TECHNISCHE UNIVERSITÄT DRESDEN

DRESDEN concept

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M. Sc. Fedor Nazarov
Chair of Fluid-Mechatronic Systems

FLUID-MECHATRONISCHE SYSTEMTECHNIK DRESDEN

Energy Efficiency Analysis & Experimental Test of a Closed-Circuit Pneumatic System

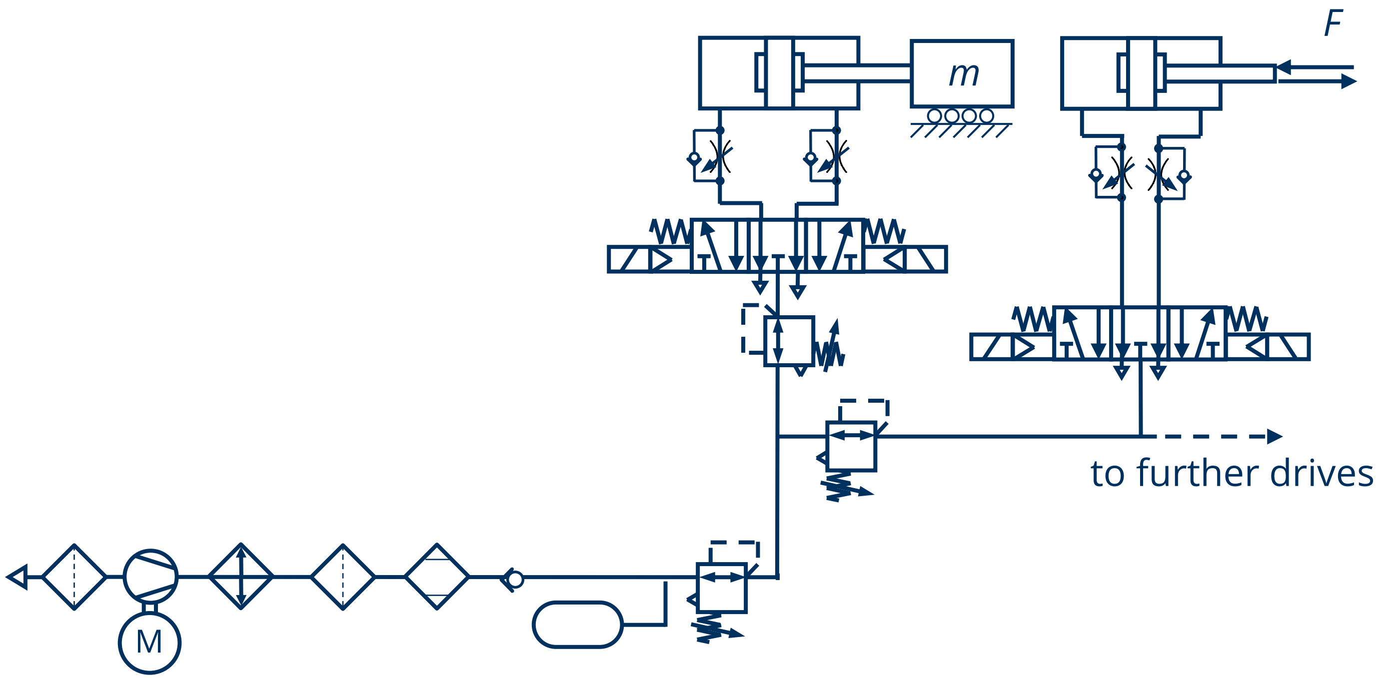
6th Workshop on Innovative Engineering for Fluid Power
November 22-23 – São Paulo – Brazil – 2022

Structure

- Introduction
- Concept of the closed-circuit systems
- State of art
- Compressor performance in a closed-circuit
- Closed-circuit pneumatics
- Summary & Outlook

Introduction
Motivation

- Pneumatics is inevitable in numerous branches
- Compressed air is a costly medium for energy transmission
- Competitiveness to electromechanical drives depends more and more on energy efficiency



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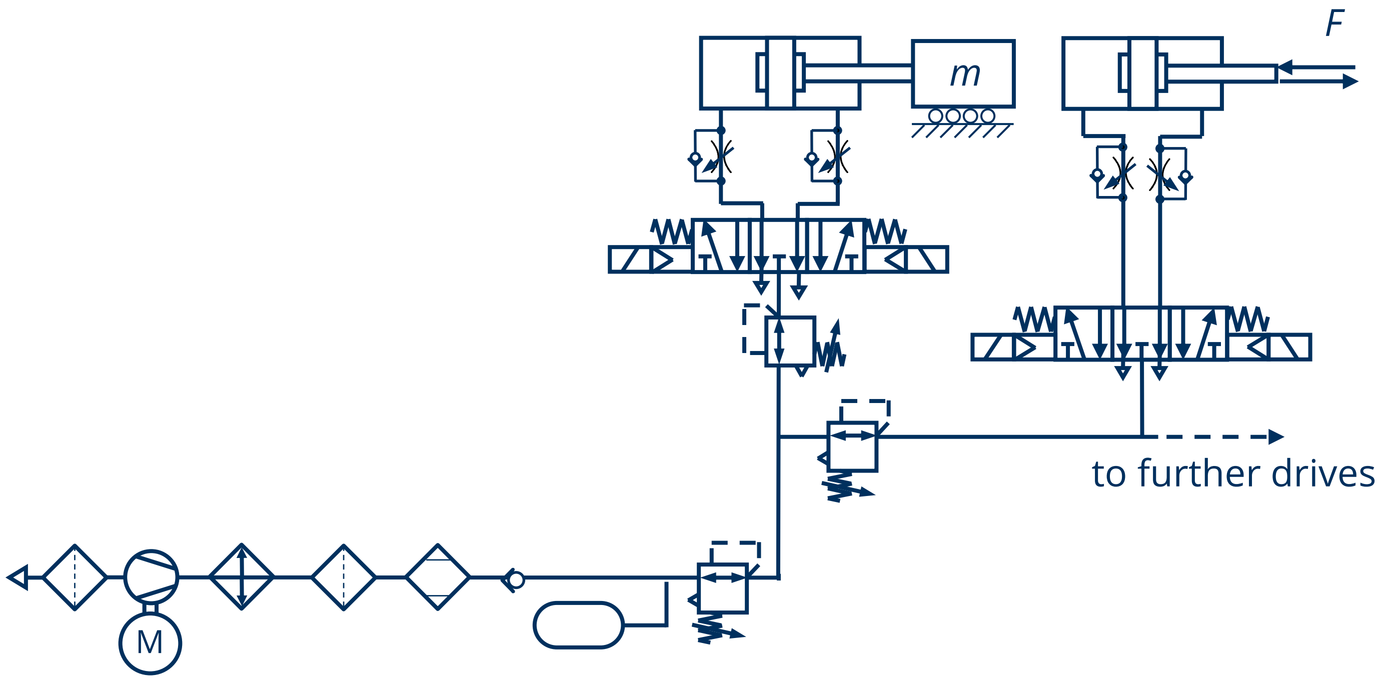
- Energy efficiency of pneumatic drives is difficult to assess:
  - one compressor, many consumers
  - various load cases for pneumatic cylinders



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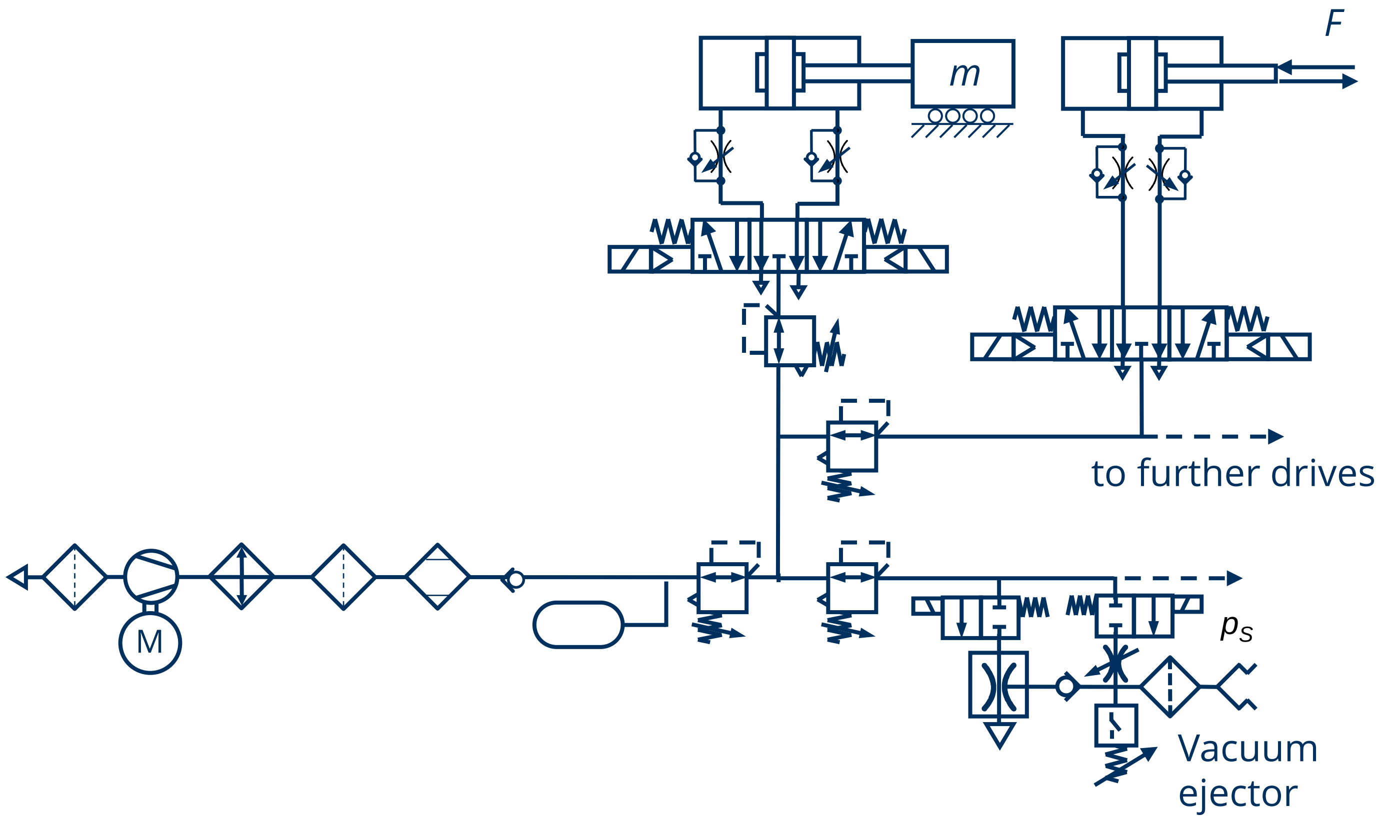

