Introduction to Aerospace Propulsion

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Lecture No - 20

In this lecture ...

- Solve numerical problems
  - Gas power cycles: Otto, Diesel, dual cycles
  - Gas power cycles: Brayton cycle, variants of Brayton cycle
  - Thermodynamic property relations

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Problem 1

- In an air standard Otto cycle, the compression ratio is 7 and the compression begins at 35^{o}C and 0.1 MPa. The maximum temperature of the cycle is 1100^{o}C. Find (a) the temperature and the pressure at various points in the cycle, (b) the heat supplied per kg of air, (c) work done per kg of air, (d) the cycle efficiency and (e) the MEP of the cycle.

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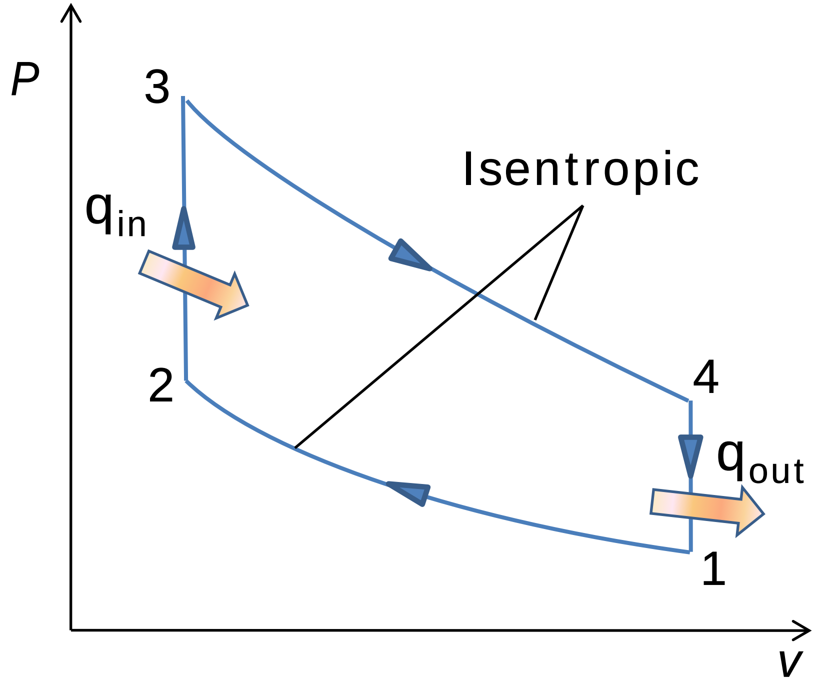
Solution: Problem 1



$T_1 = 35^oC = 308\ K$

$P_1 = 0.1\ Mpa$

$T_3 = 1100^oC = 1373\ K$

$r = v_1/v_2 = 7$

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Solution: Problem 1

- Since process, 1-2 is isentropic,

$$\frac{P_2}{P_1}=\left(\frac{v_1}{v_2}\right)^{\gamma}=7^{1.4}=15.24$$

- Hence, P_2=1524 kPa

$$\frac{T_2}{T_1}=\left(\frac{v_1}{v_2}\right)^{\gamma-1}=7^{1.4-1}=2.178$$

- Hence, T_2=670.8 K

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Solution: Problem 1

- For process, 2-3,

$$\frac{P_2 v_2}{T_2} = \frac{P_3 v_3}{T_3}, \ \therefore P_3 = \frac{T_3}{T_2} P_2 = \frac{1373}{607.8} \times 1524 = 3119.34$$

- $P_3 = 3119.34$ kPa.
- Process 3-4 is again isentropic,

$$\frac{T_3}{T_4} = \left(\frac{v_4}{v_3}\right)^{\gamma - 1} = 7^{1.4-1} = 2.178$$

$$\therefore T_4 = \frac{1373}{2.178} = 630.39\,\mathrm{K}$$

- Hence, $T_2 = 630.39$ K

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Solution: Problem 1

- Heat input,

$$Q_{in}=c_v(T_3-T_2)$$
$$=0.718(1373–670.8)$$
$$=504.18\ kJ/kg$$

- Heat rejected,

$$Q_{out}=c_v(T_4-T_1)$$
$$=0.718(630.34–308)$$
$$=231.44\ kJ/kg$$

- The net work output, $W_{net}=Q_{in}-Q_{out}$

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Solution: Problem 1

- The net work output,

$$W_{net} = Q_{in} - Q_{out}$$
$$= 272.74 \text{ kJ/kg}$$

- Thermal efficiency, $\eta_{th,otto} = W_{net}/Q_{in}$

$$= 0.54$$
$$= 54\ \%$$

- Otto cycle thermal efficiency,

$$\eta_{th,otto} = 1 - 1/r^{\gamma-1} = 1 - 1/7^{0.4}$$
$$= 0.54 \text{ or } 54\ \%$$

