Thermodynamics Problem S.65\* Carnot Cycle Analysis of CO<sub>2</sub>

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## **Problem Statement**

#### ENGR. S.65\*

A quantity of  $CO_2$  undergoes a Carnot cycle. **FIND:** Determine the work and heat transfer for each process, the thermal efficiency, and the pressures at the initial and final states of the isothermal compression.

## Schematic and Given Data

Schematic: (Refer to the

provided diagram showing a P-v or T-s diagram for the Carnot cycle)

Fluid: CO<sub>2</sub>

#### Given Data:

- ▶ *k* = 1.24
- $P_1 = 400 \, \text{lbf/in}^2$
- $P_2 = 200 \, \text{lbf/in}^2$
- $T_H = T_1 = T_2 = 910^{\circ} \text{R}$ (450°F)
- $T_L = T_3 = T_4 = 560^{\circ} \text{R}$ (100°F)

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## Assumptions

The system consists of a quantity of CO<sub>2</sub> modeled as an ideal gas with k = 1.24.

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- The cycle operates as a work mode cycle (power cycle).
- Processes are internally reversible.

# Summary Table of Results

#### Work and Heat Transfer per Unit Mass

Process	Q/m (Btu/lb)	W/m (Btu/lb)
1-2	28.46	28.46
2-3	0	65.80
3-4	-17.52	-17.52
4-1	0	-65.80
Cycle	10.94	10.94

## Process 1-2: Isothermal Expansion

#### **Description:**

• Reversible isothermal process ( $T = \text{constant} = T_H$ ).

- Expansion  $(v_2 > v_1)$ .
- Heat is added to the system.
- Work is done by the system.

First Law of Thermodynamics per unit mass:  $q_{12} - w_{12} = \Delta u_{12}$ For an ideal gas in an isothermal process, the internal energy

change is zero ( $\Delta u = c_v \Delta T = 0$ ). Therefore, the energy balance

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simplifies to:  $q_{12} = w_{12}$ 

### Process 1-2: Work Calculation

For a reversible process, the work done is given by  $w = \int P \, dv$ . For an ideal gas (Pv = RT) undergoing an isothermal process:

$$w_{12} = \int_{v_1}^{v_2} P \, dv = \int_{v_1}^{v_2} rac{RT_1}{v} \, dv = RT_1 \ln \left(rac{v_2}{v_1}
ight)$$
 Using the ideal gas

law for states 1 and 2 ( $P_1v_1 = RT_1$  and  $P_2v_2 = RT_1$ ), the volume ratio can be expressed in terms of pressures:  $\frac{v_2}{v_1} = \frac{P_1}{P_2}$  So, the work

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equation becomes:  $w_{12} = RT_H \ln \left(\frac{P_1}{P_2}\right)$ 

### Process 1-2: Calculation Details

Gas constant *R* for CO<sub>2</sub>: 
$$R = \frac{\bar{R}}{M_{CO_2}} \approx \frac{1545 \text{ ft}\cdot\text{lbf}/\text{lbmol}\cdot^{\circ}\text{R}}{44.01 \text{ lbm}/\text{lbmol}}$$
 Converting  
to Btu:  $R = \frac{1545}{44.01} \times \frac{1}{778} \frac{\text{Btu}}{\text{lbm}\cdot^{\circ}\text{R}} \approx 0.0450 \text{ Btu}/\text{lbm}\cdot^{\circ}\text{R}$   
 $w_{12} = (0.0450 \text{ Btu}/\text{lbm}\cdot^{\circ}\text{R}) \times (910^{\circ}\text{R}) \times \ln\left(\frac{400 \text{ lbf}/\text{in}^2}{200 \text{ lbf}/\text{in}^2}\right)$ 

 $w_{12} = 0.0450 \times 910 \times \ln(2) \text{ Btu/lbm } w_{12} \approx 28.46 \text{ Btu/lbm Since}$ 

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 $q_{12} = w_{12}$ :  $q_{12} \approx 28.46 \, \text{Btu/lbm}$ 

# Process 2-3: Isentropic Expansion

#### **Description:**

- Reversible adiabatic process (q = 0).
- Expansion  $(v_3 > v_2)$ .
- Temperature decreases from  $T_H$  to  $T_L$ .