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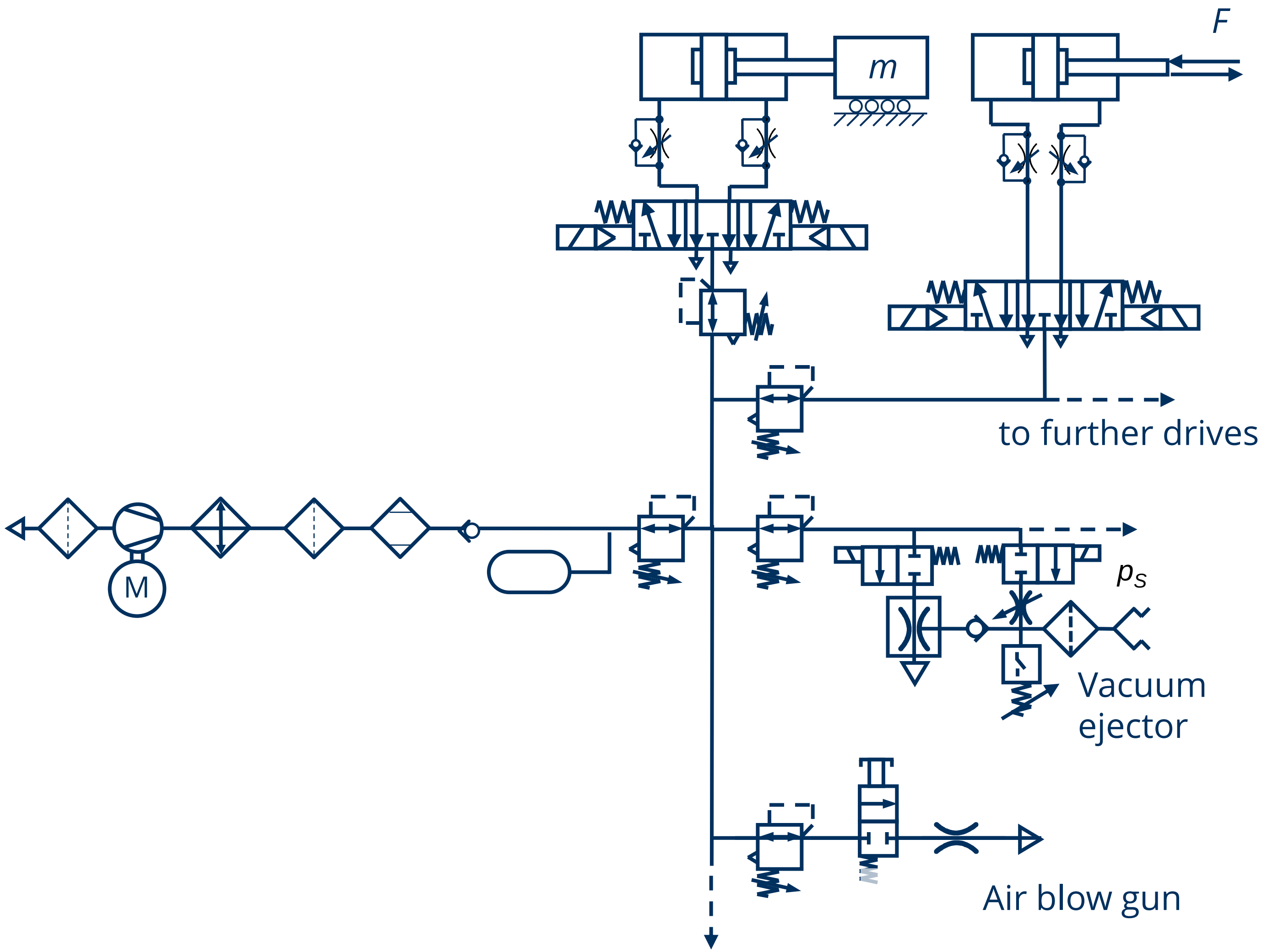

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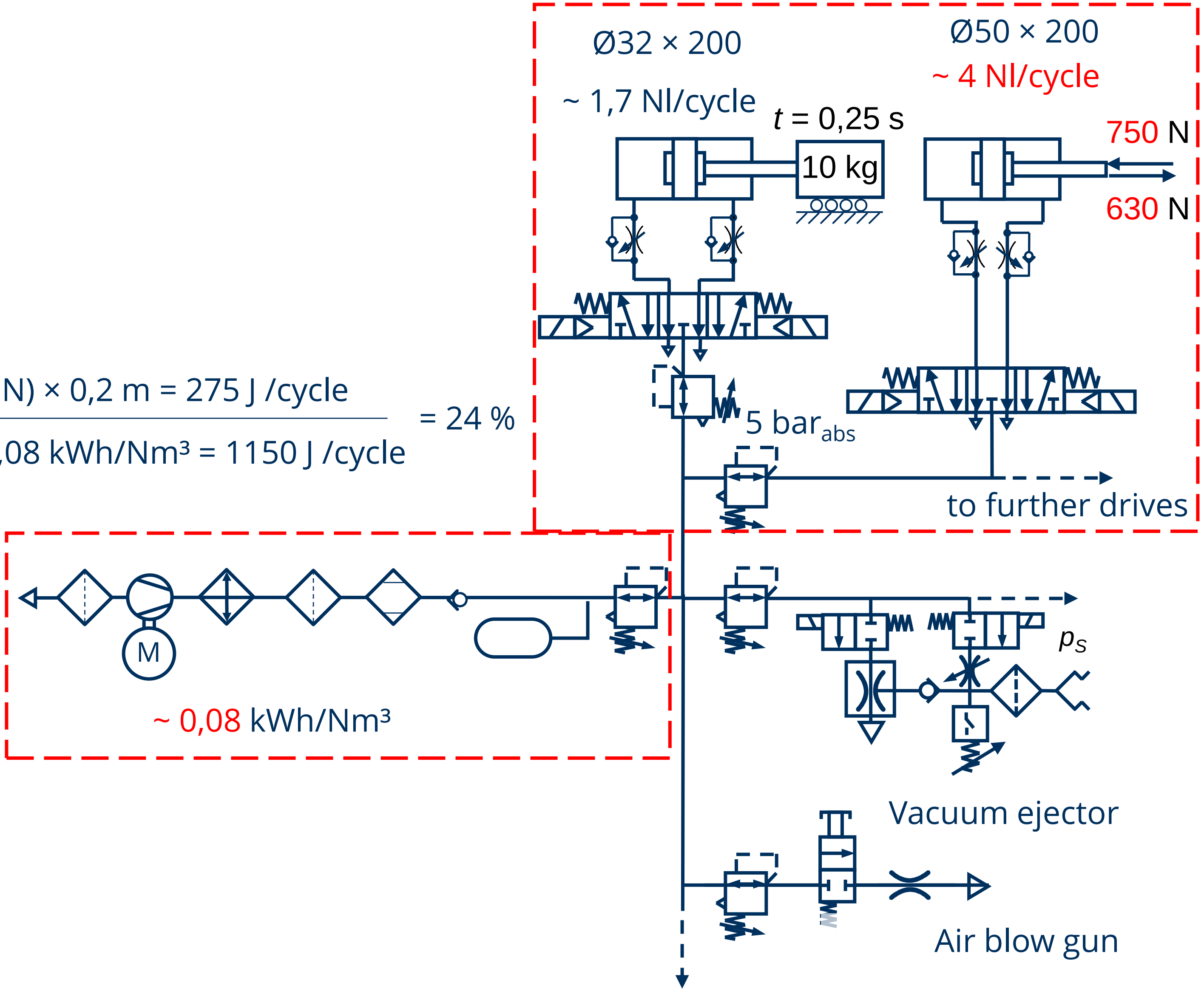
  - one compressor, many consumers
  - various load cases for pneumatic cylinders
- Splitting the energy flow between compression and consumption

$$\frac{(750 + 630\ \text{N}) \times 0{,}2\ \text{m} = 275\ \text{J /cycle}}{4\ \text{Nl/cycle} \times 0{,}08\ \text{kWh/Nm}^3 = 1150\ \text{J /cycle}} = 24\ \%$$



Introduction
Motivation

Reduce power demand per delivered m³ of compressed air:

- heat recovery
- high-performance oil-cooled compressors
- matching demand with delivery
- leakage-free infrastructure
- properly sized infrastructure (min. pressure drop)

Reduce air consumption:

- Properly sized pneumatic drive
- Minimization of volumes between valve and cylinder
- Application of energy saving measures
  - — retrofitting of an oversized cylinder (pressure regulator)
  - — in load-free direction
  - — for high-dynamic motion tasks (no force in the end position)