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Solution: Problem 1

- $v_1 = RT_1/P_1$

  $= 0.287 \times 308/100 = 0.844\ m^3/kg$

- $MEP = W_{net}/(v_1 - v_2) = 272.74/v_1\,(1-1/r)$

  $= 272.74/0.844(1-1/7)$

  $=$ 360 kPa

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Problem 2

- In a Diesel cycle, the compression ratio is 15. Compression begins at 0.1 Mpa, 40^{o}C. The heat added is 1.675 MJ/kg. Find (a) the maximum temperature in the cycle, (b) work done per kg of air (c) the cycle efficiency (d) the temperature at the end of the isentropic expansion (e) the cut-off ratio and (f) the MEP of the cycle.

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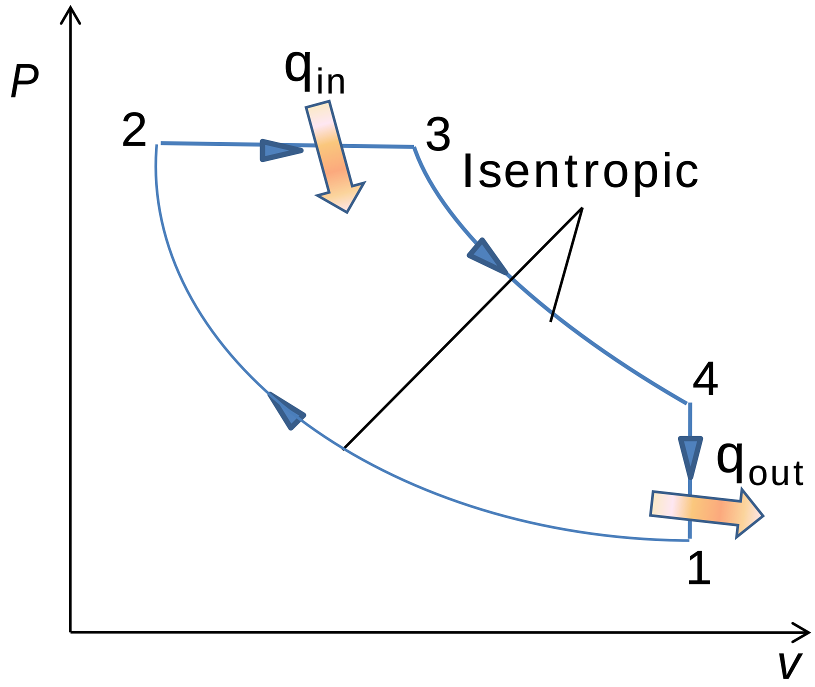
Solution: Problem 2



$T_1 = 40^oC = 313\ K$
$P_1 = 0.1\ Mpa$
$Q_{in} = 1675\ MJ/kg$
$r = v_1/v_2 = 15$

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Solution: Problem 2

$$v_1 = \frac{RT_1}{P_1} = \frac{0.287 \times 313}{100} = 0.898\,\mathrm{m^3/kg}$$

$$v_2 = v_1/15 = 0.898/15 = 0.06\,\mathrm{m^3/kg}$$

- It is given that Q_{in} = 1675 MJ/kg

$$Q_{in} = c_p(T_3 - T_2)$$

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma-1} = 15^{0.4} = 2.954$$

$$T_2 = 313 \times 2.954 = 924.66\,\mathrm{K}$$

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Solution: Problem 2

$$Q_{in} = 1675 = 1.005(T_3 - 924.66)$$

$$\therefore T_3 = 2591.33 \text{ K} = T_{\max}$$

- Hence, the maximum temperature is 2591.33 K

$$\frac{P_2}{P_1} = \left(\frac{v_1}{v_2}\right)^{\gamma} = 15^{1.4} = 44.31$$

$$\therefore P_2 = 4431 \text{kPa}$$

$$\frac{P_2 v_2}{T_2} = \frac{P_3 v_3}{T_3} \rightarrow v_3 = \frac{T_3}{T_2} v_2 = \frac{2591.33}{924.66} \times 0.06 = 0.168 \, \text{m}^3/\text{kg}$$

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Solution: Problem 2

$$r_c = \frac{v_3}{v_2} = \frac{0.168}{0.06} = 2.8$$

- The cut-off ratio is 2.8.

