Transcritical CO_2 Cycle Technology

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2002 SAE AUTOMOTIVE ALTERNATE REFRIGERANT SYSTEMS SYMPOSIUM
JULY 9-11 • SCOTTSDALE, ARIZONA

Outlines

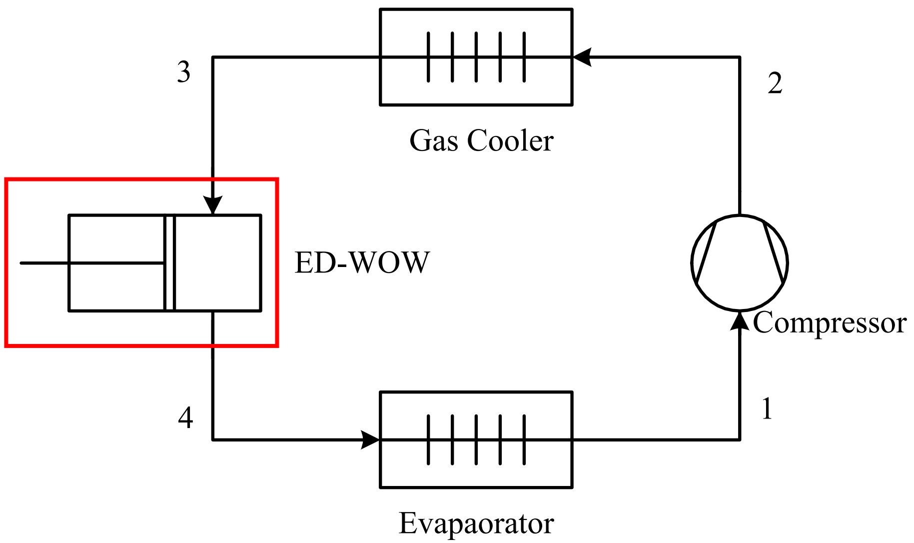
- Introduction and objective
- Design and construction of a work producing expansion device
- Experiments with the expansion device
- Suggestion of how to use the expansion device
- Conclusions
- Future work

1. Introduction and objective

- Why CO_2 as an alternative refrigerant?
  - Zero ozone depletion potential and negligible global warming potential
  - Non-toxic and non-flammable
  - Transcritical CO_2 cycle
- Advantage
  - Strong consideration of reduced weight and volume in package system
- Disadvantage
  - Poor system performance of transcritical CO_2 cycle

1. Introduction and objective (cont.)

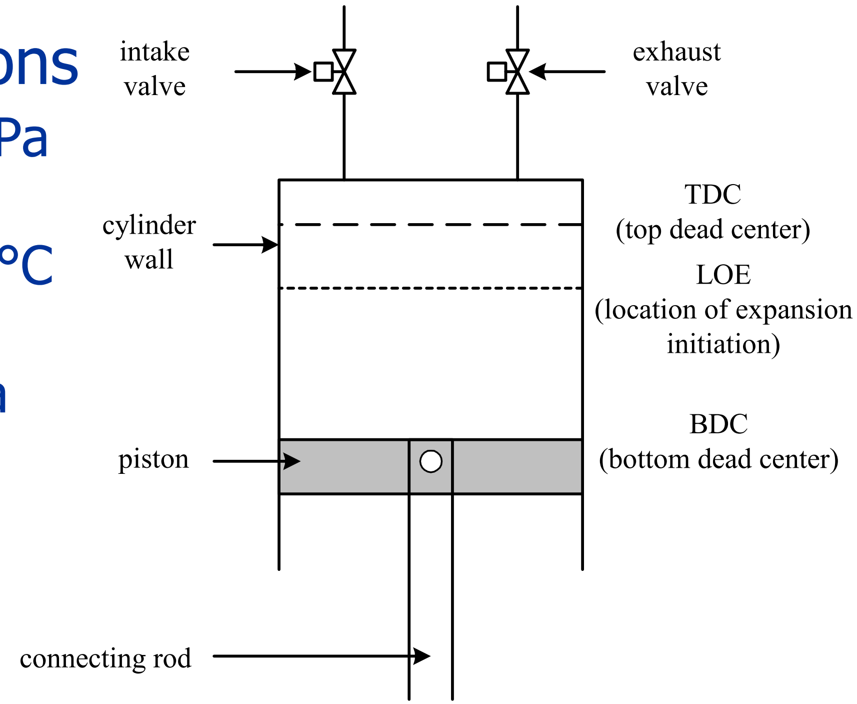
- Objective
  - To design, construct and test an expansion device with output work (ED-WOW)
- Why ED-WOW?
  - Extraction of work
    - Reduction of work input
  - Lower enthalpy at the inlet of the evaporator
    - Increase of evaporator capacity



Transcritical CO_2 cycle with ED-WOW.

