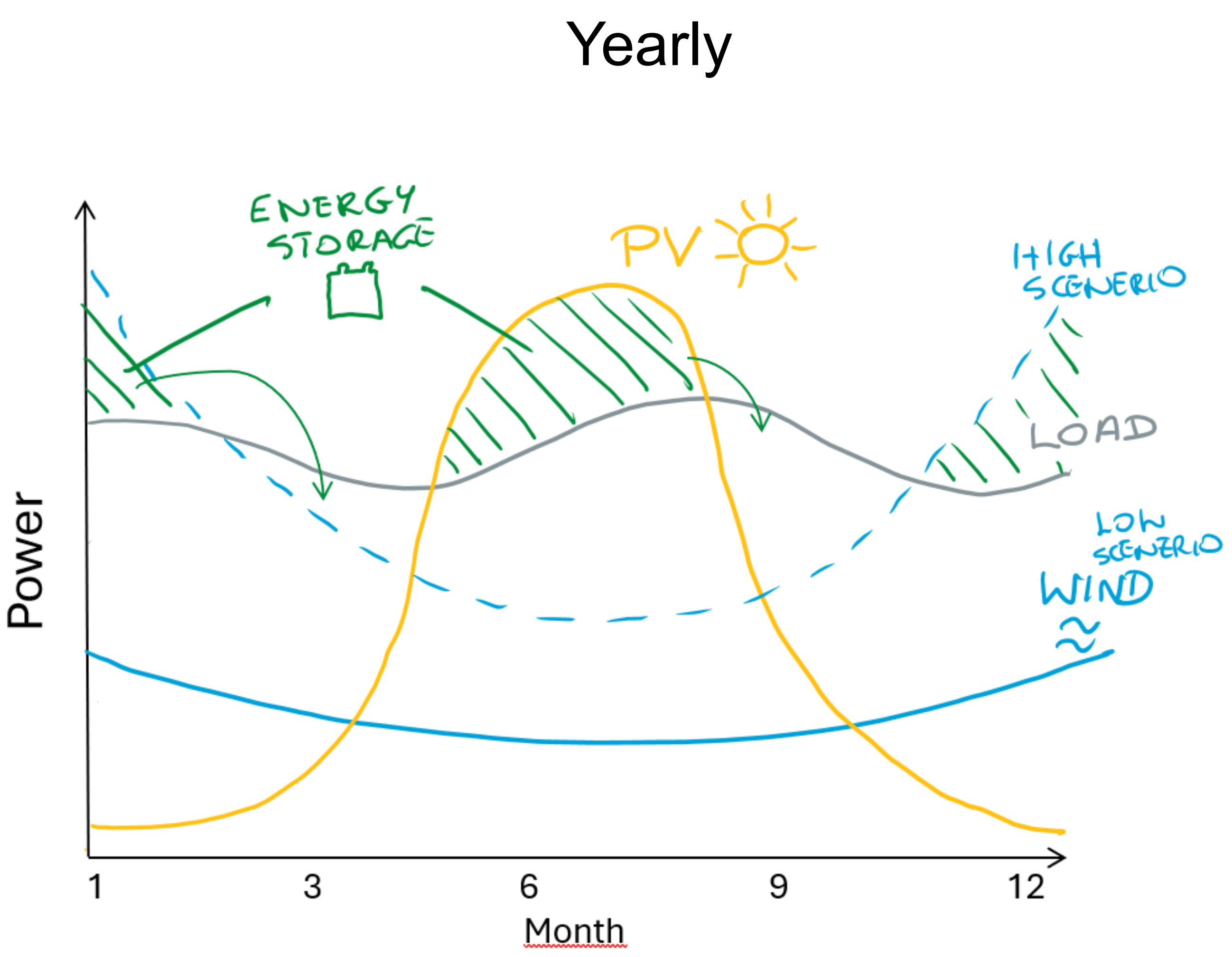


Yearly

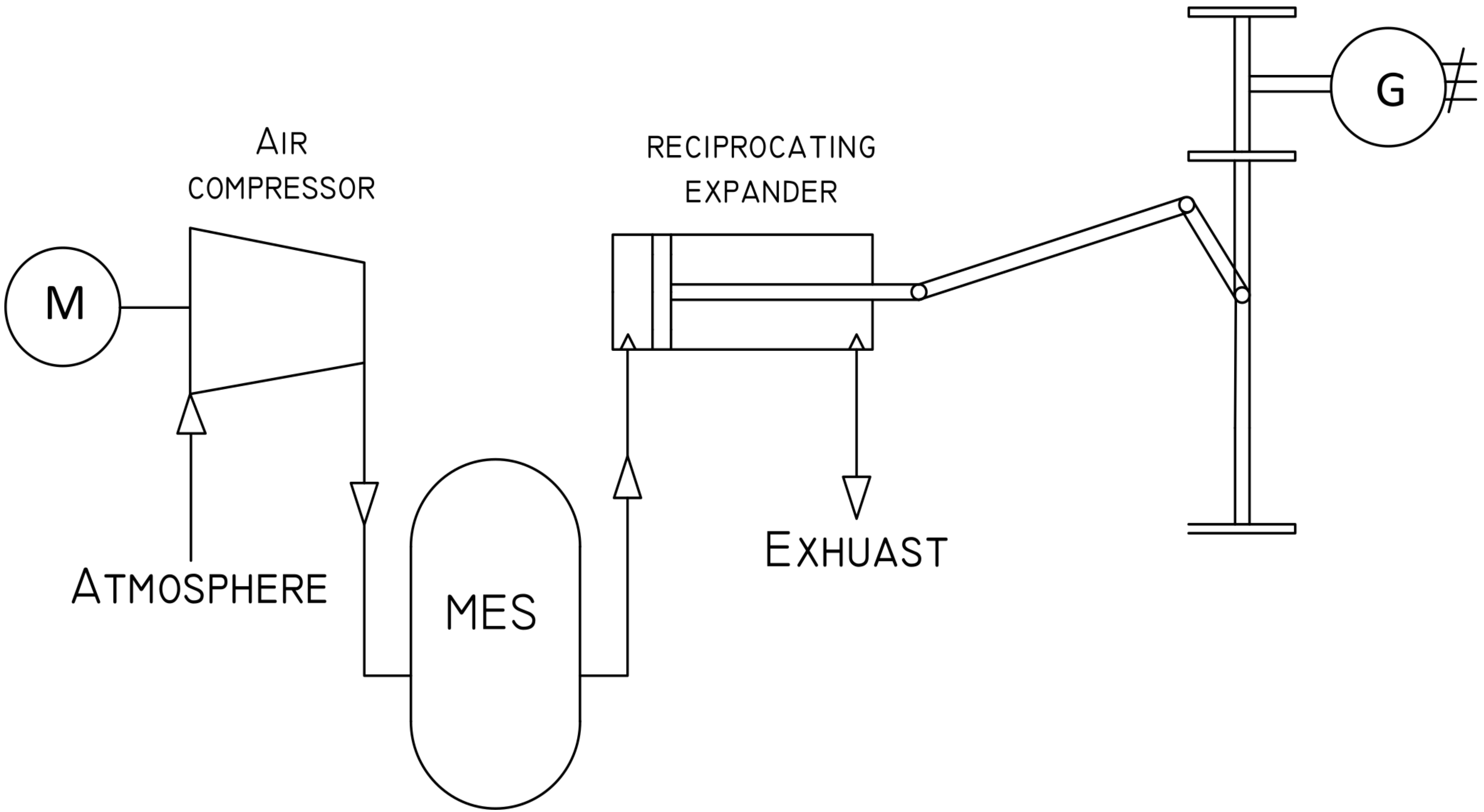


Motivation


Daily
ENERGY STORAGE
PV
LOAD
WIND
Power