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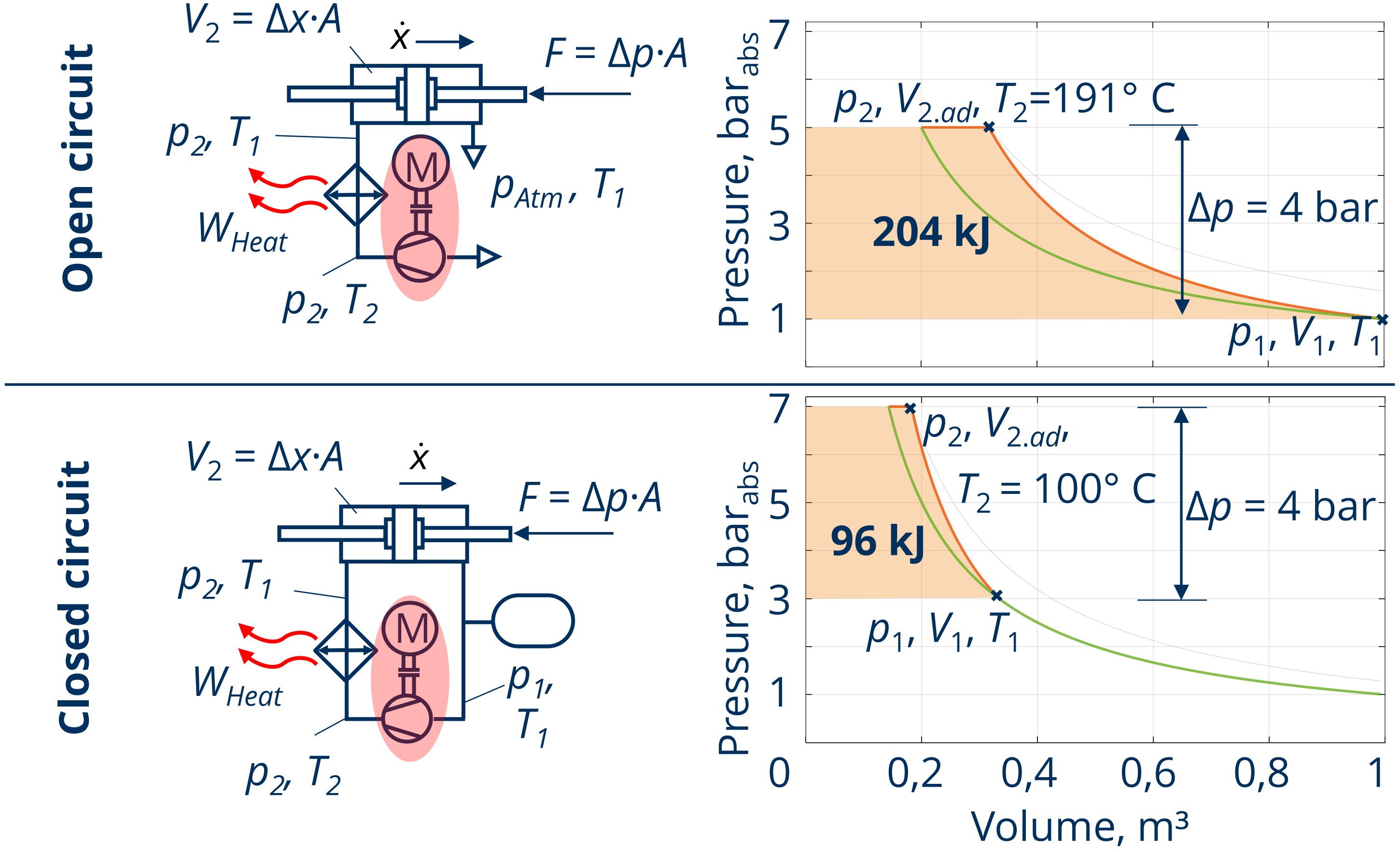
...and that‘s all?

Concept of the closed-circuit systems

Thermodynamics of compression

Adiabatic compression



Adiabatic compression

	open circuit	closed circuit
Compression work:	**204 kJ**	**96 kJ**

Concept of the closed-circuit systems

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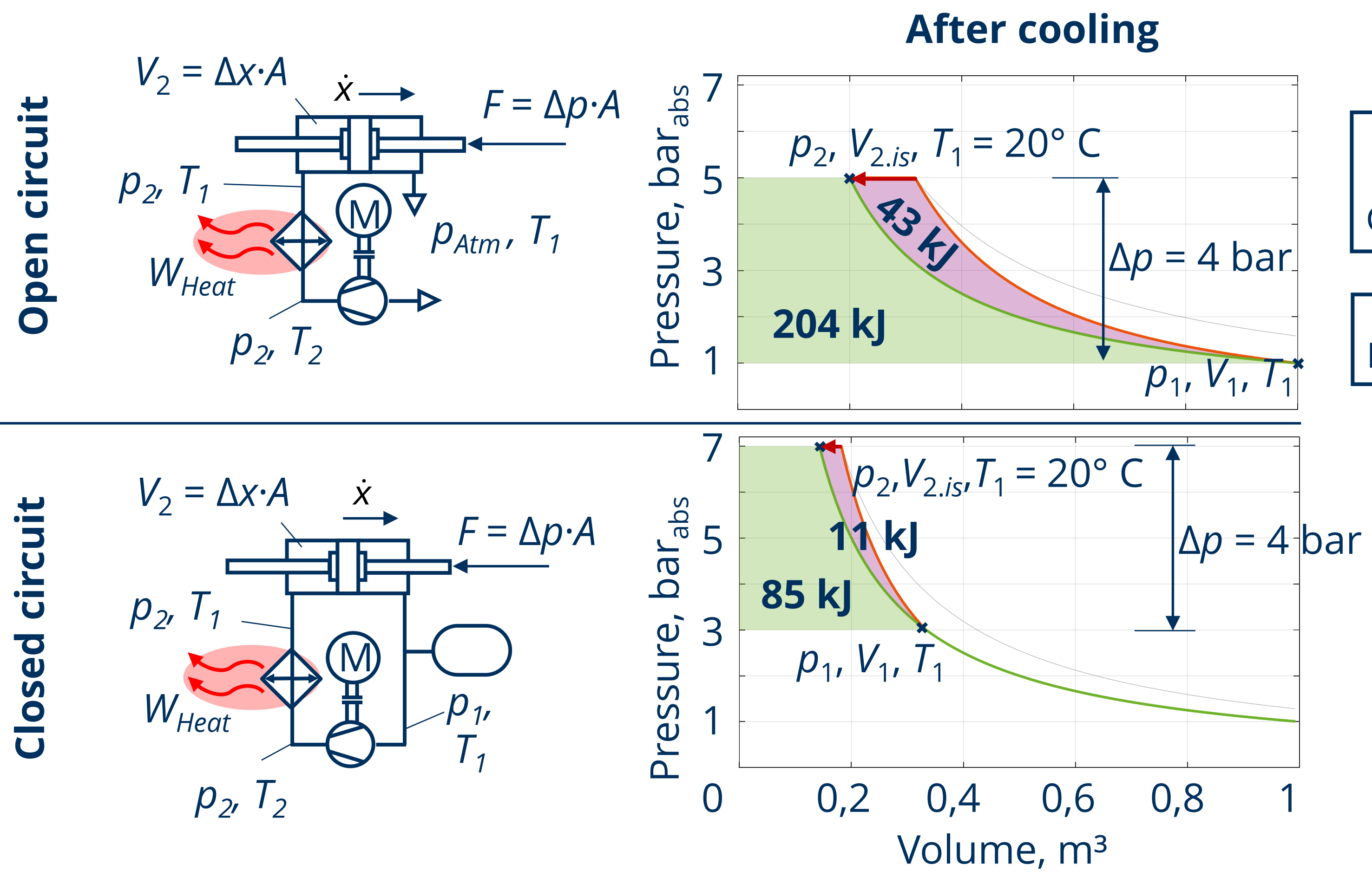


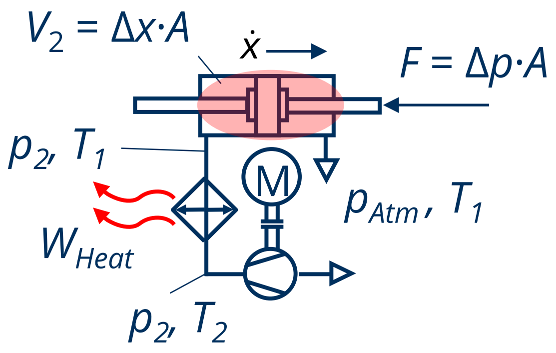
Adiabatic compression	open circuit	closed circuit
Compression work:	**204 kJ**	**96 kJ**

After cooling		
Heat loss:	**43 kJ (27%)**	**11 kJ (13%)**

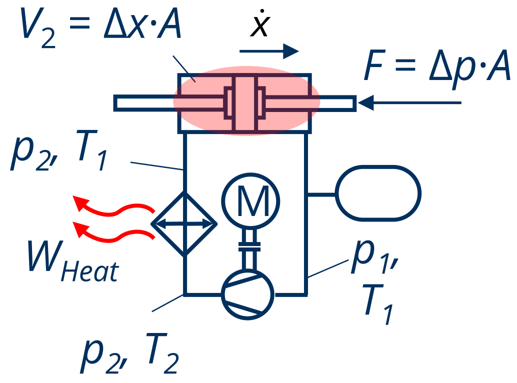
Concept of the closed-circuit systems

Thermodynamics of compression

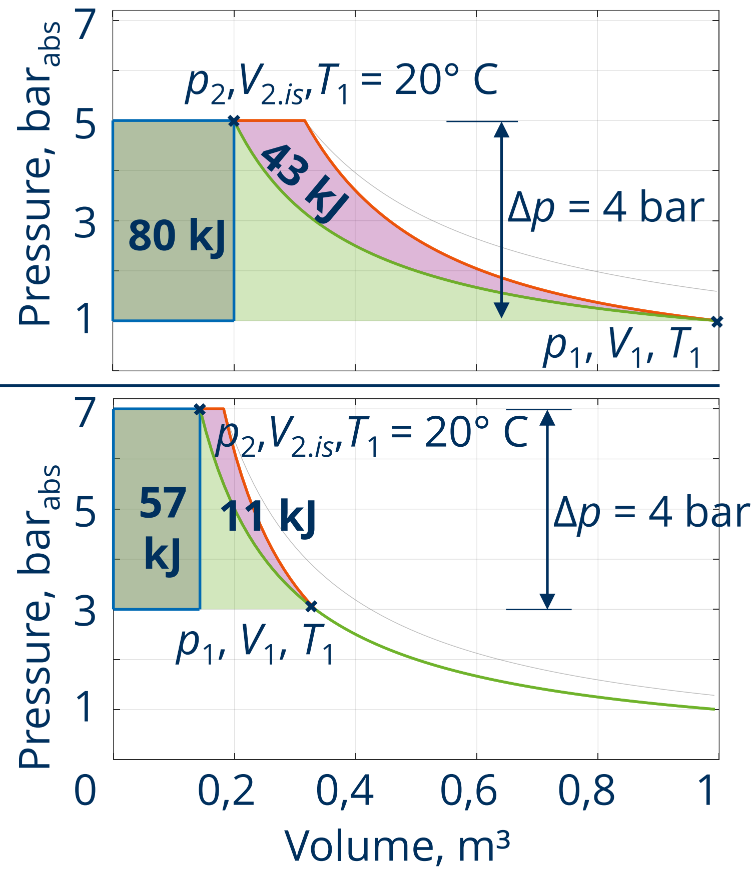
Open circuit



Closed circuit



Displacement work



Adiabatic compression

	open circuit	closed circuit
Compression work:	**204 kJ**	**96 kJ**

After cooling

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Displacement work

Work:	**80 kJ**	**57 kJ**
theor. total efficiency:	$\frac{80\ \text{kJ}}{204\ \text{kJ}}$ **= 39 %**	$\frac{57\ \text{kJ}}{96\ \text{kJ}}$ **= 60 %**