2. Design and construction of a work producing expansion device

- Design of the ED-WOW
  - Desired operating conditions
    - High-side pressure: 10.3 MPa (1500 psig)
    - High-side temperature: 49 °C (120 °F)
    - Low-side pressure: 3.4 MPa (500 psig)
  - Type of the ED-WOW
    - Piston-cylinder assembly device
    - Controlled by solenoid valves.
      - 2 intake and 1 exhaust valves



Piston-cylinder device

2. Design and construction… (cont.)

- Based on a flat two-piston device with horizontally opposing cylinders
  - Using commercially available crank, crankshaft, connecting rod and pistons
  - Modification of crankshaft.
    - Out-of-phase firing order to reduce need for mechanical inertia (flywheel)

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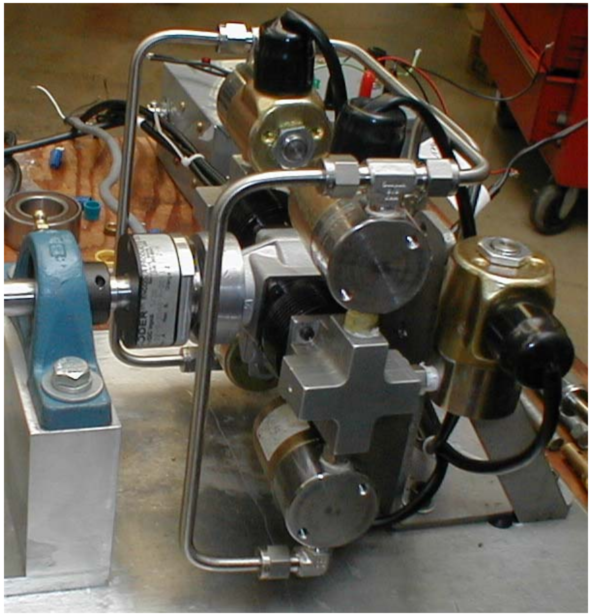
2. Design and construction… (cont.)

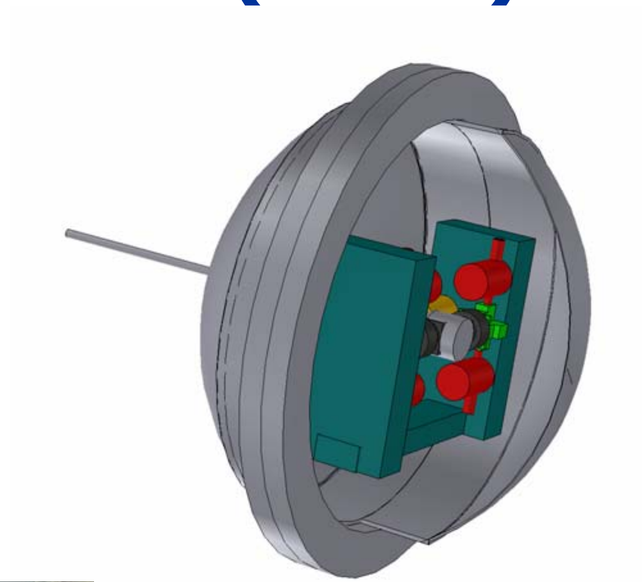
- Design of cylinder head
  - To attach solenoid valves to the expansion device
- Assembly of the ED-WOW