$$T_4 = T_3\left(\frac{v_3}{v_4}\right)^{\gamma-1} = 2591.33\times\left(\frac{0.168}{0.898}\right)^{0.4}$$

$$= 1325.37\,\mathrm{K}$$

$$\mathrm{Q_{out}} = c_v(T_4 - T_1) = 0.718(1325.4 - 313) = 726.88\,\mathrm{kJ/kg}$$

$$\text{Net work done}, W_{net} = Q_{in} - Q_{out} = 1675 - 726.88$$

$$= 948.12\ \mathrm{kJ/kg}$$

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Solution: Problem 2

- Therefore, thermal efficiency,

$$\eta_{th} = W_{net}/Q_{in}$$
$$= 948.12/1675 = 0.566 \text{ or } 56.6\%$$

- The cycle efficiency can also be calculated using the Diesel cycle efficiency determined earlier.

$$MEP = \frac{W_{net}}{v_1 - v_2} = \frac{948.12}{0.898 - 0.06} = 1131.4\,\text{kPa}$$

- The mean effective pressure is 1131. 4 Kpa.

Problem 3

- An air-standard Ericsson cycle has an ideal regenerator. Heat is supplied at 1000°C and heat is rejected at 20°C. If the heat added is 600 kJ/kg, find the compressor work, the turbine work, and the cycle efficiency.

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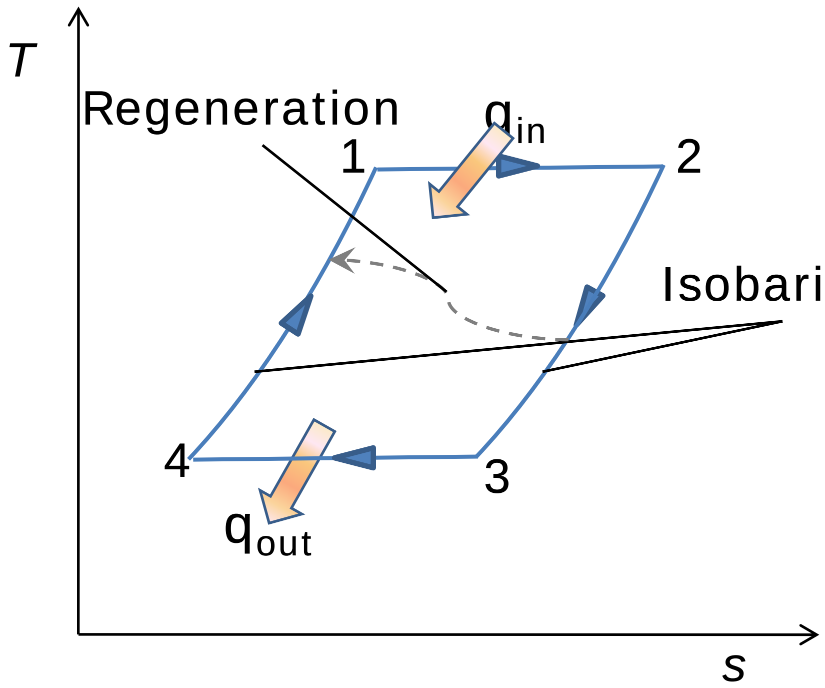
Solution: Problem 3



$T_1 = T_2 = 1000°C = 1273.15$ K
$T_3 = T_4 = 20°C = 293.15$ K

Solution: Problem 3

- Since the regenerator is given as ideal,

$$-Q_{2\text{-}3} = Q_{1\text{-}4}$$

- Also in an Ericsson cycle, the heat is input during the isothermal expansion process, which is the turbine part of the cycle. Hence the turbine work is 600 kJ/kg.

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Solution: Problem 3

- Thermal efficiency of an Ericsson cycle is equal to the Carnot efficiency.

$$\eta_{th} = \eta_{th,\ Carnot} = 1 - T_L/T_H$$
$$= 1 - 293.15/1273.15$$
$$= 0.7697$$

- Therefore the net work output is equal to:

$$w_{net} = \eta_{th} Q_H$$
$$= 0.7697 \times 600 = 461.82\ kJ/kg$$

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Solution: Problem 3

- The compressor work is equal to the difference between the turbine work and the net work output:

$$w_c = w_t - w_{net}$$
$$= 600 - 461.82 = 138.2 \text{ kJ/kg}$$

- In the Ericsson cycle the heat is rejected isothermally during the compression process. Therefore this compressor work is also equal to the heat rejected during the cycle.

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Problem 4

- In a Brayton cycle based power plant, the air at the inlet is at 27^{o}C, 0.1 MPa. The pressure ratio is 6.25 and the maximum temperature is 800^{o}C. Find (a) the compressor work per kg of air (b) the turbine work per kg or air (c) the heat supplied per kg of air, and (d) the cycle efficiency.

