Improving the Energy Efficiency of Compressed Air Systems by Use of Pressure Equalizing Modules

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Agenda

- Fundamentals

- Concept of isobaric storage on the basis of pressure equalizing modules (PEQM)

- Investigation of PEQM

- Energy savings in compressed air system with PEQM
Compressed air usage in industry

Compressed air is a widely used energy carrier

Pneumatic tools, control of plants and machines, air supply in hospitals

- Around 291,000 compressors are in operation in Germany [1]
- Accounts for ca. 8 % of the industrial electricity consumption in Germany [1]

Compressed air systems (CAS) have an overall low energy efficiency

- Only 7 % of the compressors energy consumption is usable [2]
- Control of the compressor affects the energy efficiency

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Increasing the efficiency of CAS

Compressed air receivers are important components in CAS
- Buffering of the discontinuous compressed air demand
- Reducing the cycling frequency of the engine

Significant influence on the energy efficiency of CAS
Increasing the efficiency of CAS

Compressed air receivers are important components in CAS:

- Buffering of the discontinuous compressed air demand
- Reducing the cycling frequency of the engine

Significant influence on the energy efficiency of CAS
Combined-isobaric-isochoric compressed air receiver

Concept with phase change materials

Significant capacity increase

- Isochoric (isc):
  \[ V_{receiver} = 1000 \text{ l}, \Delta p = 0.5 \text{ bar} \quad \rightarrow \quad V_{lsc1,2} = 500 \text{ l} \]

- Combined-isobaric-isochoric (cii):
  \[ \Delta V_{receiver} = 1000 \text{ l}, \quad p_{2',3'} = 7 \text{ bar} \quad \rightarrow \quad V_{cii1,4'} = 7000 \text{ l} \]

- Capacity change:
  \[ C_{theo} = \frac{V_{cii1,4'}}{V_{lsc1,2}} - 1 = 13 \]

Counter pressure by phase change material (PCM\(_{lg}\))

- Isobaric and isothermal phase change between liquid and gaseous state
- Separation of PCM\(_{lg}\) and compressed air by flexible membrane

Heat management with phase change material (PCM\(_{sl}\))

- Storage of heat of condensation
- Encapsulation of PCM\(_{sl}\) avoids mixing with PCM\(_{lg}\)
Combined-isobaric-isochoric compressed air receiver
Concept in \(\text{isoSTOR}^{\text{Retrofit}}\) - project

Concept of isobaric storage with module-based concept
- Pressure equalizing modules (PEQM) contain \(\text{PCM}_{\text{l/g}}\) and \(\text{PCM}_{\text{s/l}}\)\[1\]
- No external equipment required, e.g. heat exchangers
- Retrofitting of existing receiver possible
- Isobaric storing is achieved through many PEQM

Aim of the \(\text{isoSTOR}^{\text{Retrofit}}\) - project\[\text{a}\]
- Capacity increase of at least 600 % with PEQM
- Reducing the energy consumption by \(> 20 \%\)

\[\text{a}\] Funded within the framework of the Fraunhofer Societies internal programs, funding number MEF 602 230, 07/2018 – 12/2021
Investigation within isoSTOR\textsuperscript{Retrofit} - project

Investigation of PEQM

- Understanding of processes inside the PEQM
- Identifying suitable designs for PEQM
- Determining possible capacity increases

Investigation of potential energy savings

- Determining possible capacity increases
- Investigating the influence of PEQM on energy consumption
Experimental investigation of pressure equalizing modules

Method of investigation

Requirements for PEQM

- Chemical resistance to R-1234ze(E) and oil-fumes
- Pressure resistant up to 10 bar$_a$
- Large volume change with little deflated volume
- Tightness to avoid leakages
- Easy handling in large quantities
- ...

Concept of hose module

![Diagram of hose module](image)
Experimental investigation of pressure equalizing modules

Method of investigation

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Investigated hose module

\[ d_{out}^{PEQM} = 32 \text{ mm} \]

\[ V_{inflated}^{PEQM} = \sim 174 \text{ ml} \]

\[ V_{deflated}^{PEQM} = \sim 106 \text{ ml} \]

\[ \Delta V_{change}^{PEQM} = \sim 68 \text{ ml} \]
Experimental investigation of pressure equalizing modules

Method of investigation

- low-pressure optical cell (LP-OC)
- V_{receiver} = 1.5 l

- PR
- T1
- T2
- P1

- PEQM
- sight glass

- blowing out to the environment
- flow direction
- ring system for flow control
- FCR
- F1

- MV2
- 3WB2

- MV1
- 3WB1

- 3WB:
- 3 way ball valve
- MV:
- magnetic valve
- SV:
- safety valve
- P1 & P2:
- pressure transmitter
- T1 & T2:
- T-type thermocouple
- F1:
- thermal mass flow controller

- N2
- nitrogen supply
Charging process with three PEQM

- Capacity of receiver can be increased
- Temperature change in PEQM causes shift of vapor pressure
- Volume of receiver is not fully utilized
- Decreasing pressure range
- Design changes are required to reduce deflated volume [1]