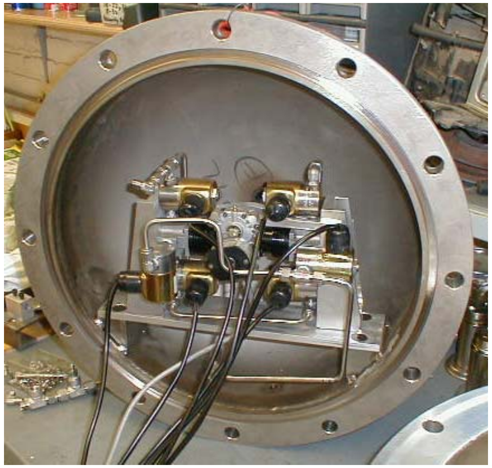


Fabricated cylinder head

2. Design and construction… (cont.)

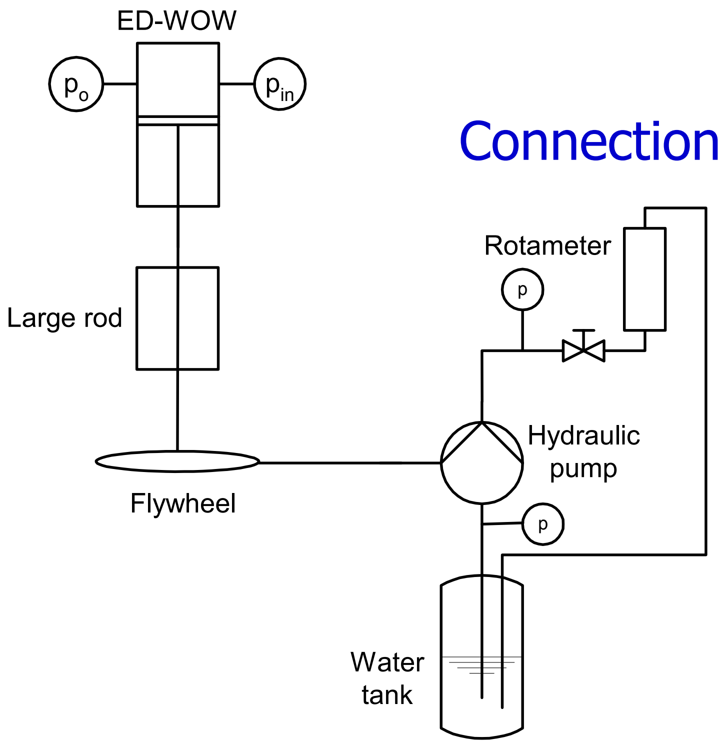
- Enclosure
  - High operating pressure (1500 psig)
  - Prevent CO_2 from leaking out of the system
  - Two domed caps with flanges





2. Design and construction... (cont.)

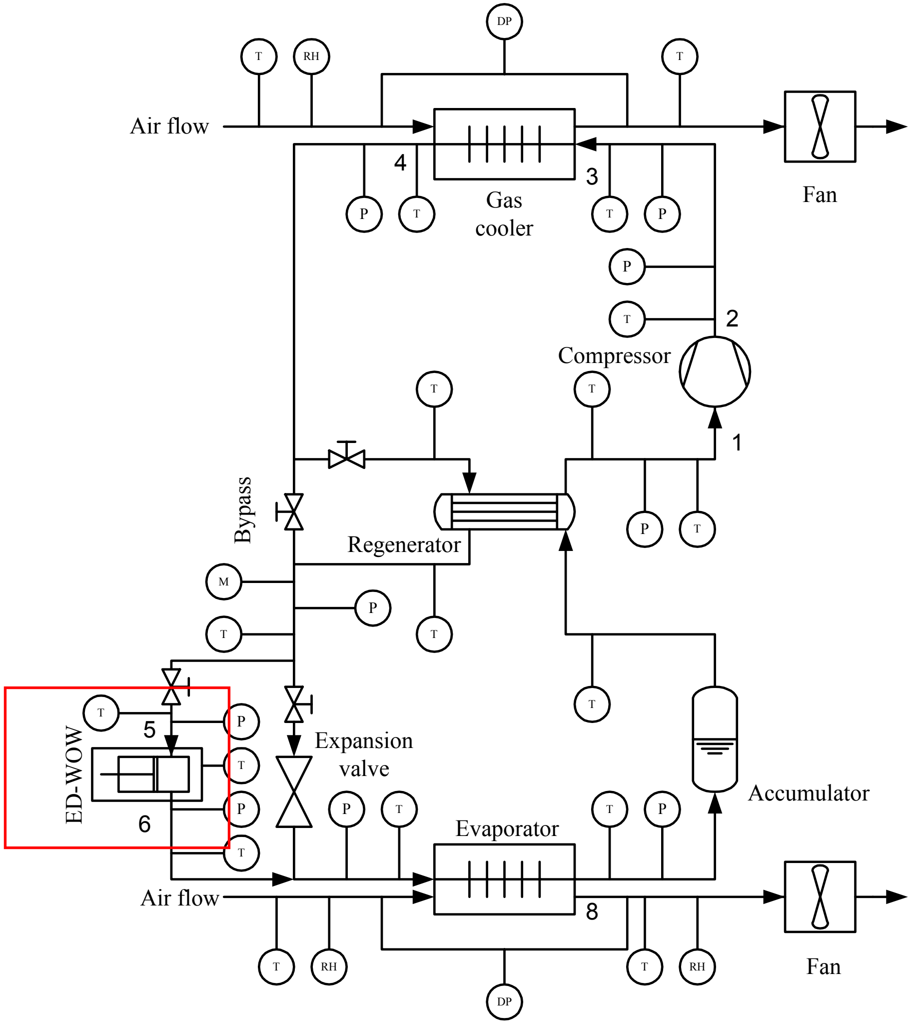
- Measurement of work output through the ED-WOW
  - Hydraulic pump connected to the ED-WOW
    - $P_{HD-Pump} = \Delta p \cdot \dot{Q}$