0
8
12
18
24
hour

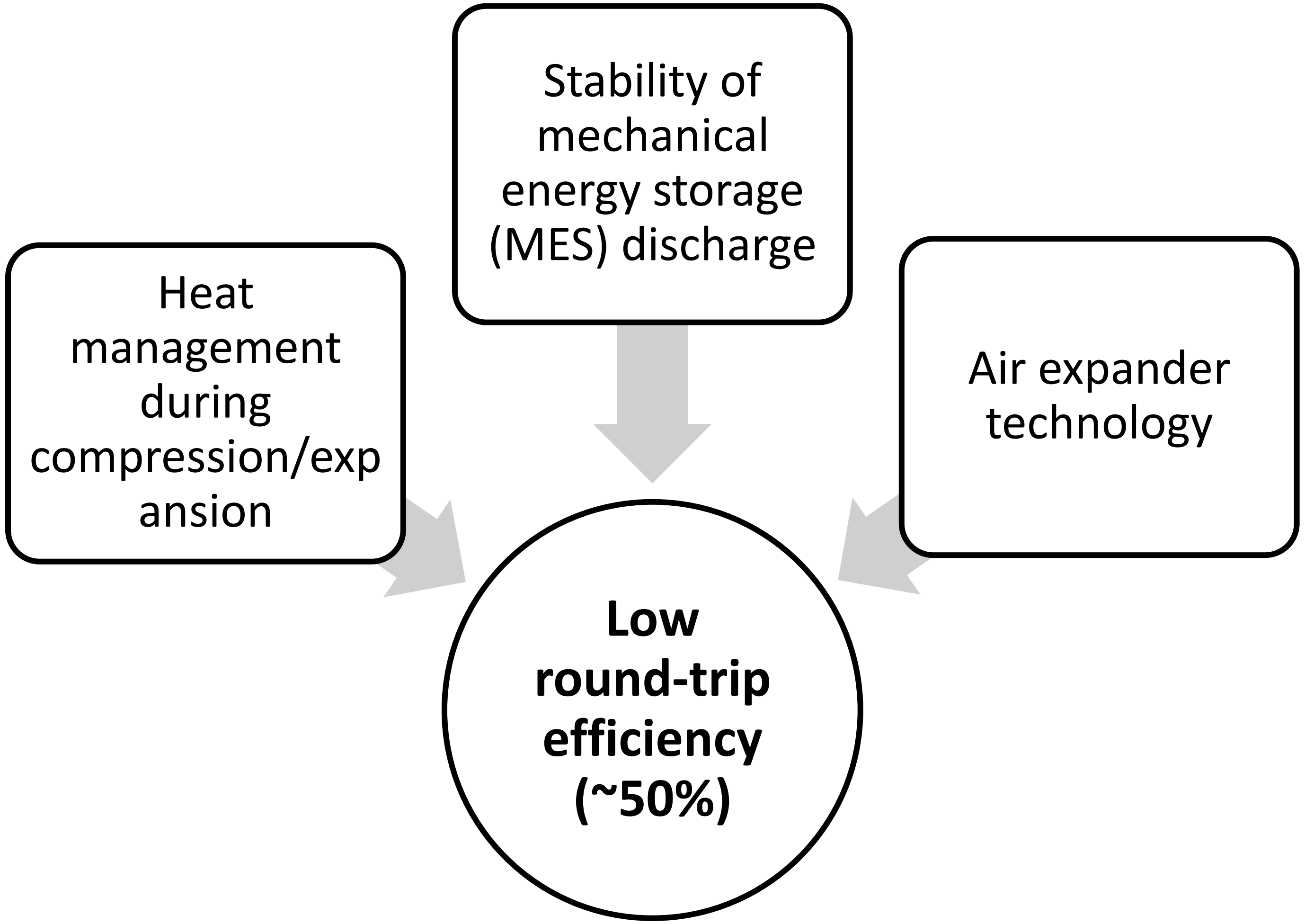

Yearly
ENERGY STORAGE
PV
HIGH SCENERIO
LOAD
LOW SCENERIO
WIND
Power
1
3
6
9
12
Month