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• Work is done by the system.

First Law of Thermodynamics per unit mass:  $q_{23} - w_{23} = \Delta u_{23}$ For an adiabatic process,  $q_{23} = 0$ . Therefore, the energy balance

is: 
$$-w_{23} = \Delta u_{23} = c_v (T_3 - T_2) w_{23} = c_v (T_2 - T_3)$$

For an ideal gas, the specific heat at constant volume  $(c_v)$  is related to the gas constant (R) and the specific heat ratio (k) by the equation:  $c_v = \frac{R}{k-1}$  Using  $R \approx 0.0450$  Btu/lbm ·° R and

$$\begin{array}{l} k = 1.24: \ c_{\nu} = \frac{0.0450 \ \text{Btu/lbm}^{.\circ} \text{R}}{1.24 - 1} \ c_{\nu} = \frac{0.0450}{0.24} \ \text{Btu/lbm} \cdot^{\circ} \text{R} \\ c_{\nu} \approx 0.188 \ \text{Btu/lbm} \cdot^{\circ} \text{R} \end{array}$$

### Process 2-3: Work Calculation Details

 $w_{23} = c_v (T_2 - T_3) w_{23} = (0.188 \text{ Btu/lbm} \cdot^{\circ} \text{R}) \times (910^{\circ} \text{R} - 560^{\circ} \text{R})$  $w_{23} = 0.188 \times 350 \text{ Btu/lbm} w_{23} \approx 65.80 \text{ Btu/lbm} q_{23} = 0$ 

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# Process 3-4: Isothermal Compression

#### **Description:**

• Reversible isothermal process ( $T = \text{constant} = T_L$ ).

- Compression ( $v_4 < v_3$ ).
- Heat is rejected by the system.
- Work is done on the system.

First Law of Thermodynamics per unit mass:  $q_{34} - w_{34} = \Delta u_{34}$ For an ideal gas in an isothermal process,  $\Delta u_{34} = 0$ . Therefore:

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 $q_{34} = w_{34}$ 

#### Process 3-4: Work Calculation

For a reversible isothermal process:  $w_{34} = \int_{v_3}^{v_4} P \, dv = RT_3 \ln \left(\frac{v_4}{v_3}\right)$ Using the ideal gas law  $(P_3v_3 = RT_3 \text{ and } P_4v_4 = RT_3)$ :  $\frac{v_4}{v_3} = \frac{P_3}{P_4}$ 

So, the work equation is:  $w_{34} = RT_L \ln \left(\frac{P_3}{P_4}\right)$  To calculate this, we

first need the pressures  $P_3$  and  $P_4$ .

State 3 is the end of the isentropic expansion (Process 2-3). For

an isentropic process of an ideal gas, the temperature and pressure are related by:  $\frac{T_3}{T_2} = \left(\frac{P_3}{P_2}\right)^{(k-1)/k}$  We know  $T_3$ ,  $T_2$ , and  $P_2$ . We

can solve for  $P_3$ .

### Calculation of Pressure $P_3$ Details

From the isentropic relation: 
$$\left(\frac{P_3}{P_2}\right)^{(k-1)/k} = \frac{T_3}{T_2}$$
  
 $P_3 = P_2 \left(\frac{T_3}{T_2}\right)^{k/(k-1)} P_3 = (200 \, \text{lbf/in}^2) \times \left(\frac{560^{\circ} \text{R}}{910^{\circ} \text{R}}\right)^{1.24/(1.24-1)}$ 

 $\begin{array}{l} P_3 = 200 \times \left(\frac{560}{910}\right)^{1.24/0.24} \ P_3 \approx 200 \times (0.61538)^{5.1667} \\ P_3 \approx 200 \times 0.08138 \ P_3 \approx 16.28 \ \text{lbf/in}^2 \end{array}$ 

State 4 is the end of the isothermal compression (Process 3-4) and the start of the isentropic compression (Process 4-1). For the

isentropic compression process 4-1, the temperature and pressure are related by:  $\frac{T_1}{T_4} = \left(\frac{P_1}{P_4}\right)^{(k-1)/k}$  We know  $T_1$ ,  $T_4$ , and  $P_1$ . We

can solve for  $P_4$ .