Connection of hydraulic pump

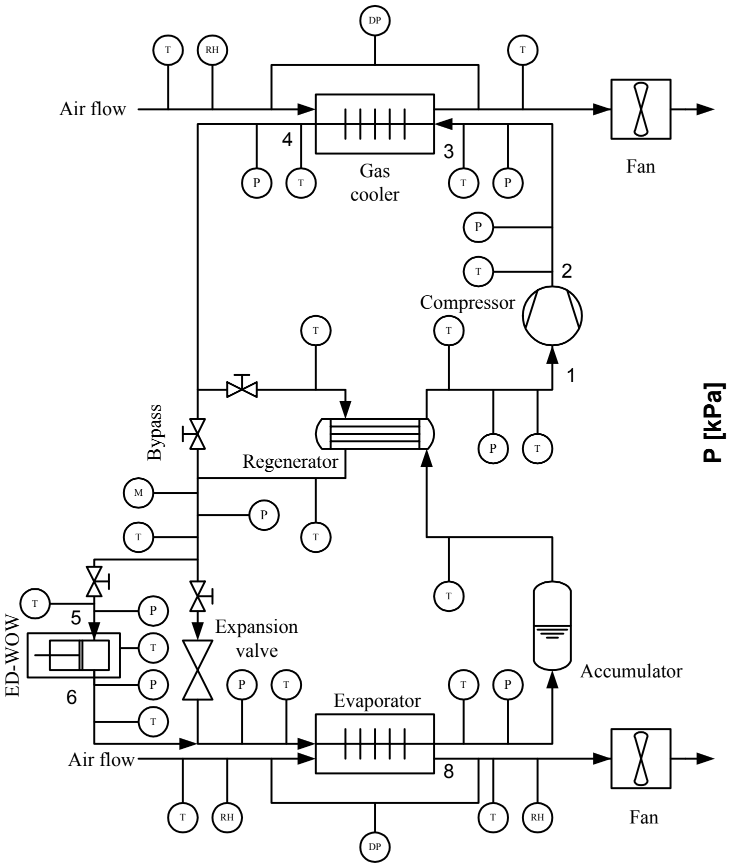
3. Experiments with the ED-WOW

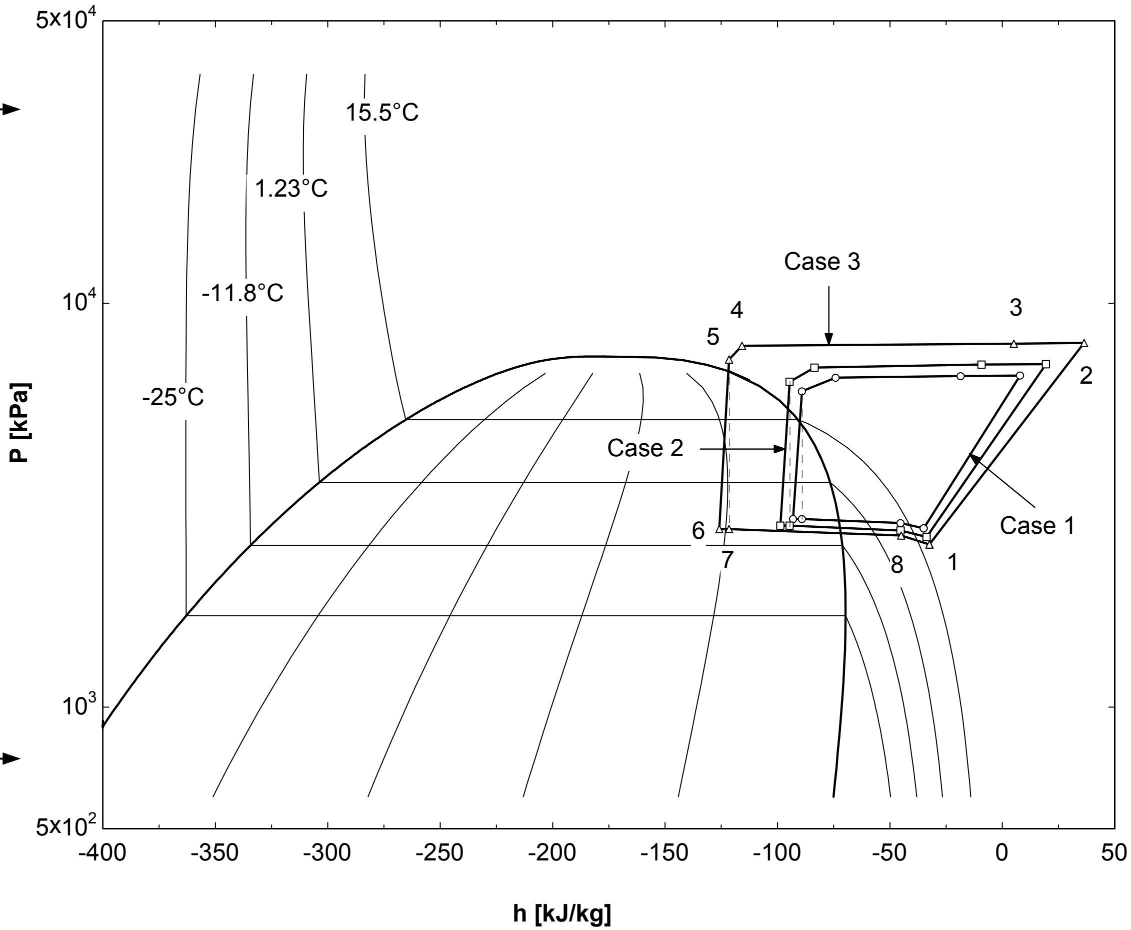
- System test
  - Incorporation of the ED-WOW into a prototype transcritical CO_2 cycle
  - Test conditions
    - Indoor temp. = 20°C
    - Outdoor temp. = 35°C
    - CO_2 mass flow rate
      - Case 1: 9.7 g/s
      - Case 2: 11.6 g/s
      - Case 3: 13.5 g/s



Prototype transcritical CO_2 cycle with ED-WOW.

3. Experiments… (cont.)





Experiment processes on p-h diagram

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3. Experiments… (cont.)

- Results of experiments with ED-WOW

Case	$P_{ED,in}$ (MPa)	$P_{ED,out}$ (MPa)	$T_{ED,in}$ (°C)	$T_{ED,out}$ (°C)	$\dot{Q}_{isen}$ (W)	$\dot{Q}_{ED}$ (W)	$\dot{W}_{comp}$ (W)	$\dot{W}_{ED}$ (W)	$\varepsilon_{ED,s}$ (%)
1	6.1	2.55	26.0	-9.6	425.6	448.7	567.6	23.18	10.5
2	6.4	2.48	27.9	-10.1	570.7	599.4	773.1	28.70	10.0
3	7.3	2.41	31.4	-11.3	1030	1064	1110	34.77	10.3