Micro-CAES



M
Air
compressor
Atmosphere
MES
Reciprocating
expander
Exhuast
G

Key barriers of CAES technology



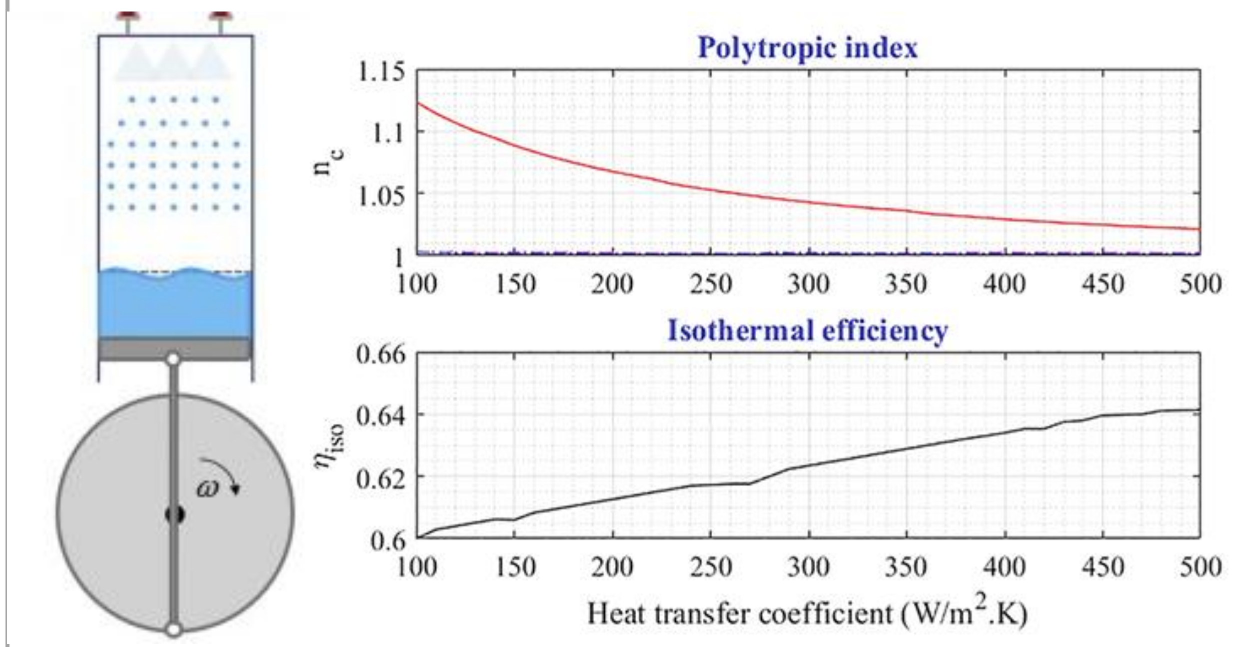
Objective: Investigate the influence of piston speed on the polytropic exponent.

Hypothesis: Lower speeds increase heat transfer, shifting the process towards near-isothermal behavior.

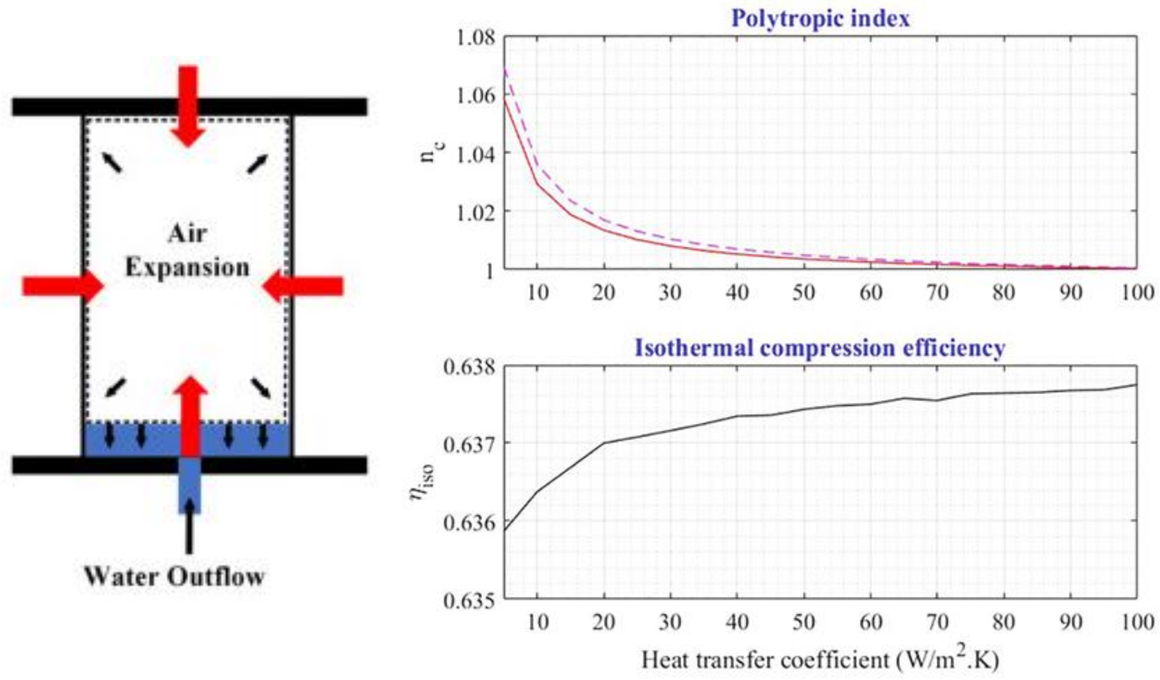
*Maia, T. A. C., Barros, J. E. M., et al., Appl Energy 182 (2016) 358–364.
*He, W. and Wang, J., Renewable and Sustainable Energy Reviews 87 (2018) 77–95.

Existing approaches to improve heat transfer

Dib & Haberschill (2021) studied heat supply methods in expanders for energy storage.



Solid piston with liquid injection



Liquid piston

G. Dib and P. Haberschill, “Thermodynamic investigation of quasi-isothermal air compression/expansion for energy storage,” Energy Conversion and Management, vol. 235, 114027, May 2021.