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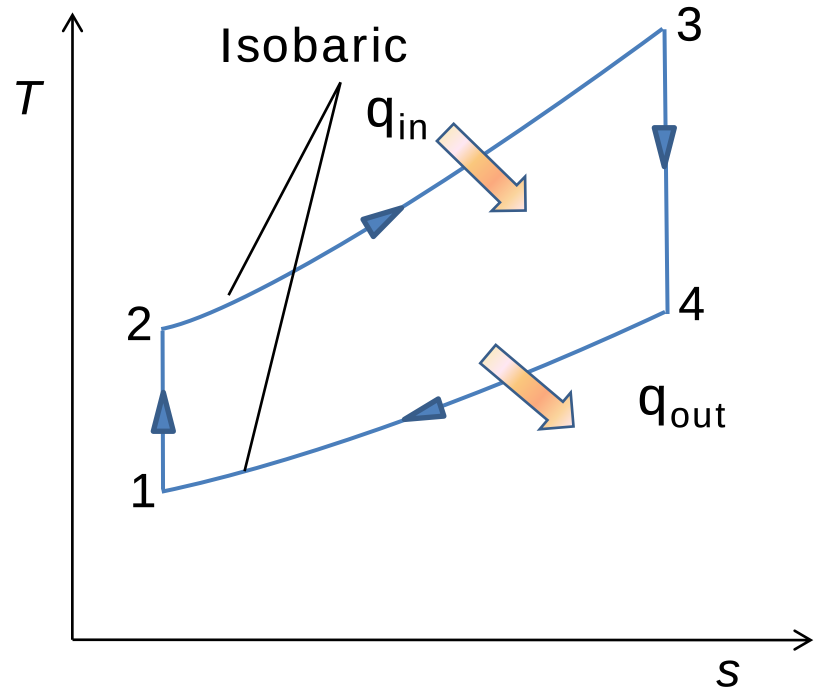
Solution: Problem 4



$T_1 = 27°C = 300\ K$
$P_1 = 100\ kPa$
$r_p = 6.25$
$T_3 = 800°C = 1073\ K$

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Solution: Problem 4

- Since process, 1-2 is isentropic,

$$\frac{T_2}{T_1} = r_p^{(\gamma-1)/\gamma} = 6.25^{(1.4-1)/1.4} = 1.689$$

$$T_2 = 506.69\,\mathrm{K}$$

$$W_{comp} = c_p(T_2 - T_1) = 1.005(506.69 - 300)$$

$$= 207.72\,\mathrm{kJ/kg}$$

- The compressor work per unit kg of air is 207.72 kJ/kg

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Solution: Problem 4

- Process 3-4 is also isentropic,

$$\frac{T_3}{T_4} = r_p^{(\gamma-1)/\gamma} = 6.25^{(1.4-1)/1.4} = 1.689$$

$$T_4 = 635.29\ \text{K}$$

$$W_{turb} = c_p(T_3 - T_4) = 1.005(1073 - 635.29)$$

$$= 439.89\ \text{kJ/kg}$$

- The turbine work per unit kg of air is 439.89 kJ/kg

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Solution: Problem 3

- Heat input, Q_{in},

$$Q_{in} = c_p(T_3 - T_2) = 1.005(1073 - 506.69)$$
$$= 569.14 \text{ kJ/kg}$$

- Heat input per kg of air is 569.14 kJ/kg
- Cycle efficiency,

$$\eta_{th} = (W_{turb} - W_{comp})/Q_{in}$$
$$= (439.89 - 207.72)/569.14$$
$$= 0.408 \text{ or } 40.8\%$$

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Problem 5

- Solve Problem 3 if a regenerator of 75% effectiveness is added to the plant.

