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POWER ENGINEERING CALCULATIONS

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1. COMBUSTION OF FUEL

High heat value (HHV [$\text{kJ} \cdot \text{kg}^{-1}$; $\text{kJ} \cdot \text{m}^{-3}$]) is the heat that we obtain by complete burning 1 kg or 1 m^3 of fuel. Water remains in the liquid state after cooling to the original fuel temperature.

Low heat value (LHV [$\text{kJ} \cdot \text{kg}^{-1}$; $\text{kJ} \cdot \text{m}^{-3}$]) is the heat that we obtain by complete burning 1 kg or 1 m^3 of fuel. After cooling to the original fuel temperature, water remains in the gaseous state.

For the interrelationship between *HHV* and *LHV* is:

$$HHV = LHV + (r \cdot m_{H_2O}) \quad [\text{kJ} \cdot \text{kg}^{-1}; \text{kJ} \cdot \text{m}^{-3}]$$

where: *r* vaporization heat of water (2 453 $\text{kJ} \cdot \text{kg}^{-1}$ for 20°C) we use $r = 2\,500 \text{ kJ} \cdot \text{kg}^{-1}$

m_{H_2O} the amount of water [kg] contained in the flue gas after complete combustion of 1 kg/m^3 of fuel

$$m_{H_2O} = \left(\frac{W}{100} + 9 \cdot \frac{H}{100} \right)$$

where: W weight per cent of water in the fuel [%]

H weight per cent of hydrogen in the fuel [%]

remember that
$$\begin{array}{l} 2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O} \\ 4 \text{ kg} + 32 \text{ kg} \rightarrow 36 \text{ kg} \end{array} \quad \left. \vphantom{\begin{array}{l} 2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O} \\ 4 \text{ kg} + 32 \text{ kg} \rightarrow 36 \text{ kg} \end{array}} \right\} 1 \text{ kg H} \rightarrow 9 \text{ kg H}_2\text{O}$$

EXERCISE 1.01

Calculate the *LHV* of 1 kg of fuel that contains 10 % w_t moisture and its *HHV* is 28 700 $\text{kJ} \cdot \text{kg}^{-1}$.

Solution:

$$LHV = HHV - (r \cdot m_{H_2O})$$

$$m_{H_2O} = \left(\frac{W}{100} + 9 \cdot \frac{H}{100} \right) = \frac{10}{100} = 0.1 \text{ kg}$$

$$LHV = 28\,700 - (2\,500 \cdot 0.1) = \underline{\underline{28\,450 \text{ kJ} \cdot \text{kg}^{-1}}}$$

EXERCISE 1.02

Calculate the *LHV* of 1 kg of coal that contains 6.6 % w_t moisture, 4.3 % w_t hydrogen and its *HHV* is 12 600 $\text{kJ} \cdot \text{kg}^{-1}$.

Solution:

$$LHV = HHV - (r \cdot m_{H_2O})$$

$$m_{H_2O} = \left(\frac{W}{100} + 9 \cdot \frac{H}{100} \right) = \left(\frac{6.60}{100} + 9 \cdot \frac{4.30}{100} \right) = 0.453 \text{ kg}$$

$$LHV = 12\,600 - (2500 \cdot 0.453) = \underline{\underline{11467.5 \text{ kJ} \cdot \text{kg}^{-1}}}$$

EXERCISE 1.03

Calculate the *HHV* of 1 kg of coal that contains 18 % w_t moisture, 2 % w_t hydrogen and its *LHV* is 12 600 kJ·kg⁻¹.

Result: *HHV* = 13 500 kJ·kg⁻¹

EXERCISE 1.04

Calculate the *LHV* of 1 kg of coal that contains 8 % w_t moisture, 2.24 % w_t hydrogen and its *HHV* is 12 600 kJ·kg⁻¹.

Result: *LHV* = 11 896 kJ·kg⁻¹

Another way to calculate *HHV* or *LHV* is using tabulated values, this is possible if we know the substance composition of the fuel. The *HHV* and *LHV* values of some substances are given in Table III. Care must be taken to distinguish the composition in weight or volume percentages. The following equations:

$$HHV = \sum x_i \cdot HHV_i$$

$$LHV = \sum x_i \cdot LHV_i$$

EXERCISE 1.05

Calculate the *HHV* and *LHV* of 1 m³ of natural gas that contains 94 % v/v CH₄ and 6 % v/v N₂.