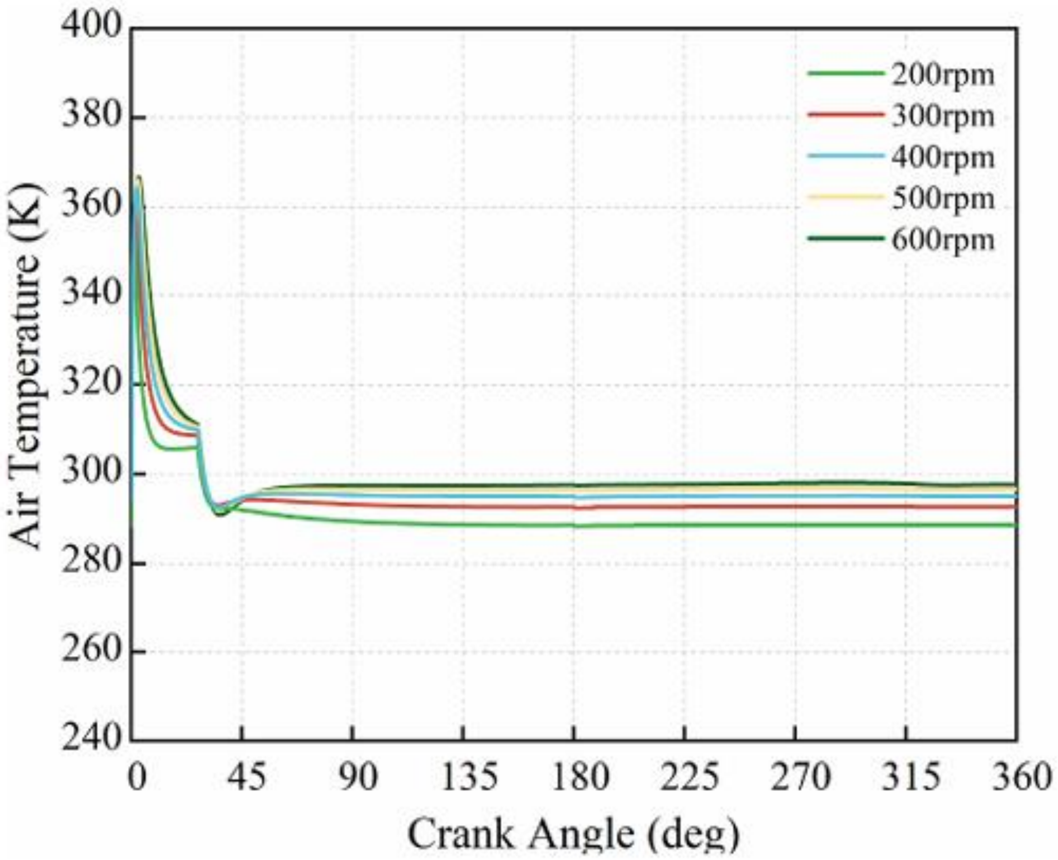
C. Qin and E. Loth, “Liquid piston compression efficiency with droplet heat transfer,” Applied Energy, vol. 114, pp. 539–550, Feb. 2014.

Rotational speed vs isothermality

Gao et al. (2023) investigated the effect of low speeds in a solid piston system with water injection.

Isothermality vs. rotation speed.

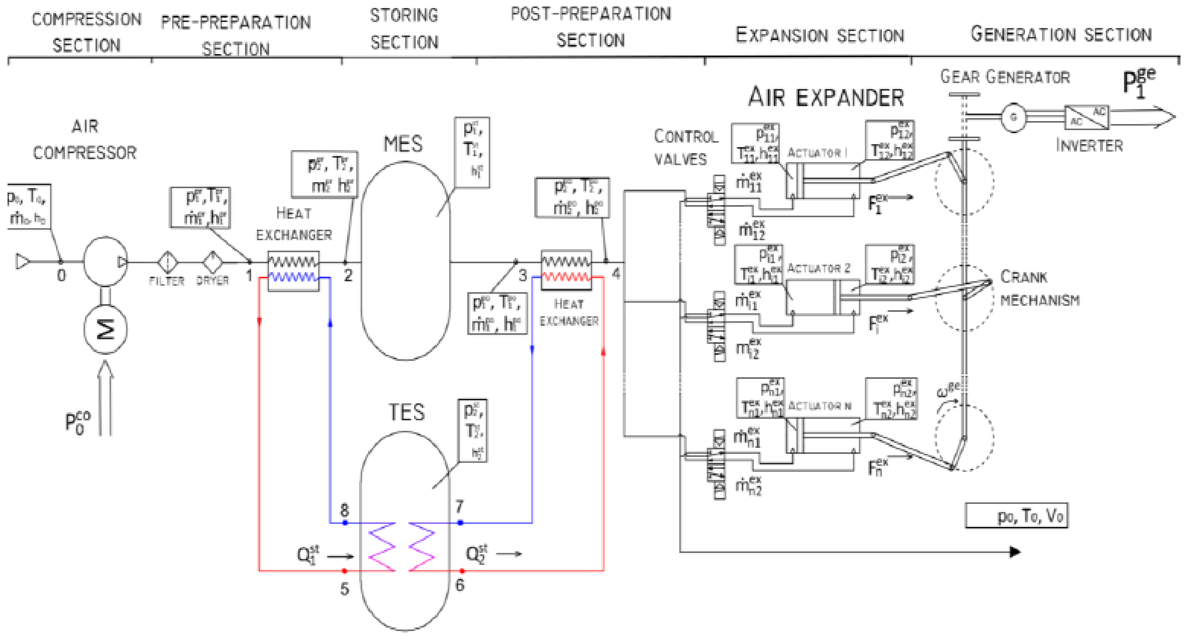
Rotation speed (rpm)	Isothermality
200	75.51 %
300	75.16 %
400	73.19 %
500	69.83 %
600	64.95 %



Gao, Z., Zhang, X., et al. (2023). “Thermodynamic analysis of isothermal compressed air energy storage system with droplets injection.” Energy, 284, 129304.