An isentropic process is a reversible adiabatic process (dS = 0 and dQ = 0). For a simple compressible system undergoing a reversible

process, the combined First and Second Laws of Thermodynamics can be written as: T dS = dU + P dV (per unit mass) or T ds = du + P dv

# Derivation of Isentropic Relation (1)

For an isentropic process, ds = 0. So, the relation becomes:

0 = du + P dv du = -P dv For an ideal gas,  $du = c_v dT$ .

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 $c_v dT = -P dv$ 

## Derivation of Isentropic Relation (2)

Using the ideal gas equation of state, Pv = RT, we can express P in terms of T and v:  $P = \frac{RT}{v}$  Substitute this into the previous

equation:  $c_v dT = -\frac{RT}{v} dv$  Rearrange the terms to separate

variables:  $\frac{c_v}{T} dT = -\frac{R}{v} dv$ 

## Derivation of Isentropic Relation (3)

Integrate both sides from state 1 to state 2 (or any two states in the isentropic process):  $\int_1^2 \frac{c_v}{T} dT = -\int_1^2 \frac{R}{v} dv$  Assuming  $c_v$  and R

are constant (ideal gas with constant specific heats):  

$$c_{\nu} \int_{1}^{2} \frac{1}{T} dT = -R \int_{1}^{2} \frac{1}{\nu} d\nu \ c_{\nu} \ln \left(\frac{T_{2}}{T_{1}}\right) = -R \ln \left(\frac{\nu_{2}}{\nu_{1}}\right)$$

$$c_{\nu} \ln \left(\frac{T_{2}}{T_{1}}\right) = R \ln \left(\frac{\nu_{1}}{\nu_{2}}\right)$$

## Derivation of Isentropic Relation (4)

Exponentiate both sides: 
$$\left(\frac{T_2}{T_1}\right)^{c_v} = \left(\frac{v_1}{v_2}\right)^R$$
 Using the properties of

logarithms, 
$$\ln(a^b) = b \ln(a)$$
:  $\ln\left(\left(\frac{T_2}{T_1}\right)^{c_v}\right) = \ln\left(\left(\frac{v_1}{v_2}\right)^R\right)$ 

 $c_v \ln\left(\frac{T_2}{T_1}\right) = R \ln\left(\frac{v_1}{v_2}\right)$  (This is the same as the last step on the previous slide - let's move to simplifying the exponent).

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### Derivation of Isentropic Relation (5)

Recall the relationships for ideal gases:  $R = c_p - c_v \ k = \frac{c_p}{c_v}$  From

these, we can write  $R = kc_v - c_v = c_v(k-1)$ . So,  $\frac{R}{c_v} = k - 1$ . Substitute this into the logarithmic equation from the previous

step: 
$$\ln\left(\frac{T_2}{T_1}\right) = \frac{R}{c_v} \ln\left(\frac{v_1}{v_2}\right) \ln\left(\frac{T_2}{T_1}\right) = (k-1) \ln\left(\frac{v_1}{v_2}\right)$$
  
 $\ln\left(\frac{T_2}{T_1}\right) = \ln\left(\left(\frac{v_1}{v_2}\right)^{k-1}\right)$  Exponentiating gives the T-v relation:

$$rac{T_2}{T_1} = \left(rac{v_1}{v_2}
ight)^{k-1}$$
 or  $T_2 v_2^{k-1} = T_1 v_1^{k-1}$ 

### Derivation of Isentropic Relation (6)

To get the P-T relation, we can use the ideal gas law to substitute for the volume ratio:  $\frac{v_1}{v_2} = \frac{RT_1/P_1}{RT_2/P_2} = \frac{T_1P_2}{T_2P_1}$  Substitute this into the