Solution:

$$HHV = \sum x_i \cdot HHV_i = (0.94 \cdot 39\,888) + (0.06 \cdot 0) = \underline{\underline{37\,494.7 \text{ kJ} \cdot \text{m}^{-3}}}$$

Table III: $HHV_i(\text{CH}_4) = 39\,888 \text{ kJ} \cdot \text{m}^{-3}$
 $HHV_i(\text{N}_2) = \text{-----}$ nitrogen as an inert

$$LHV = \sum x_i \cdot LHV_i = (0.94 \cdot 35\,850) = \underline{\underline{33\,699 \text{ kJ} \cdot \text{m}^{-3}}}$$

Table III: $LHV_i(\text{CH}_4) = 35\,850 \text{ kJ} \cdot \text{m}^{-3}$

EXERCISE 1.05

Calculate the *HHV* and *LHV* of 1 m³ of gas that contains 40 % v/v H₂, 10 % v/v CH₄, 20 % v/v C₂H₆ and 30 % v/v N₂.

Solution:

Values of *HHV_i* and *LHV_i* you can find in Table III:

	% v/v	<i>HHV_i</i> [kJ·m ⁻³]	<i>x_i·HHV_i</i>		<i>LHV_i</i> [kJ·m ⁻³]	<i>x_i·LHV_i</i>
H ₂	40	12 790	5 116		10 752	4 300.8
CH ₄	10	39 888	3 988.9		35 850	3 585
C ₂ H ₆	20	69 250	13 850		64 310	12 862
N ₂	30	----	----		---	---
<i>HHV</i> = $\sum x_i \cdot HHV_i$ = 22 954.9 kJ·m⁻³				<i>LHV</i> = $\sum x_i \cdot LHV_i$ = 20 747.8 kJ·m⁻³		

EXERCISE 1.06

Calculate the *HHV* and *LHV* of 1 m³ of gas that contains 10 % v/v H₂, 40 % v/v CH₄, 30 % v/v C₂H₆ and 20 % v/v N₂.

Results: *HHV* = 38 009.2 kJ·m⁻³; *LHV* = 34 708.2 kJ·m⁻³

Stoichiometric air consumption – *AR_S* [m³] – is the minimum amount of air needed to completely burn 1 kg or 1 m³ of fuel.

Stoichiometric flue gas – *FG_S* [m³] – is the amount of flue gases produced by the complete combustion of 1 kg or 1 m³ of fuel with a stoichiometric air consumption.

remember that:

air	% v/v	% w _t
O ₂	21	23.1
N ₂	79	76.9

EXERCISE 1.07

Calculate the stoichiometric air consumption needed to burn 100 m³ of gas of composition 7 % v/v N₂, 58 % v/v CH₄, 10 % v/v C₂H₄, 12 % v/v CO₂ and 13 % v/v CO. Calculate the amount of stoichiometric flue gas (wet – *FG_{SW}* and dry – *FG_{SD}*) generated during the process.

Solution:

	% v/v	100 m ³ of gas	V(O ₂) [m ³]	V(CO ₂) [m ³]	V(H ₂ O) [m ³]	V(N ₂) [m ³]
CO ₂	12	---	---	12	---	---
N ₂	7	---	---	---	---	7
C ₂ H ₄	10	C ₂ H ₄ + 3O ₂ → 2CO ₂ + 2H ₂ O	30	20	20	---
CO	13	CO + ½O ₂ → CO ₂	6.5	13	---	---
CH ₄	58	CH ₄ + 2O ₂ → CO ₂ + 2H ₂ O	116	58	116	---
Σ			152.5	103	136	7

Oxygen represents 21 % v/v of air → stoichiometric air consumption:

$$AR_S = V(O_2)/0.21 = 152.5 / 0.21 = \underline{726.19 \text{ m}^3}$$

Stoichiometric dry flue gas:

$$FG_{SD} = V(CO_2) + V(N_2) = 103 + 580.69 = \underline{683.69 \text{ m}^3}$$

$$V(N_2) = V(N_2)_{\text{air}} + V(N_2)_{\text{fuel}} = (0.79 \cdot AR_S) + V(N_2)_{\text{fuel}} = (0.79 \cdot 726.19) + 7 = \underline{580.69 \text{ m}^3}$$

Stoichiometric wet flue gas:

$$FG_{SW} = FG_{SD} + V(H_2O) = 683.69 + 136 = \underline{819.69 \text{ m}^3}$$

EXERCISE 1.08

Calculate the stoichiometric air consumption needed to burn 1 m³ of gas of composition 40 % v/v CH₄, 20 % v/v H₂ and 40 % v/v N₂. Calculate the amount of stoichiometric flue gas (**FG_{SW}** and **FG_{SD}**) generated during the process.