- COP improvements

Case	$\dot{Q}_{isen}$ (W)	$\dot{Q}_{ED}$ (W)	$\Delta\dot{Q}$ (%)	COP_{isen}	COP_{ED1}	ΔCOP_1 (%)	COP_{ED2}	ΔCOP_2 (%)
1	425.6	448.7	**5.4**	0.7498	0.7905	**5.4**	0.8242	**9.9**
2	570.7	599.4	**5.0**	0.7382	0.7753	**5.0**	0.8052	**9.1**
3	1030	1064	**3.3**	0.9277	0.9586	**3.3**	0.9896	**6.7**

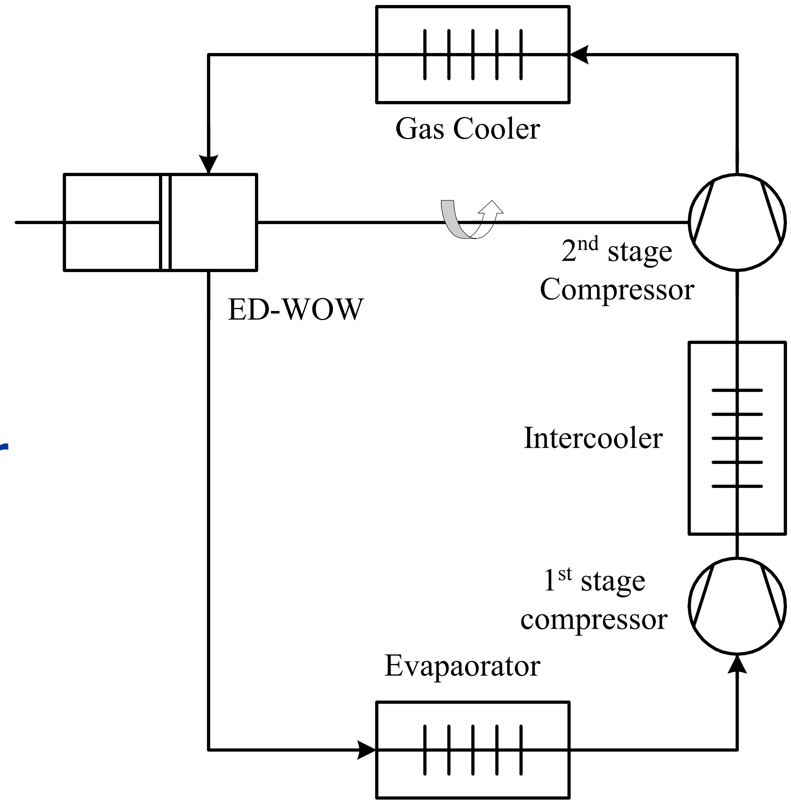
$$COP_{isen} = \frac{\dot{Q}_{isen}}{\dot{W}_{comp}}$$