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T-v relation: 
$$\frac{T_2}{T_1} = \left(\frac{T_1P_2}{T_2P_1}\right)^{k-1} \frac{T_2}{T_1} = \left(\frac{T_1}{T_2}\right)^{k-1} \left(\frac{P_2}{P_1}\right)^{k-1} \\ \left(\frac{T_2}{T_1}\right)^1 = \left(\frac{T_2}{T_1}\right)^{-(k-1)} \left(\frac{P_2}{P_1}\right)^{k-1} \left(\frac{T_2}{T_1}\right)^{1+(k-1)} = \left(\frac{P_2}{P_1}\right)^{k-1} \\ \left(\frac{T_2}{T_1}\right)^k = \left(\frac{P_2}{P_1}\right)^{k-1} \\ \text{Taking the } k\text{-th root of both sides:}$$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(k-1)/k} \text{ Or, equivalently: } \frac{T_1}{T_2} = \left(\frac{P_1}{P_2}\right)^{(k-1)/k}$$

## Applying the Isentropic Relation

We use this relation for the isentropic processes 2-3 and 4-1. For

Process 2-3 (State  $1 \rightarrow 2$  in the derivation becomes State  $2 \rightarrow 3$ ):  $\frac{T_3}{T_2} = \left(\frac{P_3}{P_2}\right)^{(k-1)/k}$  This is used to calculate  $P_3$ . For Process 4-1

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(State 1  $\rightarrow$  2 in the derivation becomes State 4  $\rightarrow$  1):  $\frac{T_1}{T_4} = \left(\frac{P_1}{P_4}\right)^{(k-1)/k}$ This is used to calculate  $P_4$ .

#### Calculation of Pressure $P_4$ Details

From the isentropic relation for Process 4-1:  $\frac{T_1}{T_4} = \left(\frac{P_1}{P_4}\right)^{(k-1)/k}$ Rearranging to solve for  $P_4$ :  $\left(\frac{P_1}{P_4}\right) = \left(\frac{T_1}{T_4}\right)^{k/(k-1)}$ 

$$\frac{P_4}{P_1} = \left(\frac{T_4}{T_1}\right)^{k/(k-1)} P_4 = P_1 \left(\frac{T_4}{T_1}\right)^{k/(k-1)} \\
P_4 = (400 \, \text{lbf/in}^2) \times \left(\frac{560^{\circ} \text{R}}{910^{\circ} \text{R}}\right)^{1.24/(1.24-1)} P_4 = 400 \times \left(\frac{560}{910}\right)^{1.24/0.24}$$

 $P_4 \approx 400 \times (0.61538)^{5.1667}$   $P_4 \approx 400 \times 0.08138$   $P_4 \approx 32.55$  lbf/in<sup>2</sup>

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### Process 3-4: Work Calculation Details

Now we can calculate the work using 
$$P_3$$
 and  $P_4$ :  
 $w_{34} = RT_L \ln \left(\frac{P_3}{P_4}\right)$   
 $w_{34} = (0.0450 \text{ Btu/lbm} \cdot^{\circ} \text{ R}) \times (560^{\circ} \text{ R}) \times \ln \left(\frac{16.28 \text{ lbf/in}^2}{32.55 \text{ lbf/in}^2}\right)$ 

 $w_{34} \approx 0.0450 \times 560 \times \ln(0.500) \ w_{34} \approx 0.0450 \times 560 \times (-0.6931) \ w_{34} \approx -17.52 \ \text{Btu/Ibm}$  Since  $q_{34} = w_{34}$ :  $q_{34} \approx -17.52 \ \text{Btu/Ibm}$ 

# Process 4-1: Isentropic Compression

#### **Description:**

- Reversible adiabatic process (q = 0).
- Compression  $(v_1 < v_4)$ .
- Temperature increases from  $T_L$  to  $T_H$ .

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• Work is done on the system.