Solution:

	% v/v	1 m ³ of gas	V(O ₂) [m ³]	V(CO ₂) [m ³]	V(H ₂ O) [m ³]	V(N ₂) [m ³]
CH ₄	40	CH ₄ + 2O ₂ → CO ₂ + 2H ₂ O	0.80	0.40	0.80	---
H ₂	20	H ₂ + ½O ₂ → H ₂ O	0.10	---	0.20	---
N ₂	40	---	---	---	---	0.40
Σ			0.90	0.40	1.0	0.40

Stoichiometric air consumption:

$$AR_S = V(O_2)/0.21 = 0.90 / 0.21 = \underline{4.29 \text{ m}^3}$$

Stoichiometric dry flue gas:

$$FG_{SD} = V(CO_2) + V(N_2) = 0.4 + 3.79 = \underline{4.19 \text{ m}^3}$$

$$V(N_2) = V(N_2)_{\text{air}} + V(N_2)_{\text{fuel}} = (0.79 \cdot AR_S) + V(N_2)_{\text{fuel}} = (0.79 \cdot 4.29) + 0.4 = \underline{3.79 \text{ m}^3}$$

Stoichiometric wet flue gas:

$$FG_{SW} = FG_{SD} + V(H_2O) = 4.19 + 1.0 = \underline{5.19 \text{ m}^3}$$

EXERCISE 1.09

Calculate the stoichiometric air consumption needed to burn 100 m³ of gas of composition 20 % v/v N₂, 40 % v/v CH₄, 30 % v/v C₂H₆ and 10 % v/v H₂. Calculate the amount of stoichiometric flue gas (**FG_{SW}** and **FG_{SD}**) generated during the process.

Results: $AR_S = 904.8 \text{ m}^3$; $FG_{SD} = 834.8 \text{ m}^3$, $FG_{SW} = 1014.8 \text{ m}^3$

Dew point

Flue gas dew point temperature – ΔT_{dp} [°C ; K] is the temperature where condensation of water vapor in the flue gas starts. (Boyle's law, Dalton's law and Avogadro's law).

The dew point temperature is the temperature corresponding to the partial pressure of saturated steam in the flue gas and read from Table XIII.

Partial pressure of saturated steam in the flue gas is calculated as follows:

$$p_{H_2O} = \frac{V(H_2O)_{FG}}{FG_W} \cdot p_b$$

p_b atmospheric pressure [kPa] or we can use the value of standard pressure 101.325 kPa

EXERCISE 1.10

Calculate the flue gas dew point temperature for the stoichiometric flue gas (FG_{SW}) generated during the combustion process in exercises 1.07, 1.08 and 1.09.

Solution:

$$\begin{aligned} \text{EX1.07} \quad V(H_2O)_{FG} &= 136 \text{ m}^3 \\ FG_{SW} &= 818.69 \text{ m}^3 \end{aligned}$$

$$p_{H_2O} = \frac{V(H_2O)_{FG}}{FG_{SW}} \cdot p_b = \frac{136}{818.69} \cdot 101.325 = \underline{16.81 \text{ kPa}} \rightarrow \text{Table XIII}$$

$$\Delta T_{dp} \approx \underline{56 - 57 \text{ }^\circ\text{C}}$$

$$\begin{aligned} \text{EX1.08} \quad V(H_2O)_{FG} &= 1.0 \text{ m}^3 \\ FG_{SW} &= 5.19 \text{ m}^3 \end{aligned}$$

$$p_{H_2O} = \frac{V(H_2O)_{FG}}{FG_{SW}} \cdot p_b = \frac{1.0}{5.19} \cdot 101.325 = \underline{19.52 \text{ kPa}} \rightarrow \text{Table XIII}$$

$$\Delta T_{dp} \approx \underline{59 - 60 \text{ }^\circ\text{C}}$$

$$\begin{aligned} \text{EX1.09} \quad V(H_2O)_{FG} &= 180 \text{ m}^3 \\ FG_{SW} &= 1014.8 \text{ m}^3 \end{aligned}$$

$$p_{H_2O} = \frac{V(H_2O)_{FG}}{FG_{SW}} \cdot p_b = \frac{180}{1014.8} \cdot 101.325 = \underline{17.97 \text{ kPa}} \rightarrow \text{Table XIII}$$

$$\Delta T_{dp} \approx \underline{57 - 58 \text{ }^\circ\text{C}}$$

The excess air coefficient

The **excess air coefficient** – λ , is the ratio of the real (total) amount of air (AR_{real}) used in the combustion to the amount of stoichiometric air (AR_S). For stoichiometrically accurate combustion (i.e. without excess air), this ratio is $\lambda = 1$.