Experimental setup

Double acting piston expander



Parameter	Value	Unit
Supply pressure p^s	5	bar
Piston diameter	50	mm
Piston stroke	500	mm
Cylinder connections size	1/2	inch
Crank length	250	mm
Cut off ratio	0.2	-
Rotational speed	20, 30, 40, 50, 60	rpm

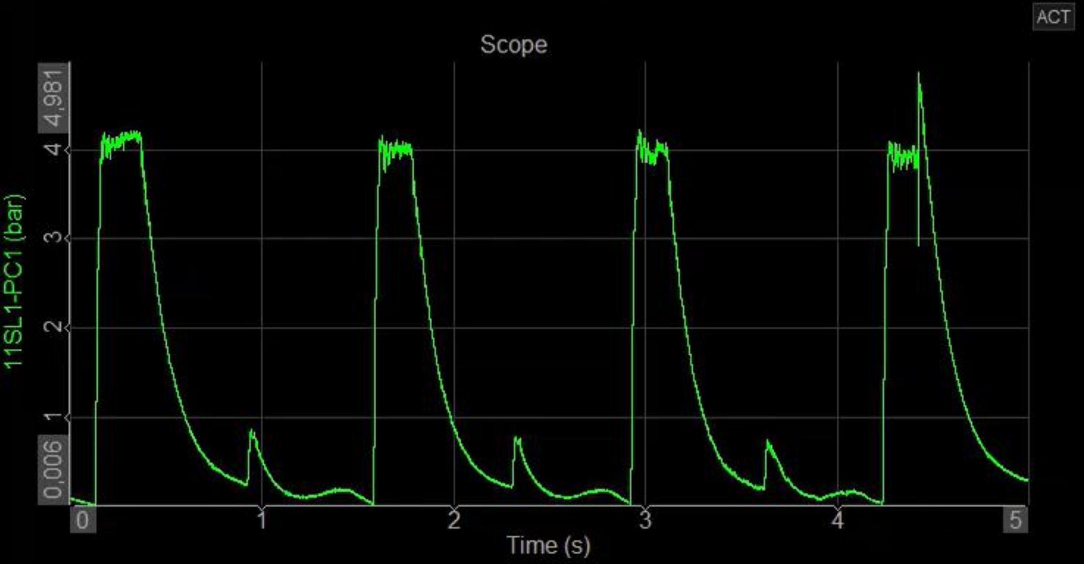
Measurement accuracy:
Pressure: ±0.25% FS (0–10 bar)
Temperature: ±1 K
Linear position: ±25 µm
Angular position: 0.04°