State of art

Closed circuit? Pros & cons

- \+ Feasible reduction in energy consumption
- \+ Decrease in compression temperature
- \+ Higher delivered mass flow rate

- — Additional low-pressure piping
- — Need in automatic leakage compensation
- — Slightly less attractive for compressor plants with heat recovery
- — Depending on form of air consumption profile: need in extra air storage or compressor delivery control
- — No design methods currently existing

State of art
Closed circuit? Pros & cons

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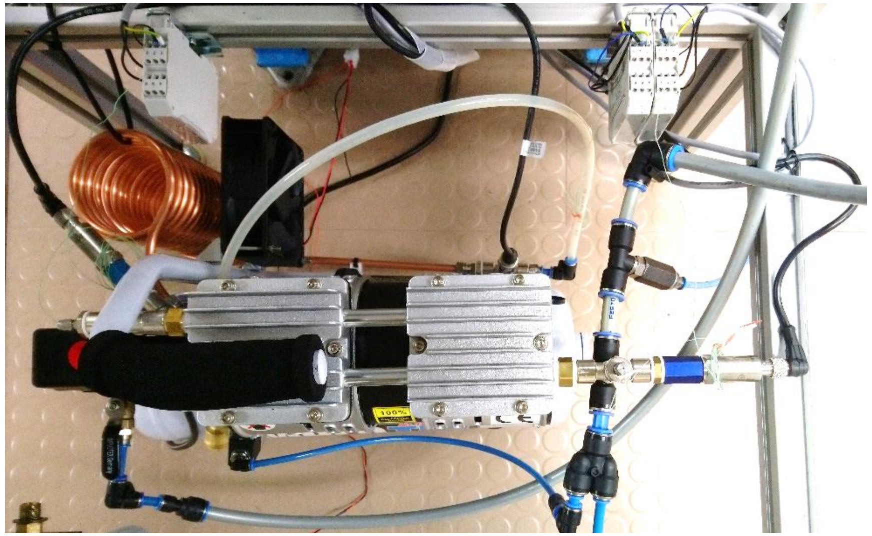
The concept of the closed circuit is already known, however:

- no experimental evidence of benefits
- doubts about pneumatic system behavior and control
- missing quantification of economic profit for an end-user

} Addressed as goals of the study

Compressor performance in a closed-circuit system

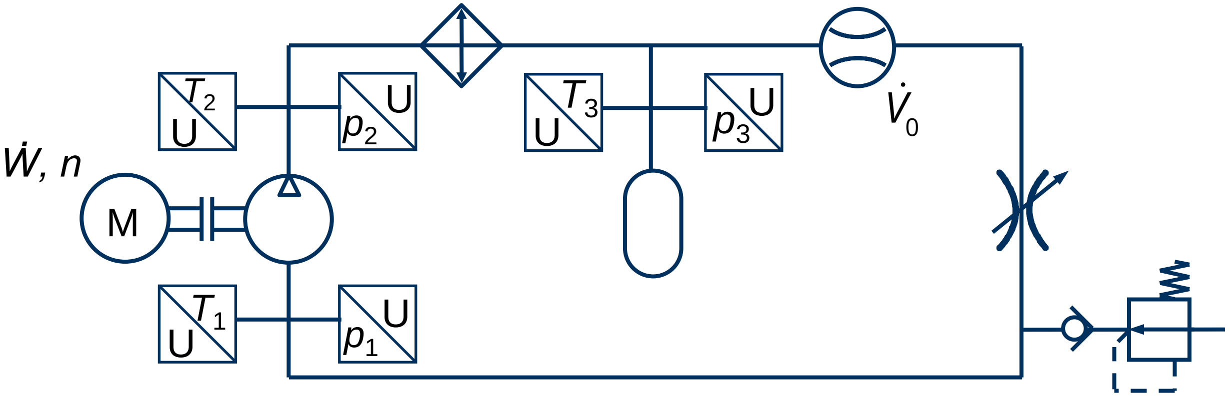
Set-up



Tested unit:

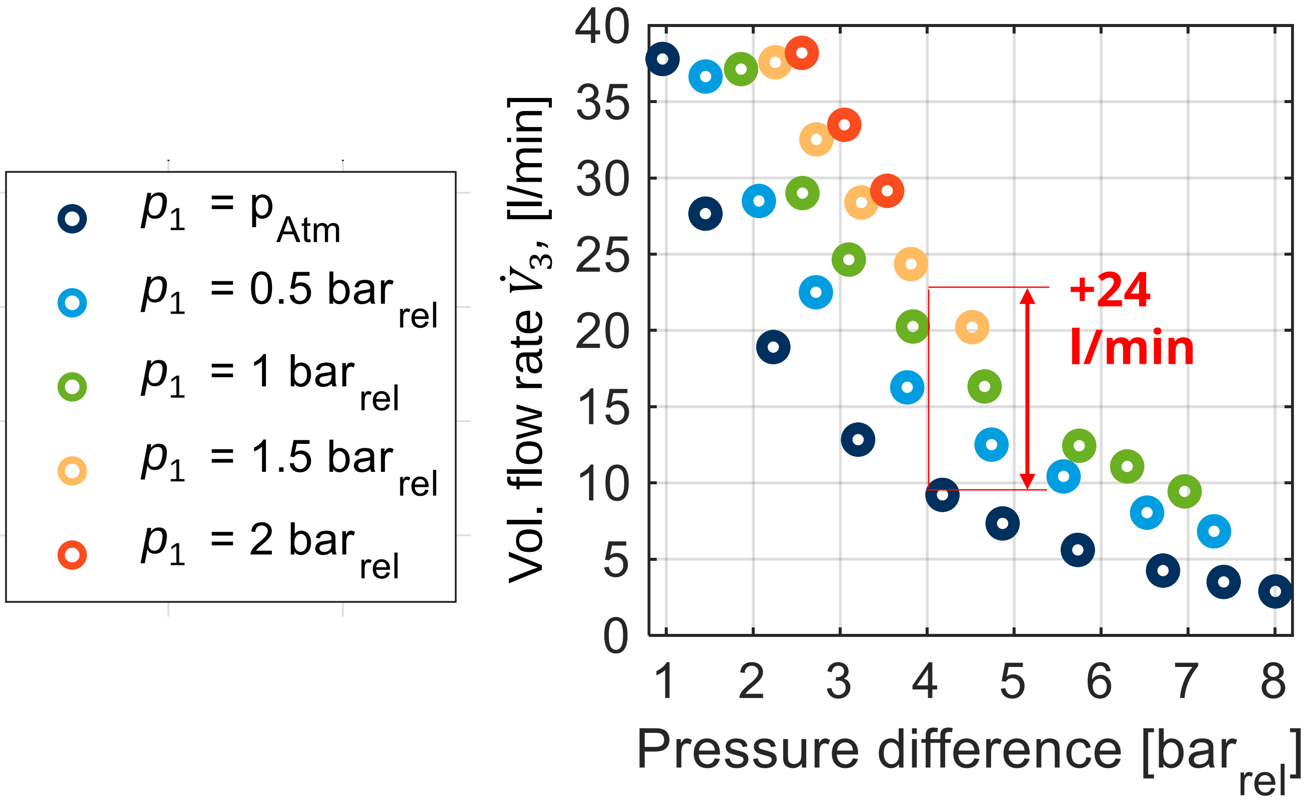
- Oil-free, one-stage, double-piston compressor
- Asynchronous Motor 220 V
  Net power 500 W
- Max. discharge pressure 8 bar_{rel},
  max delivery 89 Nl/min

Test circuit with continuous air consumption (throttling)



Compressor performance in a closed-circuit system

Measurement results



Summary

- Vol. flow rate increase of >250 % (9 → 23 Nl/min)