Remember that it applies to all types of combustion $\lambda = \frac{AR_{real}}{AR_S}$

For complete combustion of solid fuel used the following equation:

$$\lambda = \frac{(\%CO_2)_S}{(\%CO_2)_{real}}$$

$(\%CO_2)_S$ % v/v CO_2 in stoichiometric dry flue gas (FG_{SD})

$(\%CO_2)_{real}$ % v/v CO_2 in real dry flue gas ($FG_{real D}$)

However for complete combustion of liquid and gaseous fuel use the following equation:

$$\lambda = 1 + \left(\frac{(\%CO_2)_S}{(\%CO_2)_{real}} - 1 \right) \cdot \frac{FG_{SD}}{AR_S}$$

EXERCISE 1.11

Calculate the excess air coefficient and the flue gas dew point temperature for the real wet flue gas ($FG_{real W}$) generated during the combustion process of 100 m³ of gas of composition 13 % v/v N_2 , 50 % v/v CH_4 , 2 % v/v O_2 and 35 % v/v H_2 . It is known that the real dry flue gas contains 8.3 % v/v CO_2 .

Solution:

	% v/v	100 m ³ of gas	V(O_2) [m ³]	V(CO_2) [m ³]	V(H_2O) [m ³]	V(N_2) [m ³]
CH₄	50	$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$	100	50	100	---
H₂	35	$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$	17.5	---	35	---
O₂	2	---	-2	---	---	---
N₂	13	---	---	---	---	13
Σ			115.5	50	135	13

For complete combustion of liquid and gaseous fuel you must use:

$$\lambda = 1 + \left(\frac{(\%CO_2)_S}{(\%CO_2)_{real}} - 1 \right) \cdot \frac{FG_{SD}}{AR_S}$$

Stoichiometric air consumption:

$$AR_S = V(O_2)/0.21 = 115.5 / 0.21 = \underline{550 \text{ m}^3}$$

Stoichiometric dry flue gas:

$$FG_{SD} = V(CO_2) + V(N_2) = 0.4 + 3.79 = \underline{497.5 \text{ m}^3}$$

$$V(N_2) = V(N_2)_{air} + V(N_2)_{fuel} = (0.79 \cdot AR_S) + V(N_2)_{fuel} = (0.79 \cdot 550) + 13 = \underline{447.5 \text{ m}^3}$$

% v/v CO₂ in stoichiometric dry flue gas:

$$(\% CO_2)_S = \frac{V(CO_2)}{FG_{SD}} \cdot 100 = \frac{50}{497.5} = 10.05 \%$$

The excess air coefficient:

$$\lambda = 1 + \left(\frac{(\%CO_2)_S}{(\%CO_2)_{real}} - 1 \right) \cdot \frac{FG_{SD}}{AR_S} = 1 + \left(\frac{10.05}{8.3} - 1 \right) \cdot \frac{497.5}{550} = \underline{1.19}$$

Flue gas dew point temperature:

$$p_{H_2O} = \frac{V(H_2O)_{FG}}{FG_{real W}} \cdot p_b$$

real wet flue gas:

$$FG_{real W} = FG_{SD} + V(H_2O) + AR_{exc} = 497.5 + 135 + 104.5 = \underline{737 \text{ m}^3}$$

$$AR_{exc} = AR_{real} - AR_S = (\lambda \cdot AR_{real}) - AR_S = (1.19 \cdot 550) - 550 = \underline{104.5 \text{ m}^3}$$

$$p_{H_2O} = \frac{V(H_2O)_{FG}}{FG_{real W}} \cdot p_b = \frac{135}{737} \cdot 101.325 = \underline{18.56 \text{ kPa}} \rightarrow \text{Table XIII}$$

$$\Delta T_{dp} \approx \underline{58 - 59 \text{ }^\circ\text{C}}$$

EXERCISE 1.12

Calculate the excess air coefficient and the flue gas dew point temperature for the real wet flue gas ($FG_{real W}$) generated during the combustion process of 1 kg of coal of composition 75 % w_t C, 3 % w_t H, 1 % w_t O, 2 % w_t N, 4 % w_t A and 15 % w_t W. It is known that the real dry flue gas contains 12.42 % v/v CO₂.