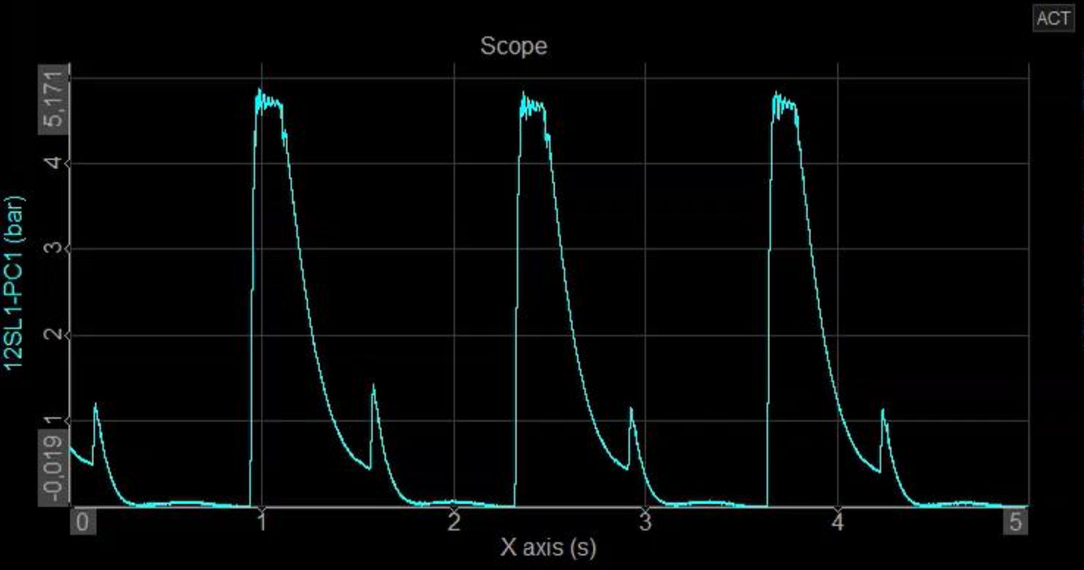
12SL-PT1 (°C) ACT

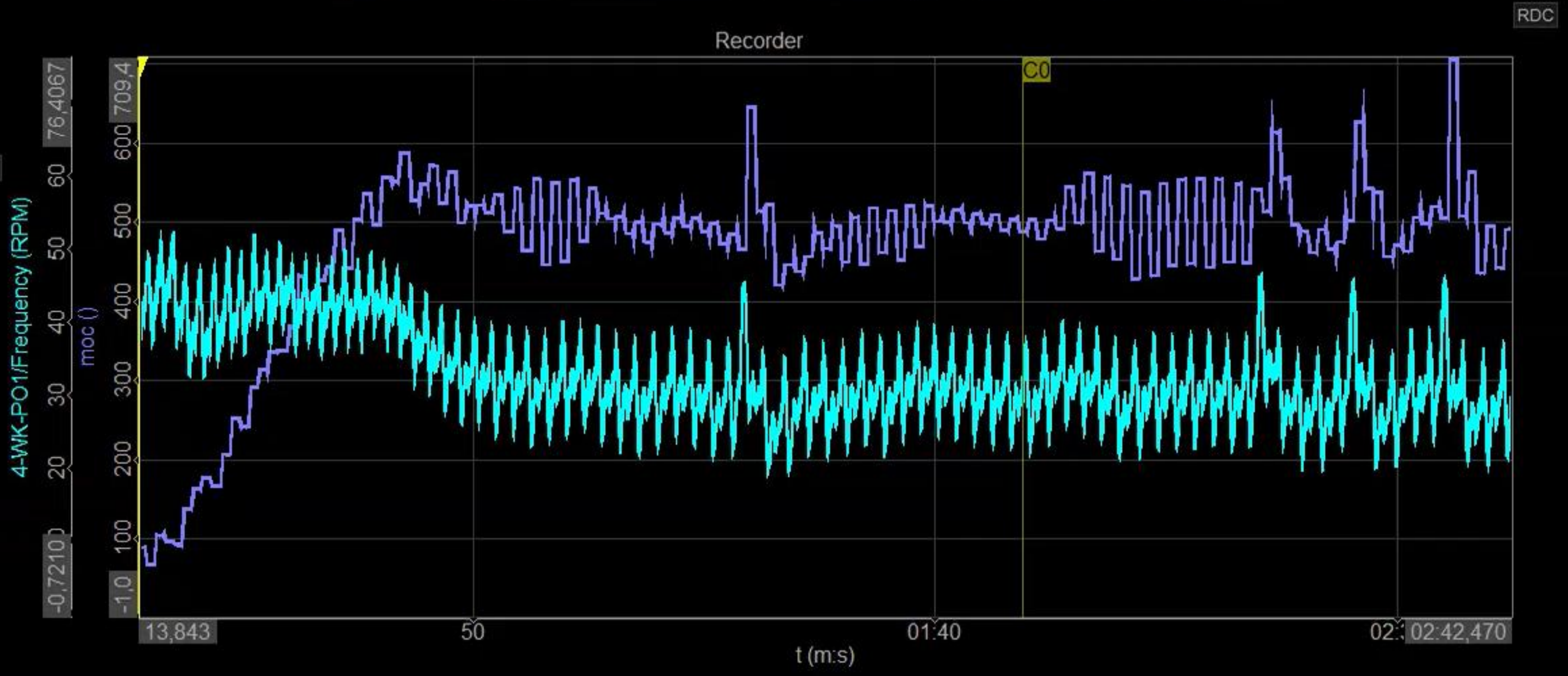
28.40

0-ZB1-PC1-1 (bar) ACT

5.023

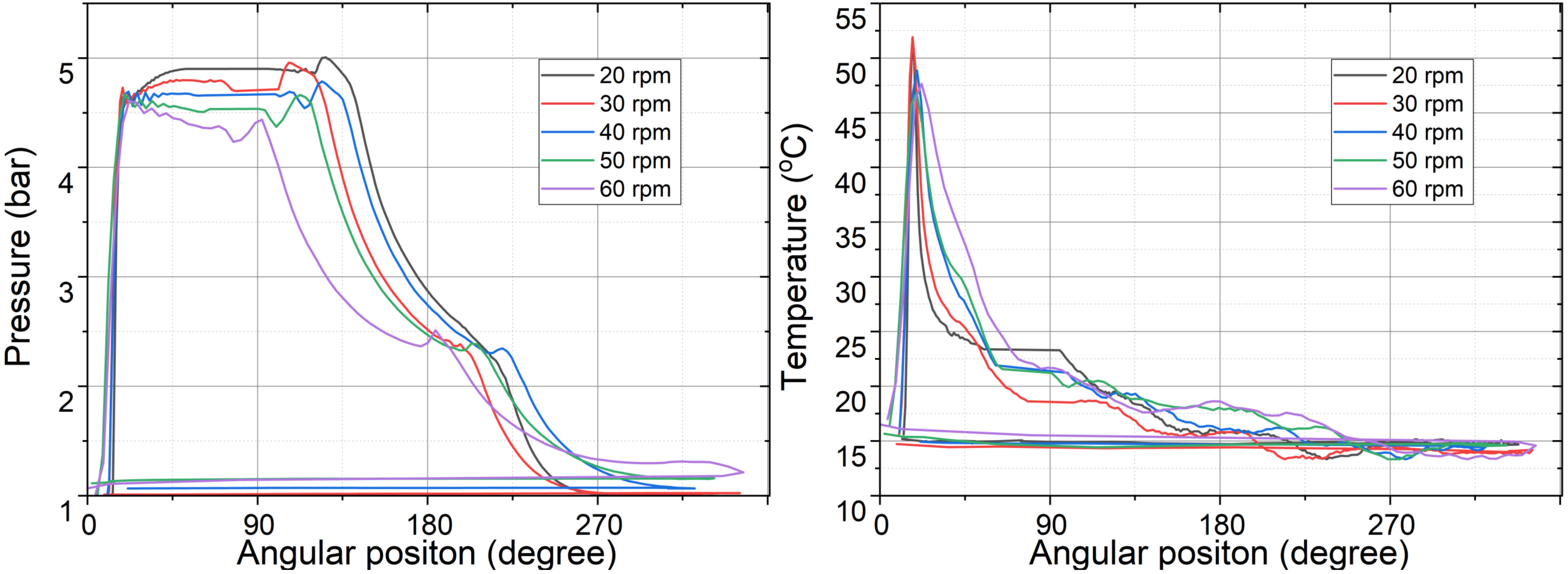




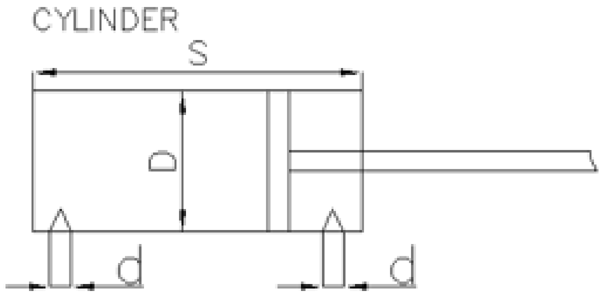


Results