Compressor performance in a closed-circuit system

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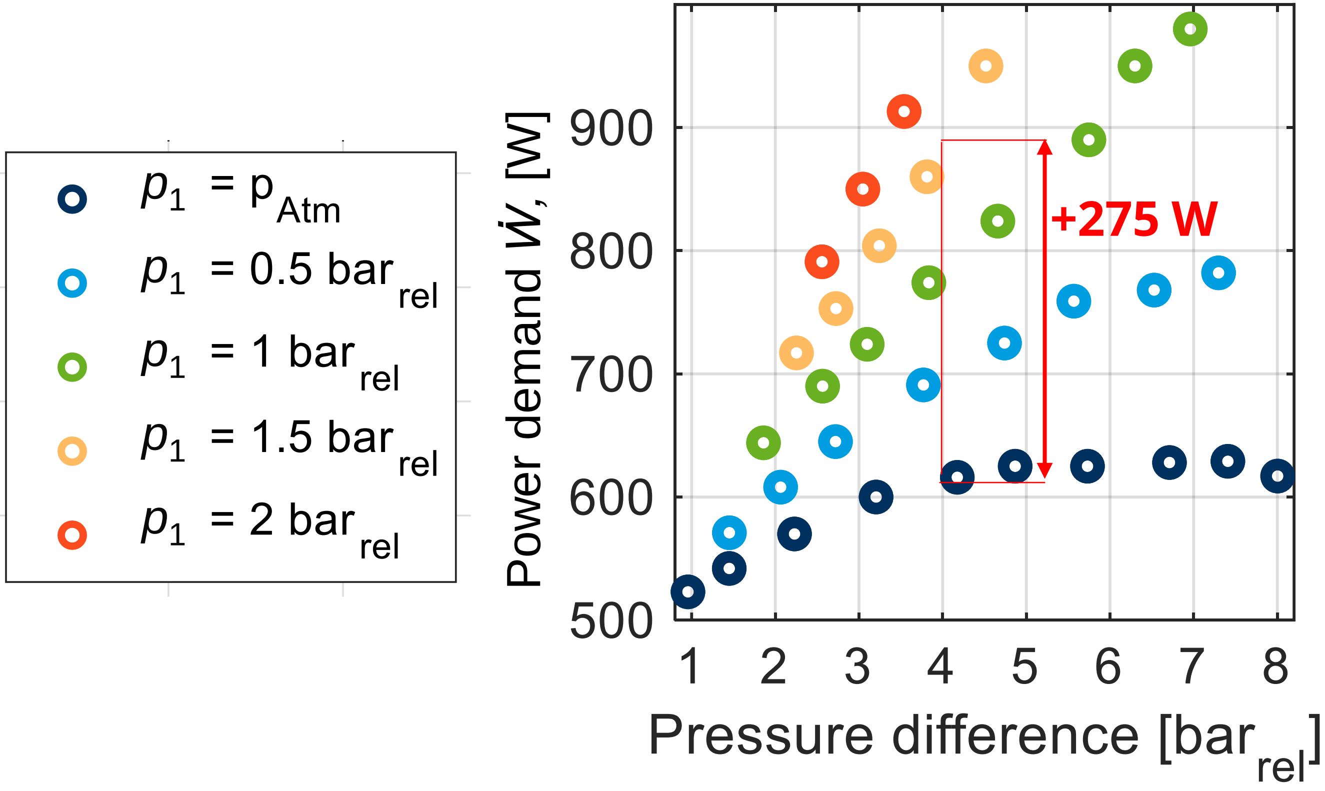

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- Vol. flow rate increase of >250 % (9 → 23 Nl/min)
- Power demand increase of < 45 % (610 → 890 W)

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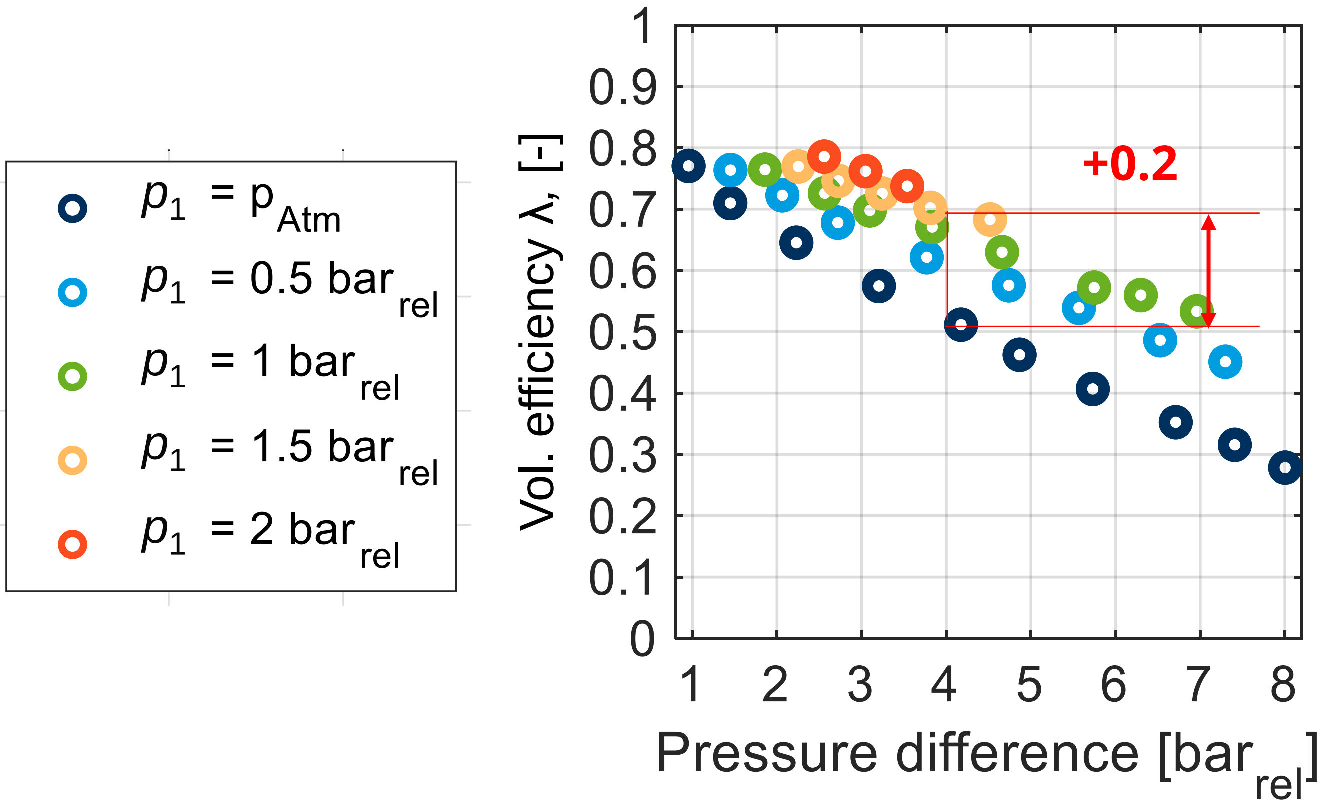

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- Vol. efficiency increase of >40 % (0.5 → 0.7)

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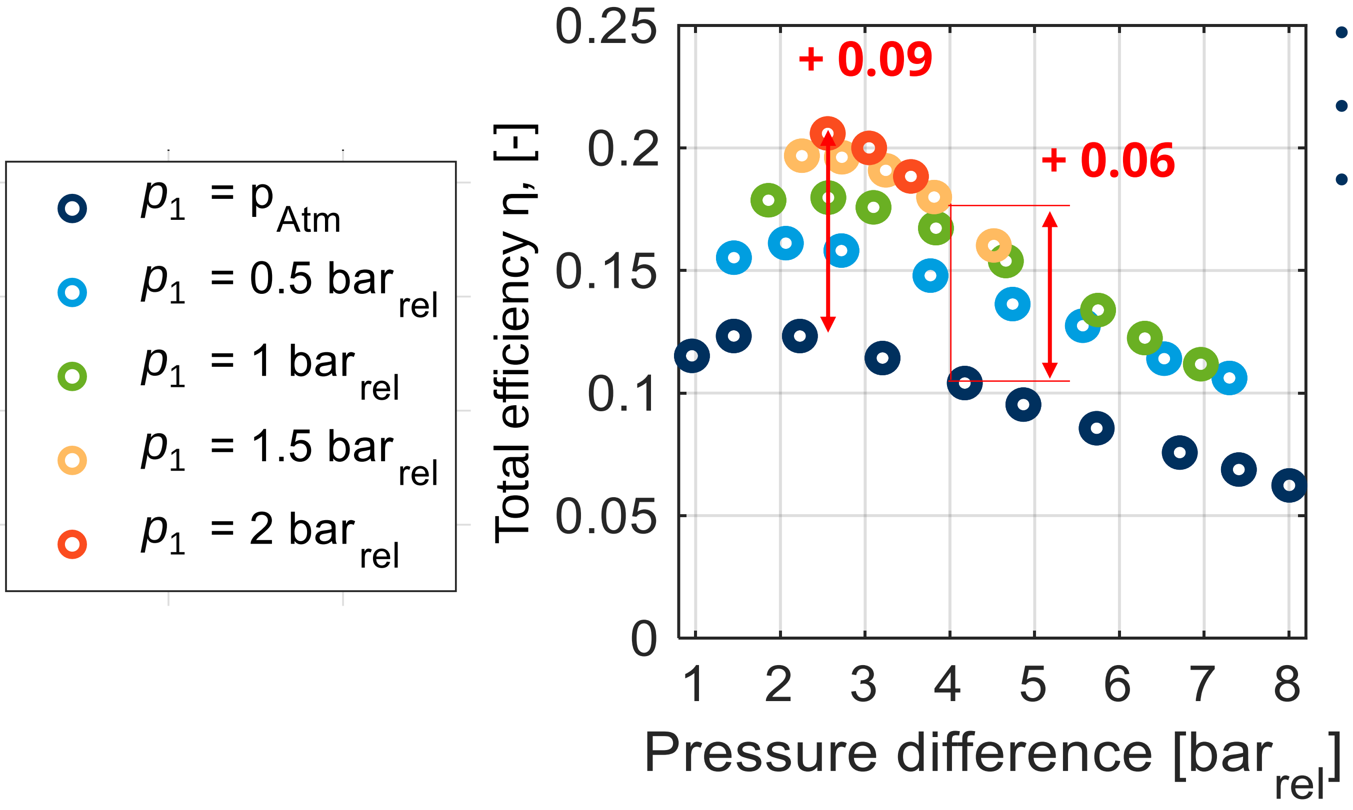