Solution: for complete combustion of solid fuel you can use:

$$\lambda = \frac{(\%CO_2)_S}{(\%CO_2)_{real}}$$

	% w _t	1 kg of coal	V(O ₂) [m ³]	V(CO ₂) [m ³]	V(H ₂ O) [m ³]	V(N ₂) [m ³]
C	75	C + O ₂ → CO ₂	$\frac{0.75}{12} \cdot 22.4$ = 1.400	1.400	---	---
H	3	H + ¼O ₂ → ½ H ₂ O	$\frac{0.03}{1 \cdot 4} \cdot 22.4$ = 0.168	---	0.336	---
O	1	---	$-\frac{0.01}{32} \cdot 22.4$ = -0.007	---	---	---
N	2	---	---	---	---	$\frac{0.02}{28} \cdot 22.4$ = 0.016
A	4	---	---	---	---	---
W	15	---	---	---	$\frac{0.15}{18} \cdot 22.4$ = 0.187	---
Σ			1.561	1.400	0.523	0.016

Stoichiometric air consumption:

$$AR_S = V(O_2)/0.21 = 1.561 / 0.21 = \underline{7.43 \text{ m}^3}$$

Stoichiometric dry flue gas:

$$FG_{SD} = V(CO_2) + V(N_2) = 1.4 + 5.89 = \underline{7.29 \text{ m}^3}$$

$$V(N_2) = V(N_2)_{\text{air}} + V(N_2)_{\text{fuel}} = (0.79 \cdot AR_S) + V(N_2)_{\text{fuel}} = (0.79 \cdot 7.43) + 0.016 = \underline{5.89 \text{ m}^3}$$

% v/v CO₂ in stoichiometric dry flue gas:

$$(\% CO_2)_S = \frac{V(CO_2)}{FG_{SD}} \cdot 100 = \frac{1.4}{7.29} = 19.21 \%$$

The excess air coefficient:

$$\lambda = \left(\frac{(\%CO_2)_S}{(\%CO_2)_{\text{real}}} \right) = \left(\frac{19.21}{12.42} \right) = \underline{1.545}$$

or

$$\lambda = 1 + \left(\frac{(\%CO_2)_S}{(\%CO_2)_{\text{real}}} - 1 \right) \cdot \frac{FG_{SD}}{AR_S} = 1 \left(\frac{19.21}{12.42} - 1 \right) \cdot \frac{7.29}{7.43} = \underline{1.536}$$

Flue gas dew point temperature:

$$p_{H_2O} = \frac{V(H_2O)_{FG}}{FG_{\text{real } W}} \cdot p_b$$

real wet flue gas:

$$FG_{real\ W} = FG_{SD} + V(H_2O) + AR_{exc} = 7.29 + 0.523 + 4.05 = \underline{11.86\ m^3}$$

$$AR_{exc} = AR_{real} - AR_S = (\lambda \cdot AR_{real}) - AR_S = (1.545 \cdot 7.43) - 7.73 = \underline{4.05\ m^3}$$

$$p_{H_2O} = \frac{V(H_2O)_{FG}}{FG_{real\ W}} \cdot p_b = \frac{0.523}{11.86} \cdot 101.325 = \underline{4.47\ kPa} \rightarrow \text{Table XIII}$$

$$\Delta T_{dp} \approx \underline{31\ ^\circ C}$$

Combustion by moist air

EXERCISE 1.13

Calculate the excess air coefficient and the flue gas dew point temperature for the real wet flue gas ($FG_{real\ W}$) generated during the combustion process of 100 m³ of gas of composition 8 % v/v N₂, 40 % v/v CH₄, 2 % v/v O₂, 6 % v/v CO₂, 12 % v/v CO and 32 % v/v C₂H₄. It is known that the real dry flue gas contains 10.5 % v/v CO₂ and

a) temperature of combustion air is 30 °C

b) temperature of combustion air is 30 °C and relative air humidity is 0.8

Solution:

	% v/v	100 m ³ of gas	V(O ₂) [m ³]	V(CO ₂) [m ³]	V(H ₂ O) [m ³]	V(N ₂) [m ³]
CH ₄	40	CH ₄ + 2O ₂ → CO ₂ + 2H ₂ O	80	40	80	---
CO	12	CO + ½O ₂ → CO ₂	6	12	---	---
CO ₂	6	---	---	6	---	---
C ₂ H ₄	32	C ₂ H ₄ + 3O ₂ → 2CO ₂ + 2H ₂ O	96	64	64	---
O ₂	2	---	-2	---	---	---
N ₂	8	---	---	---	---	8
Σ			180	122	144	8

For complete combustion of liquid and gaseous fuel you must use:

$$\lambda = 1 + \left(\frac{(\%CO_2)_S}{(\%CO_2)_{real}} - 1 \right) \cdot \frac{FG_{SD}}{AR_S}$$

Stoichiometric air consumption:

$$AR_S = V(O_2)/0.21 = 180 / 0.21 = \underline{857.14\ m^3}$$

Stoichiometric dry flue gas:

$$FG_{SD} = V(CO_2) + V(N_2) = 122 + 685.14 = \underline{807.14\ m^3}$$

$$V(N_2) = V(N_2)_{air} + V(N_2)_{fuel} = (0.79 \cdot AR_S) + V(N_2)_{fuel} = (0.79 \cdot 857.14) + 8 = \underline{685.14\ m^3}$$

% v/v CO₂ in stoichiometric dry flue gas:

$$(\% \text{ CO}_2)_S = \frac{V(\text{CO}_2)}{FG_{SD}} \cdot 100 = \frac{122}{807.14} = 15.12 \%$$

The excess air coefficient:

$$\lambda = 1 + \left(\frac{(\% \text{ CO}_2)_S}{(\% \text{ CO}_2)_{real}} - 1 \right) \cdot \frac{FG_{SD}}{AR_S} = 1 + \left(\frac{15.12}{10.50} - 1 \right) \cdot \frac{807.14}{857.14} = \underline{\underline{1.414}}$$

A) flue gas dew point temperature:

$$p_{H_2O} = \frac{V(H_2O)_{FG}}{FG_{real W}} \cdot p_b$$

real wet flue gas:

$$FG_{real W} = FG_{SD} + V(H_2O) + AR_{exc} = 807.14 + 196.94 + 354.86 = \underline{\underline{1358.94 \text{ m}^3}}$$

$$AR_{exc} = AR_{real} - AR_S = (\lambda \cdot AR_{real}) - AR_S = (1.414 \cdot 857.14) - 857.14 = \underline{\underline{354.86 \text{ m}^3}}$$

$$V(H_2O)_{FG} = V(H_2O)_R + V(H_2O)_{AR} = 144 + 52.94 = \underline{\underline{196.94 \text{ m}^3}}$$

$$V(H_2O)_{AR} = \frac{p_{H_2O}(\Delta t_{AR})}{p_b - p_{H_2O}(\Delta t_{AR})} \cdot AR_{real} = \frac{4.214}{101.325 - 4.241} \cdot 1212 = \underline{\underline{52.94 \text{ m}^3}}$$

$p_{H_2O}(\Delta t_{AR})$...partial pressure of saturated steam in temperature of air Table XIII

$$p_{H_2O}(30^\circ \text{C}) = \underline{\underline{4.241 \text{ kPa}}}$$

$$p_{H_2O} = \frac{V(H_2O)_{FG}}{FG_{real W}} \cdot p_b = \frac{196.94}{1358.94} \cdot 101.325 = \underline{\underline{14.68 \text{ kPa}}} \rightarrow \text{Table XIII}$$

$$\Delta T_{dp} \approx \underline{\underline{53 - 54^\circ \text{C}}}$$

B) flue gas dew point temperature:

$$p_{H_2O} = \frac{V(H_2O)_{FG}}{FG_{real W}} \cdot p_b$$

real wet flue gas:

$$FG_{real W} = FG_{SD} + V(H_2O) + AR_{exc} = 807.14 + 186 + 354.86 = \underline{\underline{1348 \text{ m}^3}}$$

$$AR_{exc} = AR_{real} - AR_S = (\lambda \cdot AR_{real}) - AR_S = (1.414 \cdot 857.14) - 857.14 = \underline{\underline{354.86 \text{ m}^3}}$$

$$V(H_2O)_{FG} = V(H_2O)_R + V(H_2O)_{AR} = 144 + 42 = \underline{\underline{186 \text{ m}^3}}$$

$$V(H_2O)_{AR} = \frac{p_{H_2O}(\Delta t_{AR}) \cdot \varphi}{p_b - (p_{H_2O}(\Delta t_{AR}) \cdot \varphi)} \cdot AR_{real} = \frac{4.214 \cdot 0.8}{101.325 - (4.241 \cdot 0.8)} \cdot 1212 = \underline{42 \text{ m}^3}$$