First Law of Thermodynamics per unit mass:  $q_{41} - w_{41} = \Delta u_{41}$ For an adiabatic process,  $q_{41} = 0$ . Therefore:

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$$-w_{41} = \Delta u_{41} = c_{\nu}(T_1 - T_4) \ w_{41} = c_{\nu}(T_4 - T_1)$$

## Process 4-1: Work Calculation Details

Using  $c_v \approx 0.188 \text{ Btu/lbm} \cdot^{\circ} \text{R}$ :  $w_{41} = (0.188 \text{ Btu/lbm} \cdot^{\circ} \text{R}) \times (560^{\circ} \text{R} - 910^{\circ} \text{R})$  $w_{41} = 0.188 \times (-350) \text{ Btu/lbm} w_{41} \approx -65.80 \text{ Btu/lbm} q_{41} = 0$ 

For any thermodynamic cycle, the net heat transfer must equal the net work transfer according to the First Law of Thermodynamics.  $Q_{cycle} = \sum Q_i \ W_{cycle} = \sum W_i$  We should verify that

$$Q_{cycle} = W_{cycle}.$$

# Cycle Work and Heat Check Details

Net Heat Transfer: 
$$Q_{cycle}/m = q_{12} + q_{23} + q_{34} + q_{41}$$
  
 $Q_{cycle}/m = 28.46 + 0 + (-17.52) + 0 \text{ Btu/Ibm}$   
 $Q_{cycle}/m = 10.94 \text{ Btu/Ibm}$  Net Work Transfer:

$$W_{cycle}/m = w_{12} + w_{23} + w_{34} + w_{41}$$
  
 $W_{cycle}/m = 28.46 + 65.80 + (-17.52) + (-65.80) \text{Btu/lbm}$   
 $W_{cycle}/m = 10.94 \text{Btu/lbm} \ Q_{cycle}/m = W_{cycle}/m$ , confirming the

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calculations.

**Definition:** The thermal efficiency  $(\eta)$  of a heat engine is the ratio of the net work output to the total heat input.  $\eta = \frac{W_{cycle}}{Q_{in}}$  In this

cycle, heat is only input during the isothermal expansion (Process 1-2), so  $Q_{in} = Q_{12}$ .

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# Thermal Efficiency Calculation

Using the calculated cycle work and heat input:  $\eta = \frac{10.94 \text{ Btu/lbm}}{28.46 \text{ Btu/lbm}}$  $\eta \approx 0.384 \text{ Expressed as a percentage: } \eta \approx 38.4\%$ 

# Thermal Efficiency (Carnot Cycle)

For any reversible heat engine operating between two thermal reservoirs at temperatures  $T_H$  (hot) and  $T_L$  (cold), the thermal efficiency is given by the Carnot efficiency formula:  $\eta = 1 - \frac{T_L}{T_H}$ 

Where temperatures must be in absolute units (Rankine or Kelvin).

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# Thermal Efficiency Calculation (Carnot Formula)

Using the given reservoir temperatures:  $T_H = 910^{\circ} R \ T_L = 560^{\circ} R \ \eta = 1 - \frac{560^{\circ} R}{910^{\circ} R} \ \eta = 1 - 0.61538... \ \eta \approx 0.3846 \ \text{Expressed}$  as a

percentage:  $\eta \approx 38.5\%$  This result is consistent with the efficiency

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calculated from work and heat.

### Pressures at Each State

The pressures at the initial and final states of the isothermal compression (Process 3-4) are  $P_3$  and  $P_4$ . We have calculated

these values:

- $\blacktriangleright$   $P_3 \approx 16.28 \, \text{lbf/in}^2$
- $\blacktriangleright P_4 \approx 32.55 \, \mathrm{lbf/in}^2$

For completeness, the pressures at all states are:

# Conclusion

We have performed a detailed thermodynamic analysis of a Carnot cycle operating with  $CO_2$ . Key findings include:

- Work and heat transfer for each process of the cycle.
- A thermal efficiency of approximately 38.4%, which matches the theoretical Carnot efficiency.
- The pressures at all states of the cycle, including P<sub>3</sub> and P<sub>4</sub> for the isothermal compression.

The results demonstrate the application of the First Law of Thermodynamics and ideal gas relations to analyze a reversible power cycle.