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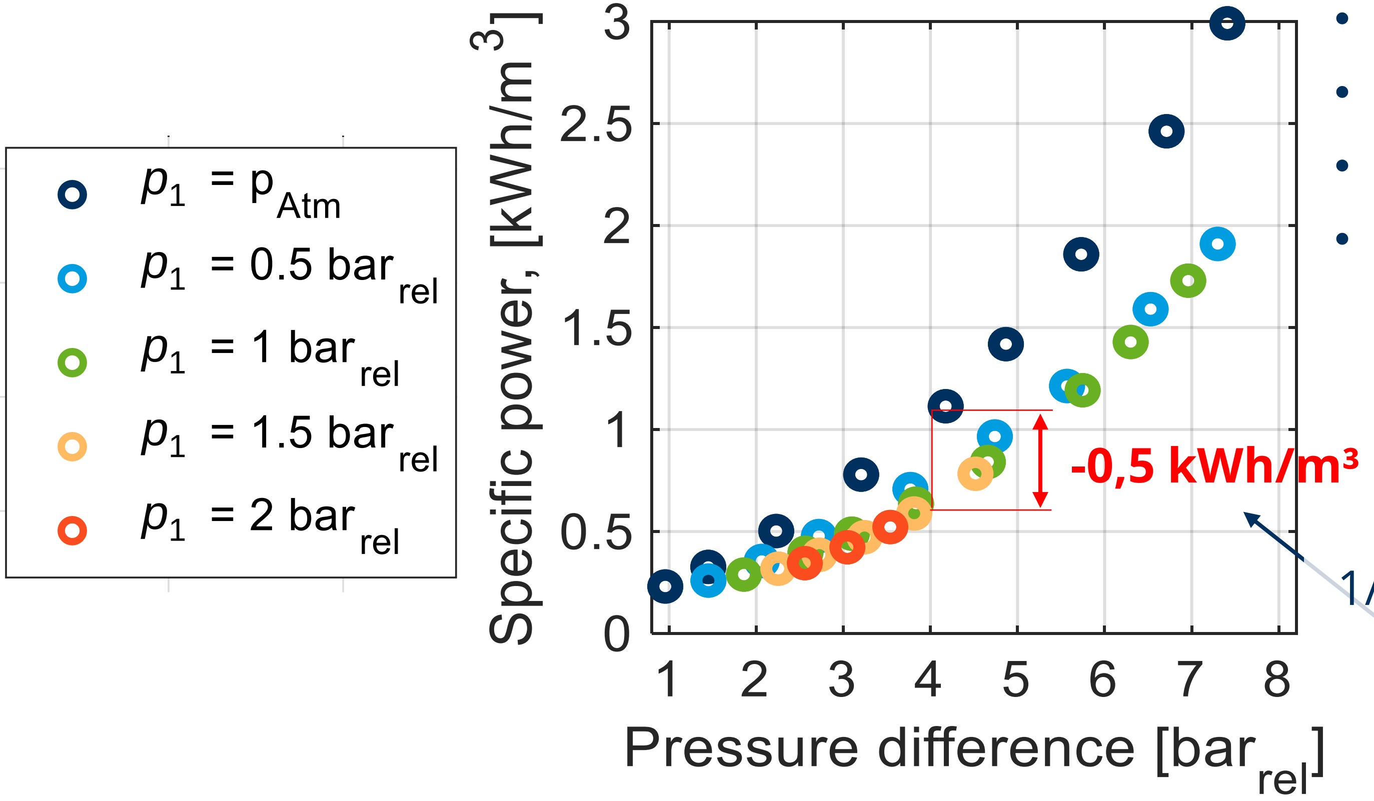

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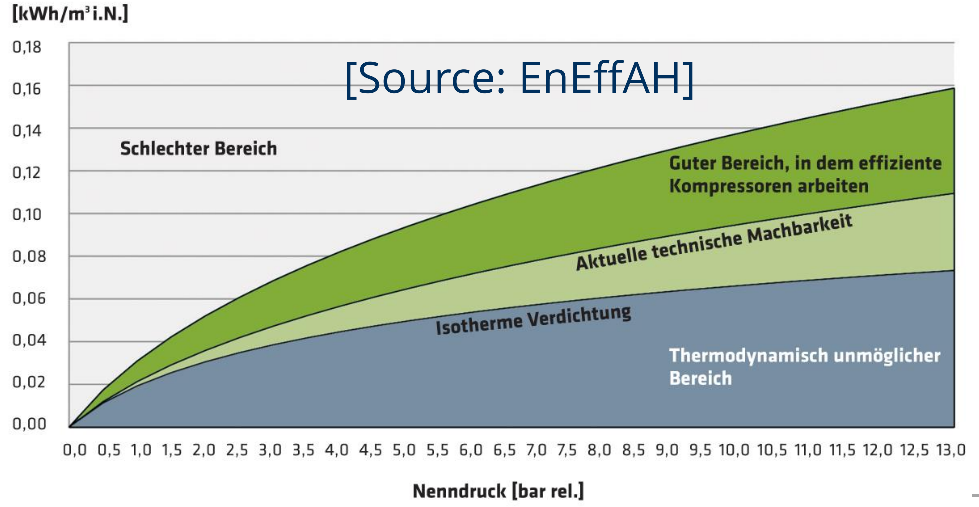
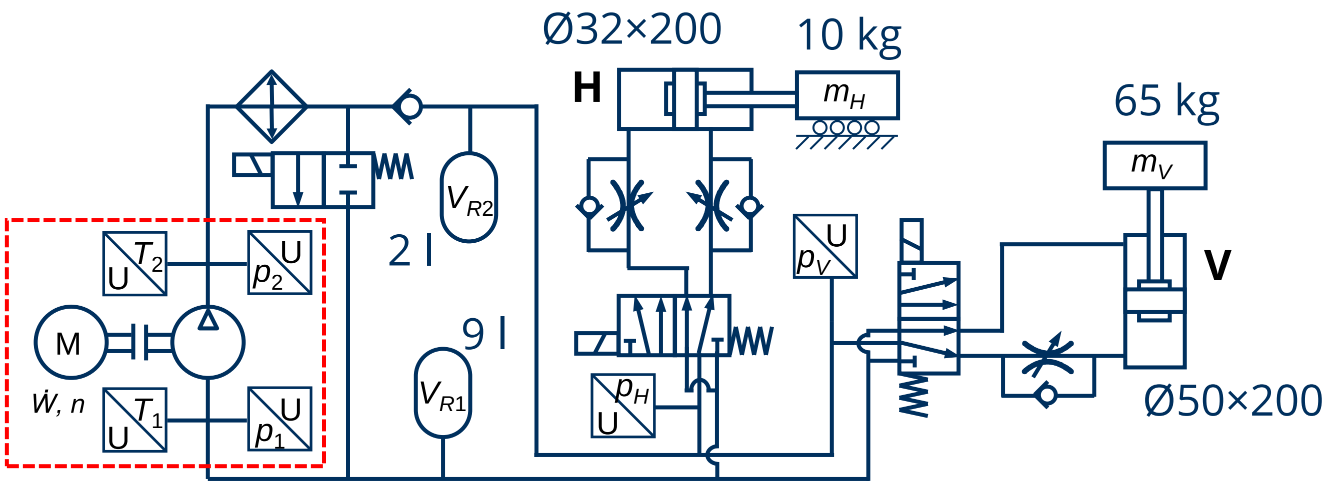
- Vol. efficiency increase of >40 % (0.5 → 0.7)
- Efficiency increase of >65 % (0.125 → 0.21)
- Reduction in specific power of >65 %
  (1,1 → 0,65 kWh/m³)



Closed-circuit pneumatic system

Set-up



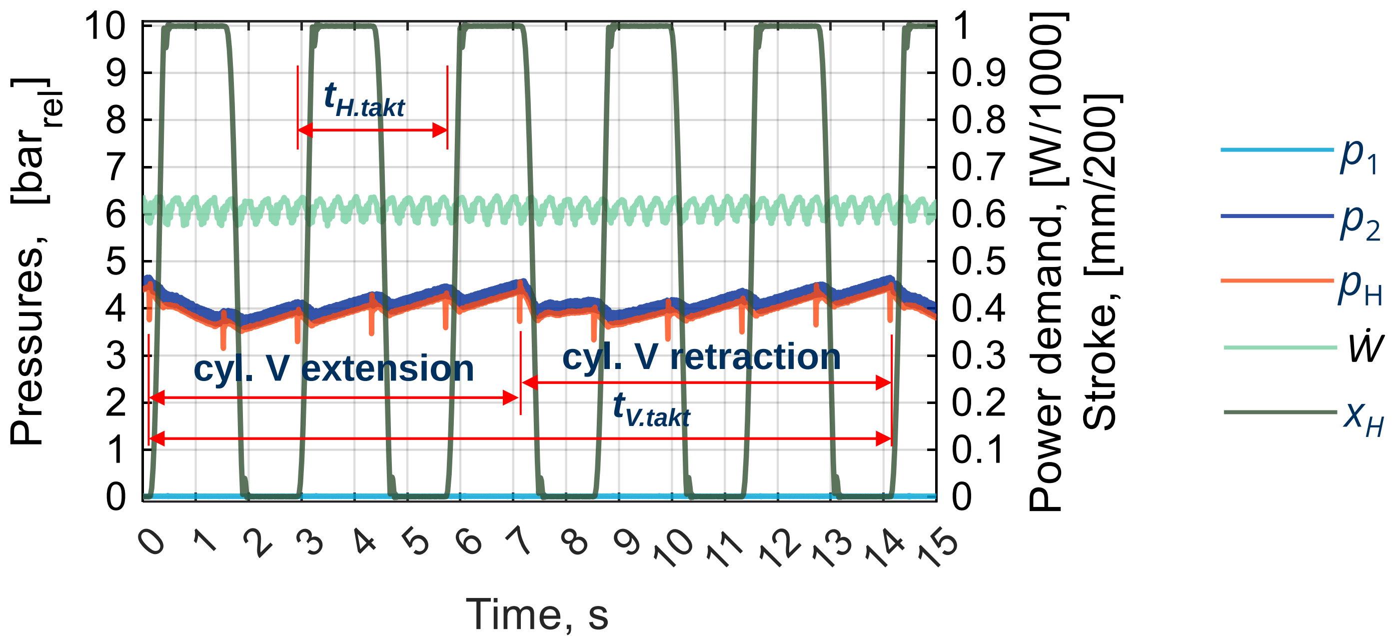
Test circuit with discontinuous air consumption