- Pressure range 4.5–5.5 bar
- Room temperature
- N₂ flow rate 0.27 l/min
- Three PEQM without PCM

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Investigation within isoSTOR\textsuperscript{Retrofit} - project

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- Understanding of processes inside PEQM
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Investigation of potential energy savings

- Determining possible capacity increases
- Investigating the influence of PEQM on energy consumption
Theoretical investigation of potential energy savings

Method

1. Measuring the energy consumption at a fixed air demand
   - Determining storage capacity for isochoric process

2. Determining theoretical number of PEQM
   - Determining storage capacity for cii-process
   - Determining new cycle frequency

3. Determining the operation times for cii-process
   - Determining the energy consumption for cii-process

- 4 kW rotary screw compressor
- Receiver volume: 250 l
- Storage volume: 253.2 l
- Dew point: 3 °C
- Measurement frequency: 20 Hz

[1] Specht: The best known packings of equal circles in a circle (complete up to N = 2600), accessed 11/02/2022
Results of isochoric process
Capacity and load ratio

- At the beginning of load mode:
  - Pressure: \( \bar{p}_1 = 7.63 \text{ bar}_a \), \( \sigma_{p1} \ll 0.01 \text{ bar}_a \)
  - Temperature: \( \bar{\vartheta}_1 = 23.58 \, ^\circ\text{C} \), \( \sigma_{\vartheta1} = 0.12 \, ^\circ\text{C} \)

- At the end of load mode
  - Pressure: \( \bar{p}_2 = 9.53 \text{ bar}_a \), \( \sigma_{p2} \ll 0.01 \text{ bar}_a \)
  - Temperature: \( \bar{\vartheta}_2 = 25.58 \, ^\circ\text{C} \), \( \sigma_{\vartheta2} = 0.14 \, ^\circ\text{C} \)

<table>
<thead>
<tr>
<th>Isochoric process</th>
<th>cii-process</th>
<th>change</th>
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<tbody>
<tr>
<td>Capacity</td>
<td>424 l(_n)</td>
<td></td>
</tr>
<tr>
<td>No. of cycles</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Load ratio</td>
<td>42.2 %</td>
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Diagram showing power consumption for the compressor over time.
Theoretical investigation of potential energy savings

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Isochoric and combined-isobaric-isochoric process

Capacity and load ratio

- At the beginning of load mode:
  - Pressure: $p_1 = 7.63 \, \text{bar}$, $\sigma_{p1} \ll 0.01 \, \text{bar}$
  - Temperature: $\theta_1 = 23.58 \, ^\circ\text{C}$, $\sigma_{\theta1} = 0.12 \, ^\circ\text{C}$

- At the end of load mode
  - Pressure: $p_2 = 9.53 \, \text{bar}$, $\sigma_{p2} \ll 0.01 \, \text{bar}$
  - Temperature: $\theta_2 = 25.58 \, ^\circ\text{C}$, $\sigma_{\theta2} = 0.14 \, ^\circ\text{C}$

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<td>Capacity</td>
<td>424 l</td>
<td>642 l</td>
</tr>
<tr>
<td>No. of cycles</td>
<td>20</td>
<td>12.6</td>
</tr>
<tr>
<td>Load ratio</td>
<td>42.2 %</td>
<td>50.6 %</td>
</tr>
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401 l isochoric receiver yields same capacity increase
Isochoric and combined-isobaric-isochoric process

Operation time and energy consumption

Operating times for each operation mode

- Isochoric process:
  - 20 cycles: 77.6 s/cycle, 35.3 s/cycle, 68.6 s/cycle, 2.4 s/cycle
- Cii-process:
  - 12.6 cycles: 123.1 s/cycle, 35.3 s/cycle, 82.3 s/cycle, 2.4 s/cycle

Total energy consumption for each operation mode

- Isochoric process:
  - 1830 Wh, 109 Wh, 648 Wh, 24 Wh
- Cii-process:
  - 1828 Wh, 69 Wh, 461 Wh, 15 Wh

-238 Wh (-9.1 %)

Switch-to-unload - Switch-to-load - Stop - Unloading - Loading - Stop

0 50 100 150 200 250 300
Time [s/cycle]

0 500 1000 1500 2000 2500 3000
Energy consumption [Wh]

Public information

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Isochoric and combined-isobaric-isochoric process

Operation time and energy consumption

- PEQM increases the capacity of the receiver by 58.5%
- Capacity increase results in lower cycling frequency and higher load ratio
- Compressor can be stopped
- Control of compressor can be improved
- Energy consumption can be reduced
Summary and future work

1. Concept of PEQM is suitable to increase the capacity of receiver

2. Heat management is essential for isobaric storage on a PCM\textsubscript{lg}-basis

3. PEQM improves control and energy consumption of compressor
Summary and future work

1. Concept of PEQM is suitable to increase the capacity of receiver

2. Heat management is essential for isobaric storage on a PCM/kg-basis

3. PEQM improves control and energy consumption of compressor

1. Investigation of the effects taking place inside the PEQM

2. Realizing a combined-isobar-isochoric compressed air receiver
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