$p_{H_2O}(\Delta t_{AR})$...partial pressure of saturated steam corresponding to the temperature of air:

Table XIII $p_{H_2O}(30^\circ\text{C}) = \underline{4.241 \text{ kPa}}$

$$p_{H_2O} = \frac{V(H_2O)_{FG}}{V_{FG_{realW}}} \cdot p_b = \frac{186}{1348} \cdot 101.325 = \underline{13.98 \text{ kPa}} \rightarrow \text{Table XIII}$$

$$\Delta T_{dp} \approx \underline{52 - 53^\circ\text{C}}$$

EXERCISE 1.14

Calculate the excess air coefficient and the flue gas dew point temperature for the real wet flue gas (FG_{realW}) generated during the combustion process of 100 kg of coal of composition 55 % w_t C, 9 % w_t H, 2 % w_t O, 7 % w_t N, 7 % w_t S, 8 % w_t A and 12 % w_t W. It is known that the real dry flue gas contain 12.5 % v/v CO₂ and temperature of combustion air is 22 °C and relative air humidity is 0.9.

Solution: for complete combustion of solid fuel you can use:

$$\lambda = \frac{(\%CO_2)_S}{(\%CO_2)_{real}}$$

	% w _t	100 kg of coal	V(O ₂) [m ³]	V(CO ₂) [m ³]	V(SO ₂) [m ³]	V(H ₂ O) [m ³]	V(N ₂) [m ³]
C	55	C + O ₂ → CO ₂	$\frac{55}{12} \cdot 22.4$ = 102.7	102.7	---	---	---
H	9	H + ¼O ₂ → ½H ₂ O	$\frac{9}{1 \cdot 4} \cdot 22.4$ = 50.4	---	---	100.8	---
O	2	---	$-\frac{2}{32} \cdot 22.4$ = -1.4	---	---	---	---
S	7	S + O ₂ → CO ₂	$\frac{7}{32} \cdot 22.4$ = 4.9	---	4.9	---	---
N	7	---	---	---	---	---	$\frac{7}{28} \cdot 22.4$ = 5.6
A	8	---	---	---	---	---	---
W	12	---	---	---	---	$\frac{12}{18} \cdot 22.4$ = 14.93	---
Σ			156.6	102.7	4.9	115.73	5.6

Stoichiometric air consumption:

$$AR_S = V(O_2)/0.21 = 156.6 / 0.21 = \underline{745.71 \text{ m}^3}$$

Stoichiometric dry flue gas:

$$FG_{SD} = V(CO_2) + V(SO_2) + V(N_2) = 102.7 + 4.9 + 594.71 = \underline{702.31 \text{ m}^3}$$

$$V(N_2) = V(N_2)_{air} + V(N_2)_{fuel} = (0.79 \cdot AR_S) + V(N_2)_{fuel} = (0.79 \cdot 745.71) + 5.6 = \underline{594.71 \text{ m}^3}$$

% v/v CO₂ in stoichiometric dry flue gas:

$$(\% CO_2)_S = \frac{V(CO_2)}{FG_{SD}} \cdot 100 = \frac{102.7}{702.31} = 14.62 \%$$

The excess air coefficient:

$$\lambda = \left(\frac{(\%CO_2)_S}{(\%CO_2)_{real}} \right) = \left(\frac{14.62}{12.50} \right) = \underline{1.170}$$

Flue gas dew point temperature:

$$p_{H_2O} = \frac{V(H_2O)_{FG}}{FG_{real W}} \cdot p_b$$

Real wet flue gas:

$$FG_{real W} = FG_{SD} + V(H_2O) + AR_{exc} = 702.31 + 136.7 + 126.77 = \underline{965.78 \text{ m}^3}$$

$$AR_{exc} = AR_{real} - AR_S = (\lambda \cdot AR_{real}) - AR_S = (1.17 \cdot 745.71) - 745.71 = \underline{126.77 \text{ m}^3}$$

$$V(H_2O)_{FG} = V(H_2O)_R + V(H_2O)_W + V(H_2O)_{AR} = 100.8 + 14.93 + 20.98 = \underline{136.7 \text{ m}^3}$$

$$V(H_2O)_{AR} = \frac{p_{H_2O}(\Delta t_{AR}) \cdot \varphi}{p_b - (p_{H_2O}(\Delta t_{AR}) \cdot \varphi)} \cdot AR_{real} = \frac{2.643 \cdot 0.9}{101.325 - (2.643 \cdot 0.9)} \cdot 872.48 = \underline{20.98 \text{ m}^3}$$