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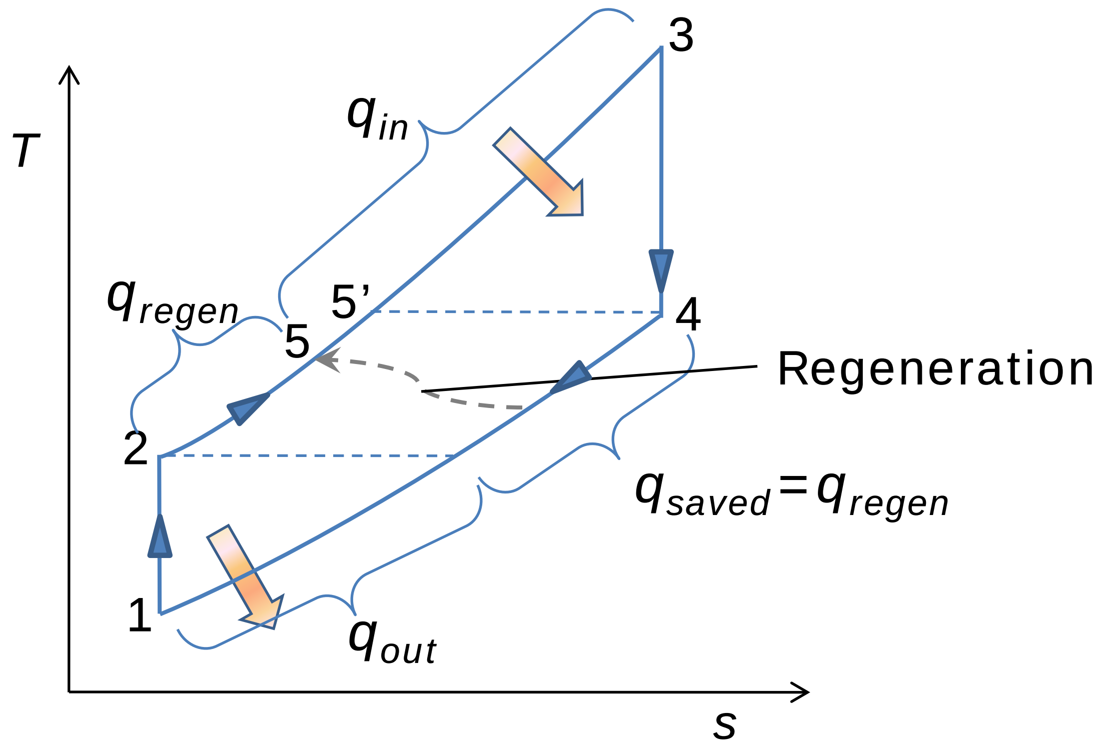
Solution: Problem 5



Solution: Problem 5

$$\varepsilon = \frac{T_5 - T_2}{T_4 - T_2} = 0.75$$

$$or, \frac{T_5 - 506.69}{635.29 - 506.69} = 0.75$$

$$T_5 = 603.14\,K$$

- T_4, W_{comp}, W_{turb} remain unchanged
- The new heat input, $Q_{in}=c_p(T_3-T_5)$
  $=472.2$ kJ/kg
- Therefore $\eta_{th}=(W_{turb}-W_{comp})/Q_{in}$
  $=(439.89-207.72)/472.2$
  $=$ *0.492 or 49.2 %*

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Exercise Problem 1

- A gasoline engine receives air at 10^{o}C, 100 kPa, having a compression ratio of 9:1 by volume. The heat addition by combustion gives the highest temperature as 2500 K. use cold air properties to find the highest cycle pressure, the specific energy added by combustion, and the mean effective pressure.
- Ans: 7946.3 kPa, 1303.6 kJ/kg, 0.5847, 1055 kPa

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Exercise Problem 2

- A diesel engine has a compression ratio of 20:1 with an inlet of 95 kPa, 290 K, with volume 0.5 L. The maximum cycle temperature is 1800 K. Find the maximum pressure, the net specific work and the thermal efficiency.
- Ans: 6298 kPa , 550.5 kJ/kg, 0.653

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Exercise Problem 3

- Consider an ideal Stirling-cycle engine in which the state at the beginning of the isothermal compression process is 100 kPa, 25°C, the compression ratio is 6, and the maximum temperature in the cycle is 1100°C. Calculate the maximum cycle pressure and the thermal efficiency of the cycle with and without regenerators.
- Ans: 2763 kPa, 0.374, 0.783

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Exercise Problem 4

- A large stationary Brayton cycle gas-turbine power plant delivers a power output of 100 MW to an electric generator. The minimum temperature in the cycle is 300 K, and the maximum temperature is 1600 K. The minimum pressure in the cycle is 100 kPa, and the compressor pressure ratio is 14 to 1. Calculate the power output of the turbine. What fraction of the turbine output is required to drive the compressor? What is the thermal efficiency of the cycle?
- Ans: 166.32 MW, 0.399, 0.530

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In the next lecture ...

- Properties of pure substances
  - Compressed liquid, saturated liquid, saturated vapour, superheated vapour
  - Saturation temperature and pressure
  - Property diagrams of pure substances
  - Property tables
  - Composition of a gas mixture
  - P-v-T behaviour of gas mixtures
  - Ideal gas and real gas mixtures
  - Properties of gas mixtures