$$COP_{ED1} = \frac{\dot{Q}_{ED}}{\dot{W}_{comp}}$$

$$COP_{ED2} = \frac{\dot{Q}_{ED}}{\dot{W}_{comp} - \dot{W}_{ED}}$$

4. Suggestion of how to use the expansion device

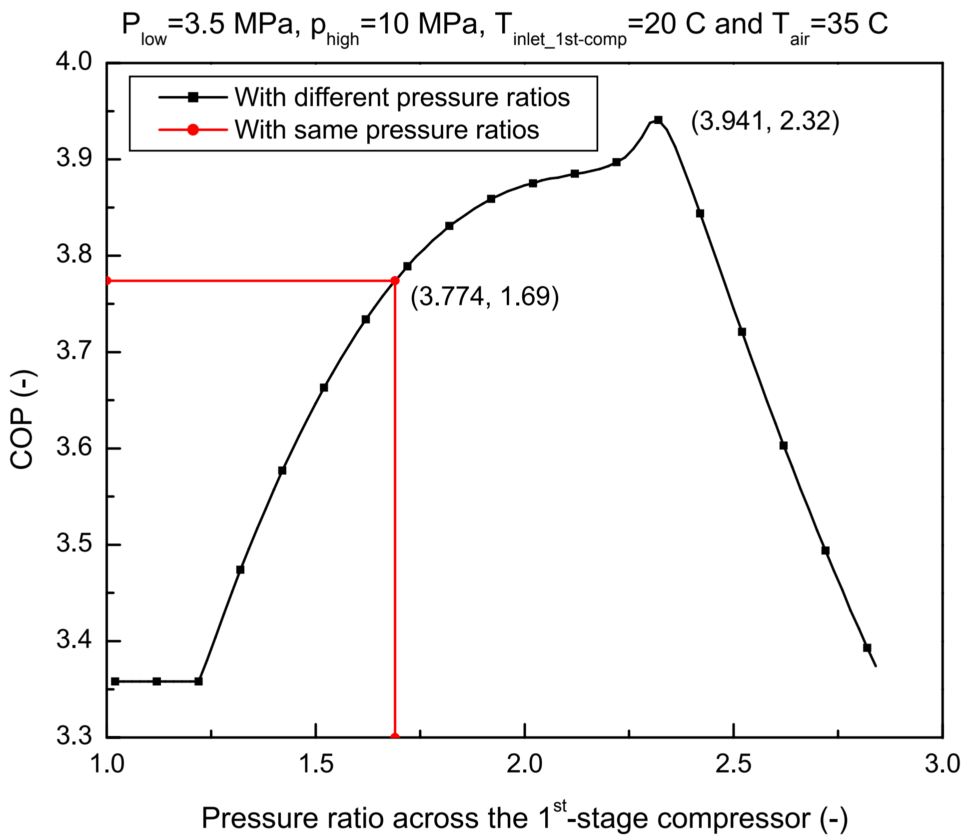
- CO_2 cycle with two-stage compression including intercooling
  - Different pressure ratios across the compressors should be considered for the maximum system performance during warm weather season
    - $pr1 \neq pr2$
  - Using the ED-WOW to run the 2nd-stage compressor



Two-compressor system (Intercooler cycle)

4. Suggestion… (cont.)

- Without using ED-WOW
  - With same p-ratios
    - COP = 3.774
    - P-ratio = 1.69
  - With different p-ratios
    - COP = 3.941
    - P_1-ratio = 2.32
    - P_2-ratio = 1.23
  - Maximum COP occurs at considerably large p_1-ratio compared to p_2-ratio



COP of Intercooler cycle with different pressure ratios across the compressors.

4. Suggestion… (cont.)

- Significant system improvements with ED-WOW
  - $T_{inlet\ of\ 1st\text{-}compressor}$ = 20°C, T_{air} = 35°C, and p_{high} = 10 MPa

Case	P_{low} (MPa)	COP[1] (Basic)	COP with expansion valve	Work –1 (kJ/kg)	Work-2 (kJ/kg)	$Work_{ED}$[2] (kJ/kg)	COP with ED-WOW	COP improve -ments (%)
1	2.5	2.432	2.765	63.153	3.698	**8.944**	3.081	**11.43 (26.7)**
2	3.0	2.868	3.241	50.211	3.698	**7.542**	3.714	**14.59 (29.5)**
3	3.5	3.358	3.774	39.969	3.576	**6.410**	4.454	**18.02 (32.6)**
4	4.0	3.917	4.381	31.202	3.835	**5.475**	5.414	**23.58 (38.2)**
5	4.5	4.565	5.081	24.197	3.698	**4.691**	6.563	**29.17 (43.8)**

Note: [1] COP of Basic cycle with one compressor and expansion valve
[2] Isentropic efficiency of 50%

5. Conclusions

- A work producing expansion device has been designed and constructed
  - Piston-cylinder assembly device
- Experiments have been conducted with the ED-WOW in a transcritical CO_2 cycle
  - Improvements of system performance: 6.7~9.9%
- Suggestion for the use of the ED-WOW to run the 2nd-stage compressor in a two-stage compression CO_2 cycle
  - Significant improvement of system efficiency up to 29% based on thermodynamic analysis

6. Future work

- Design optimization of ED-WOW
  - Improvement of piston ring reducing the leakage of CO_2
  - Increase of the rotational speed of the ED-WOW to reduce torque loading
  - A hermetically sealed expansion device should be constructed