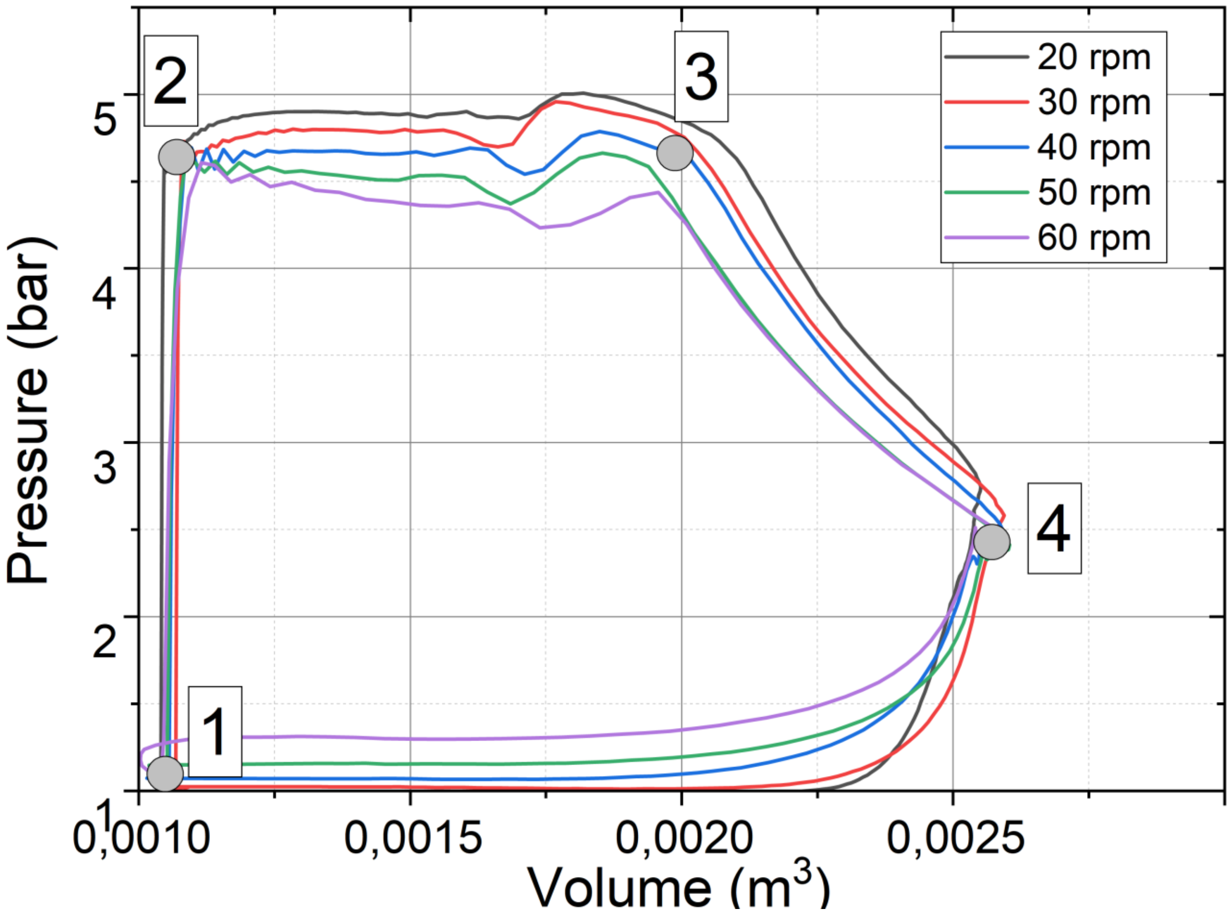
Pressure and temperature over crank angle at different piston speeds

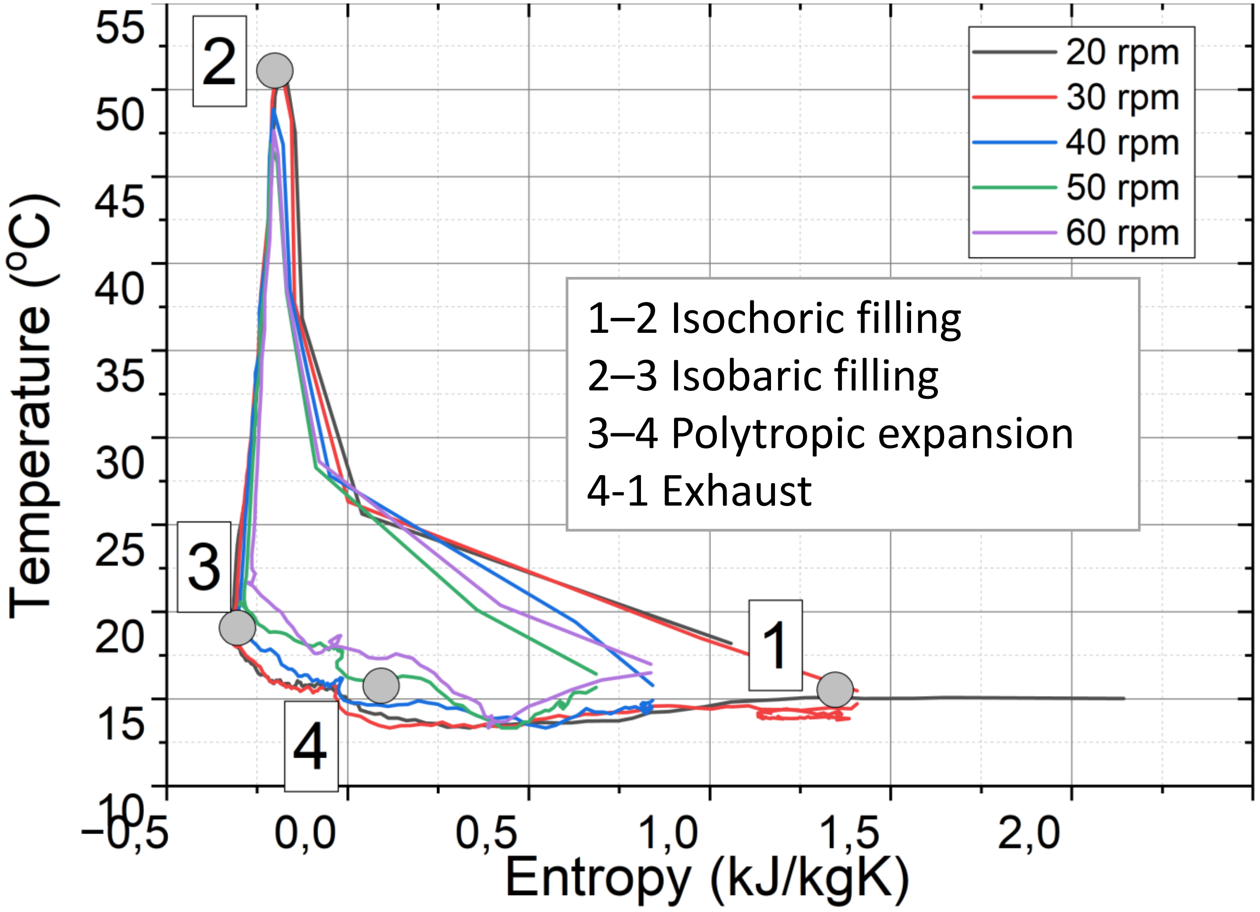


Results



Thermodynamic cycle (p-V and T-s) approaching near - isothermal conditions





Results

Polytropic exponent:

$$n = \frac{\ln\left(\frac{p_3}{p_4}\right)}{\ln\left(\frac{p_3}{p_4}\right) - \ln\left(\frac{T_3}{T_4}\right)}$$

p_1, p_2 – initial and final pressure of the expansion process
T_1, T_2 – initial and final temperature of the expansion process

Isothermality:

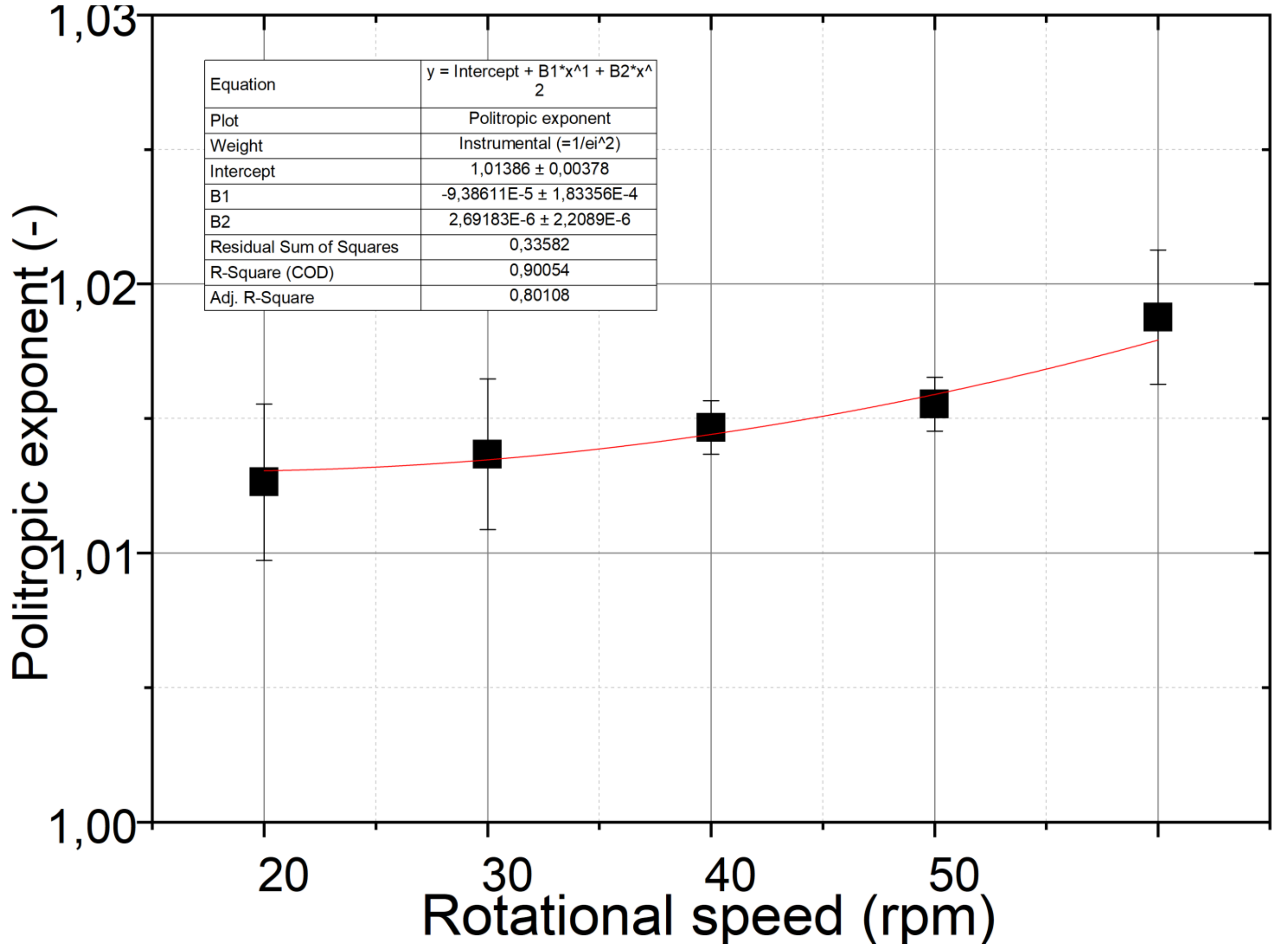
$$\phi = \frac{n-\kappa}{\kappa-1}$$

κ − isentropic exponent − for air $\kappa = 1.4$

Results

Effect of rotational speed on the polytropic exponent and isothermal efficiency

Rotational speed (rpm)	Polytropic exponent (-)	Isothermality (-)
20	1.0126	0.968
30	1.0137	0.966
40	1.0147	0.963
50	1.0155	0.961
60	1.0188	0.953



CONCLUDING REMARKS

Very low piston speed regimes enable near-isothermal expansion without external heat supply

Heat transfer significantly increases at low speeds, resulting in reduced temperature gradients

The polytropic exponent approaches unity — experimentally confirmed ($n \approx 1.01$–1.02 for 20–60 rpm, 5-6 bar.)

Lower operating speeds correspond to larger machine dimensions, reduced power output, and higher efficiency

The results highlight the need for optimization of machine dimensions under combined criteria: power output, efficiency, and isothermality

Thank you

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