- Simultaneous operation of cylinders:
  - with inertial load
  - against constant force
- different load profiles $\dot{V}(t)$:
  - base load: high-frequency & low-amplitude oscilations
  - peak load: low frequency & high-amplitude

Load specification	Horizontal cylinder H, Ø32×200	Vertical cylinder V, Ø50×200
Handled mass m, [kg]	10	65
Force, F_{ext} // F_{restr}, [N]	0 // 0	640 // -640
Travel time, t_{ext} // t_{retr}, [s]	0.34±0.02 // 0.44±0.03	<3 // <3

Closed-circuit pneumatic system

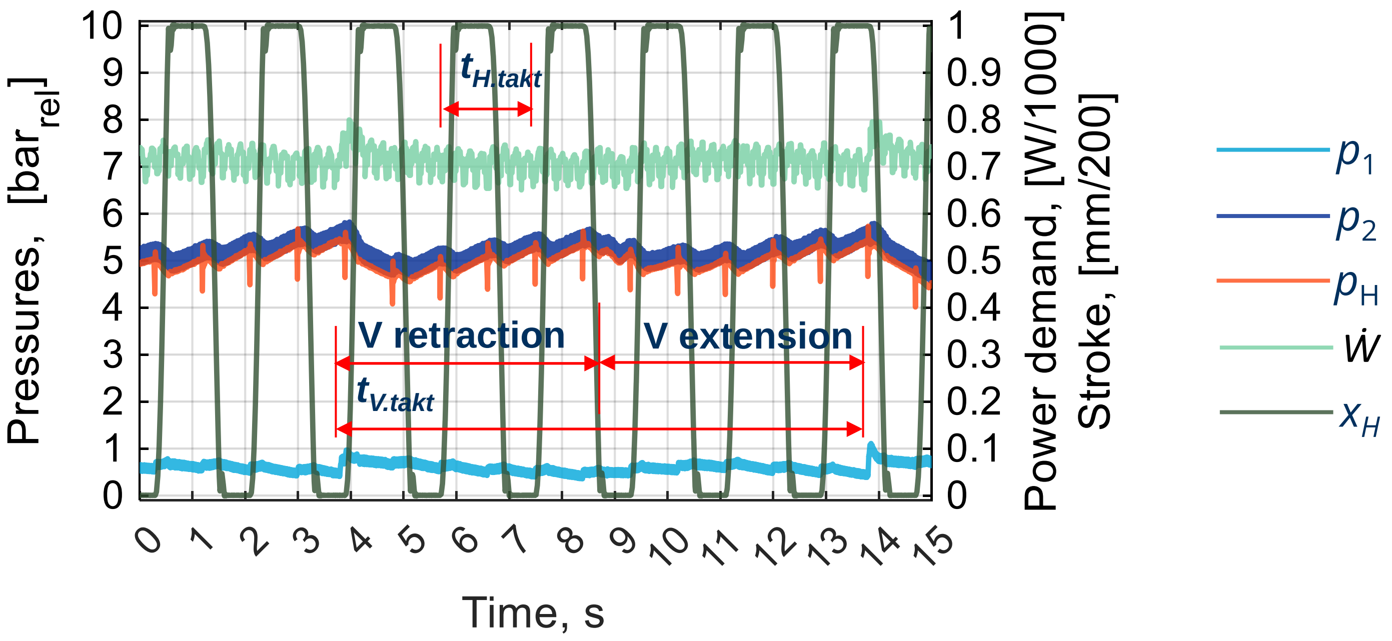
Measurement results, $p_1 = p_{atm}$



$p_{1.mean}$, [bar$_{rel}$]	0
Δp, [bar$_{rel}$]	4.07
Δp_{cyl}, [bar$_{rel}$]	3.93
$t_{H.takt}$, [s]	2.8
$t_{V.takt}$, [s]	14
$t_{H.ext}$, [s]	0.36… …0.37
$t_{H.retr}$, [s]	0.43… …0.46
$t_{V.ext}$, [s]	2.3… …2.65
$t_{V.retr}$, [s]	2.64… …2.65
$\dot{W}_{mean}$, W]	620
$\dot{V}_3$, l/min]	10.1
η_{cyl}, [-]	0.107

Closed-circuit pneumatic system

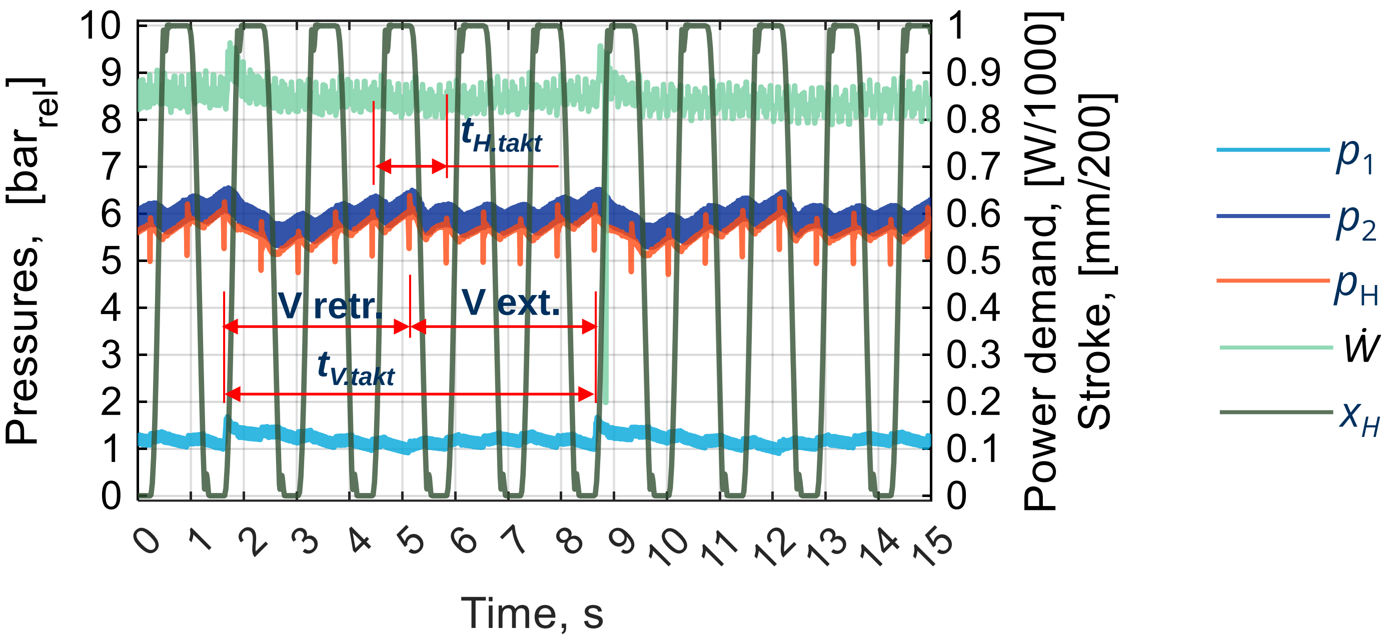
Measurement results, $p_1 \approx 0{,}5\ bar_{rel}$



$p_{1.mean}$, $[bar_{rel}]$	0	0.59
Δp, $[bar_{rel}]$	4.07	4.52
Δp_{cyl}, $[bar_{rel}]$	3.93	4.42
$t_{H.takt}$, [s]	2.8	1.8
$t_{V.takt}$, [s]	14	10
$t_{H.ext}$, [s]	0.36… …0.37	0.33… …0.34
$t_{H.retr}$, [s]	0.43… …0.46	0.41… …0.43
$t_{V.ext}$, [s]	2.3… …2.65	1.64… …1.67
$t_{V.retr}$, [s]	2.64… …2.65	2.74… …2.77
$\dot{W}_{mean}$, W]	620	720
$\dot{V}_3$, l/min]	10.1	15.2
η_{cyl}, [-]	0.107	0.155

Closed-circuit pneumatic system

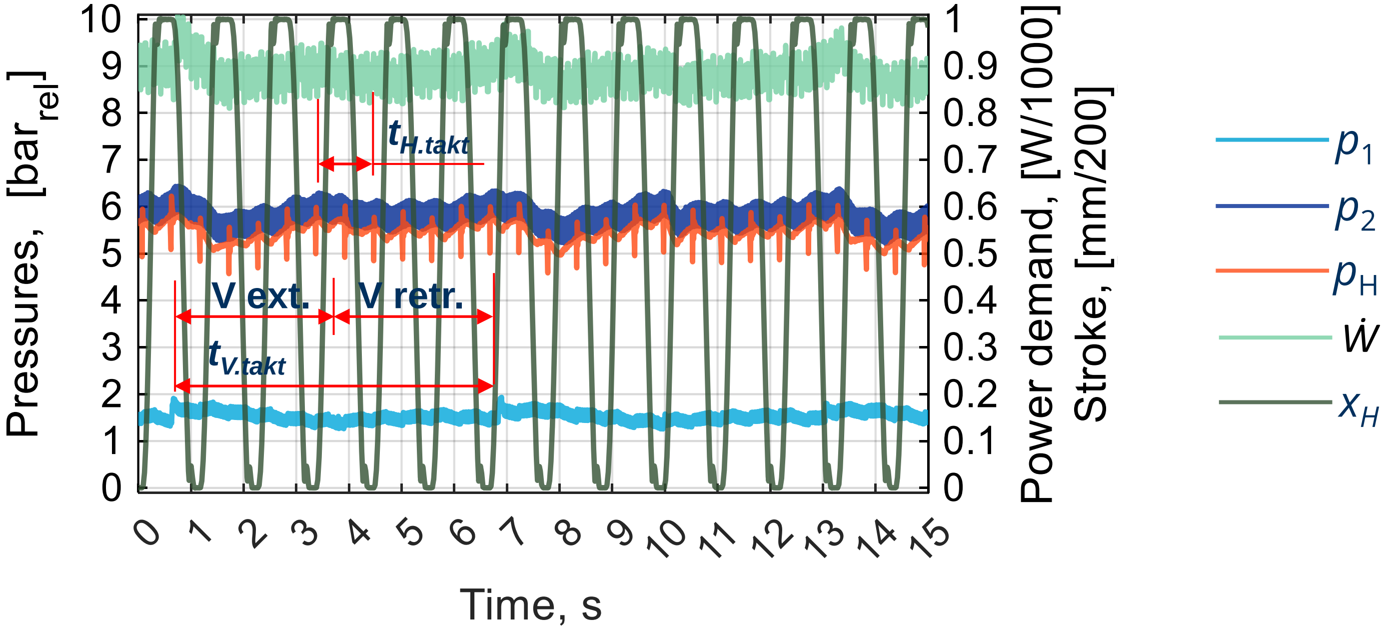
Measurement results, $p_1 \approx 1\ bar_{rel}$



$p_{1.mean}$, [bar_{rel}]	0	0.59	1.17
Δp, [bar_{rel}]	4.07	4.52	4.82
Δp_{cyl}, [bar_{rel}]	3.93	4.42	4.52
$t_{H.takt}$, [s]	2.8	1.8	1.4
$t_{V.takt}$, [s]	14	10	7
$t_{H.ext}$, [s]	0.36… …0.37	0.33… …0.34	0.33… …0.34
$t_{H.retr}$, [s]	0.43… …0.46	0.41… …0.43	0.42… …0.45
$t_{V.ext}$, [s]	2.3… …2.65	1.64… …1.67	1.61… …1.69
$t_{V.retr}$, [s]	2.64… …2.65	2.74… …2.77	2.84… …2.85
$\dot{W}_{mean}$, W]	620	720	851
$\dot{V}_3$, l/min]	10.1	15.2	20.2
η_{cyl}, [-]	0.107	0.155	0.181

Closed-circuit pneumatic system

Measurement results, $p_1 \approx 1{,}5\ \text{bar}_{rel}$



$p_{1.mean}$, [bar_{rel}]	0	0.59	1.17	1.5
Δp, [bar_{rel}]	4.07	4.52	4.82	4.41
Δp_{cyl}, [bar_{rel}]	3.93	4.42	4.52	4.04
$t_{H.takt}$, [s]	2.8	1.8	1.4	1.1
$t_{V.takt}$, [s]	14	10	7	6.2
$t_{H.ext}$, [s]	0.36... ...0.37	~const 0.33... ...0.34	0.33... ...0.34	0.33... ...0.35
$t_{H.retr}$, [s]	0.43... ...0.46	~const 0.41... ...0.43	0.42... ...0.45	0.43... ...0.46
$t_{V.ext}$, [s]	2.3... ...2.65	~const 1.64... ...1.67	1.61... ...1.69	1.95... ...1.96
$t_{V.retr}$, [s]	2.64... ...2.65	~const 2.74... ...2.77	2.84... ...2.85	2.76... ...2.8
$\dot{W}_{mean}$, W]	620	720	851	906
$\dot{V}_3$, l/min]	10.1	15.2	20.2	24.8
η_{cyl}, [-]	0.107	0.155	0.181	0.184

Summary & Outlook

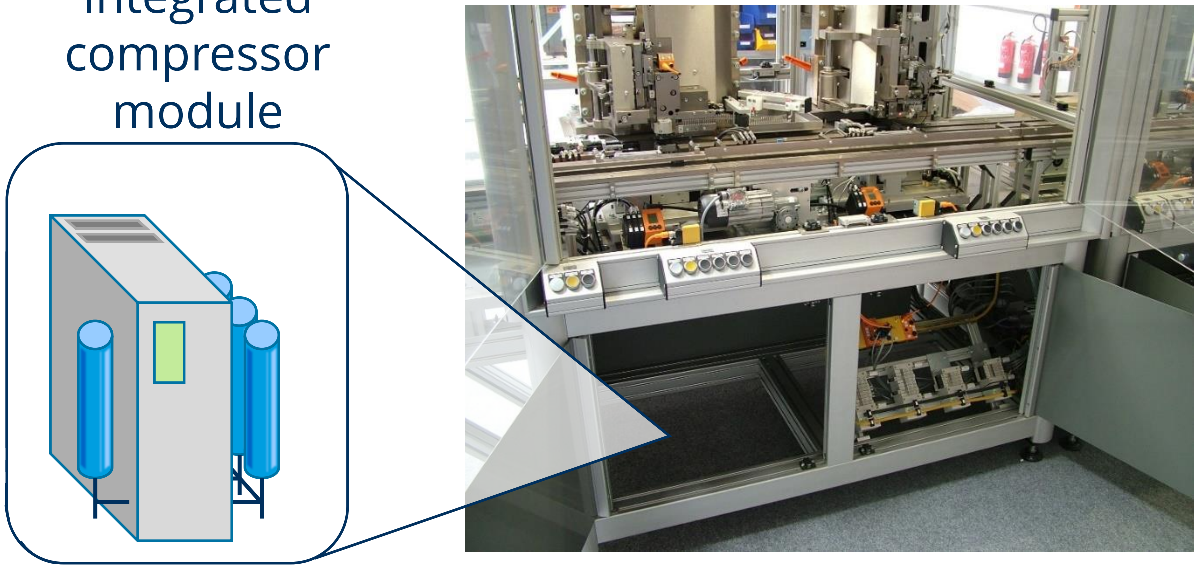
Potential applications

ideal system: **24 %** vs. simple demonstrator **18.4 %**

Closed circuit enables cost-effective exploitation of advantages of the decentralized air supply:

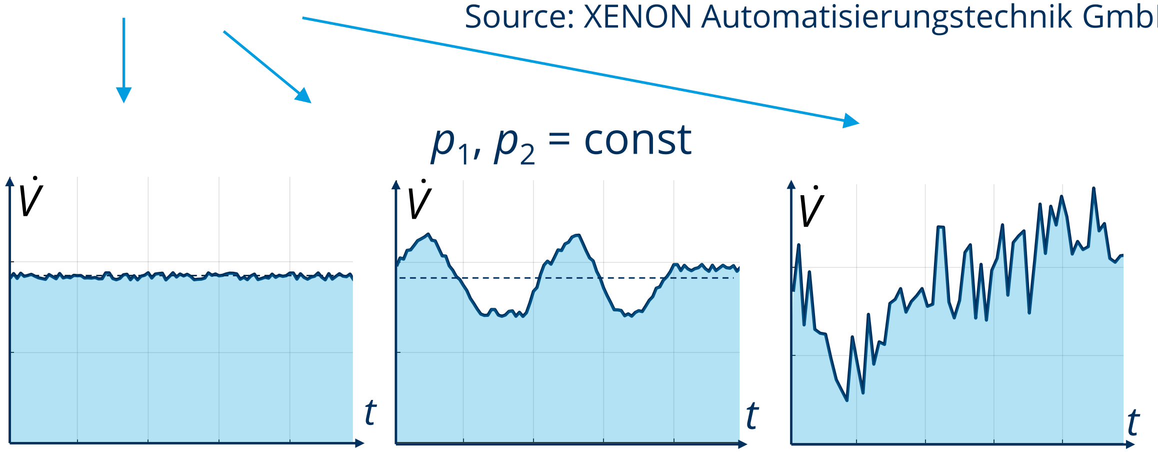
- No expensive piping infrastructure, easily extendable, low pressure losses, low probability of leakage appearance
- small industrial compressor in closed circuit can be more efficient than a large high-end compressor in open circuit
- Low local noise emission
- Modular & plug&play-capable
- Leakage ratio → 0
- Easy & transparent energy monitoring

Integrated compressor module



Source: XENON Automatisierungstechnik GmbH

p_1, p_2 = const



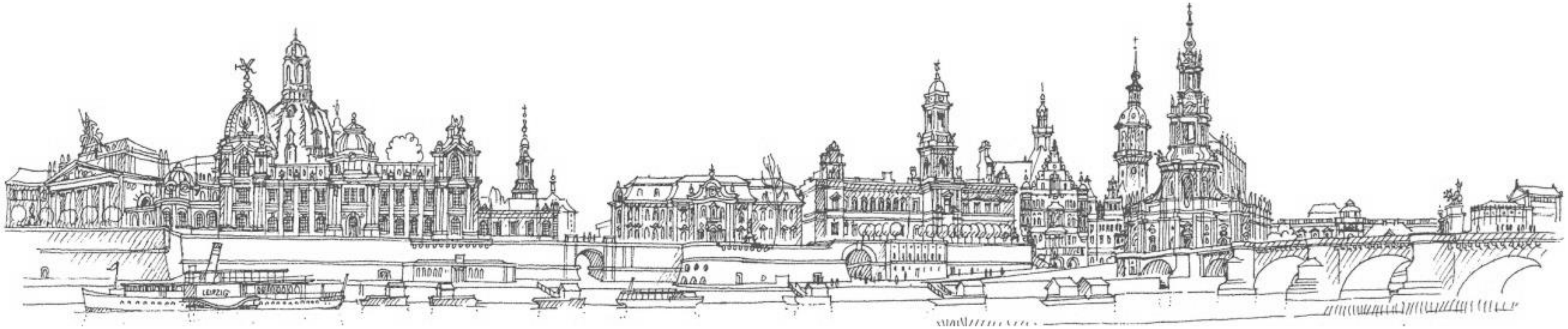
Summary & Outlook
Potential applications

- Closed-circuit system operates without any disturbance
- Transition times t_{ext} and t_{retr} of both cylinders are repeatable and reach the desired values
- Both dynamic and force tasks performed perfectly
- Compressor delivery rate 2.5 times higher (→ compressor downsizing possible)
- Increase in total efficency in 72 %: from 10.1 % to 18.4 %
- Lower noise level in the closed-circuit operation

Outlook for further research:

- Cost-efficient strategies for compressor delivery control
- Methods for integral system design: compressor and motor sizing, filling pressure and air reservoir estimation basing on the data about the operation cycle
- Automatic compensation of inevitable leakage (e. g. in rod sealings)

Thank you for your attention!



Technische Universität Dresden | Institut für Mechatronischen Maschinenbau
Professur für Fluid-Mechatronische Systemtechnik
Prof. Dr.-Ing. J. Weber | Tel. 0351- 463 33559 | fluidtronik@mailbox.tu-dresden.de