$p_{H_2O}(\Delta t_{AR})$... partial pressure of saturated steam corresponding to the temperature of air:

Table XIII

$$p_{H_2O} (22^\circ C) = \underline{2.643 \text{ kPa}}$$

$$p_{H_2O} = \frac{V(H_2O)_{FG}}{FG_{real W}} \cdot p_b = \frac{136.7}{965.78} \cdot 101.325 = \underline{14.31 \text{ kPa}} \rightarrow \text{Table XIII}$$

$$\Delta T_{dp} \approx \underline{53 - 54^\circ C}$$

EXERCISE 1.15

Calculate the flue gas dew point temperature for the real wet flue gas for exercise 1.05 when you know that temperature of combustion air is 35 °C and the excess air coefficient is 1.25.

Result: $\Delta T_{dp} \approx 59^\circ C$

Theoretical adiabatic flame temperature

This is the temperature Δt_{FG} [°C or K] that we achieve by complete burning 1 kg of fuel with a stoichiometric air consumption, provided that there is no heat exchange with the environment.

HEAT SUPPLIED = FLUE GAS HEAT

HEAT SUPPLIED: $E = LHV \cdot V(FUEL)$

FLUE GAS HEAT: $Q_{FG} = \Delta t_{FG} \cdot c_{ps} \cdot FG_{SW}$

Theoretical adiabatic flame temperature

$$\Delta t_T = \frac{LHV \cdot V_{fuel}}{c_{ps} \cdot FG_{SW}}$$

c_{ps} ... specific heat capacity at constant pressure (values in Table V and Table VI)

Remember that the **reference temperature for calculating** the theoretical adiabatic flame temperature is **0 °C**.

Specific heat capacity depends on the temperature, however, if this temperature, is unknown we calculate the approximate flame temperature:

$$\Delta t_A = \frac{LHV \cdot V_{fuel}}{1.7 \cdot FG_{SW}}$$

EXERCISE 1.16

Calculate the theoretical adiabatic flame temperature for the combustion process of 100 m³ of natural gas of composition 6 % v/v N₂ and 94 % v/v CH₄.

$$\Delta t_A = \frac{LHV \cdot V_{fuel}}{1.7 \cdot FG_{SW}}$$

$$LHV_{NG} = \sum x_i \cdot LHV_i = 0.94 \cdot 35\,850 = \underline{\underline{33\,699 \text{ kJ} \cdot \text{m}^{-3}}}$$

	% v/v	100 m ³ of gas	V(O ₂) [m ³]	V(CO ₂) [m ³]	V(H ₂ O) [m ³]	V(N ₂) [m ³]
CH₄	94	CH ₄ + 2O ₂ → CO ₂ + 2H ₂ O	188	94	188	---
N₂	6	---	---	---	---	6
Σ			188	94	188	6

$$FG_{WD} = V(\text{CO}_2) + V(\text{H}_2\text{O}) + V(\text{N}_2) = 94 + 188 + 713.24 = \underline{\underline{995.24 \text{ m}^3}}$$

$$V(\text{N}_2) = V(\text{N}_2)_{\text{air}} + V(\text{N}_2)_{\text{fuel}} = (0.79 \cdot AR_S) + V(\text{N}_2)_{\text{fuel}} = (0.79 \cdot 895.24) + 6 = \underline{\underline{713.24 \text{ m}^3}}$$

$$AR_S = V(\text{O}_2)/0.21 = 188 / 0.21 = \underline{\underline{895.24 \text{ m}^3}}$$

$$\Delta t_A = \frac{LHV \cdot V_{\text{fuel}}}{1.7 \cdot FG_{SW}} = \frac{33699 \cdot 100}{1.7 \cdot 995.24} = \underline{\underline{1991 \text{ }^\circ\text{C}}}$$

$$E = LHV_{NG} \cdot V(\text{FUEL}) = 33\,699 \cdot 100 = \mathbf{3\,369\,900 \text{ kJ}}$$

All supplied energy is transferred to the flue gas $Q_{FG} = \Delta t_{FG} \cdot \sum c_{psi} \cdot V(FG)_i$

$\Delta t_A = 1991 \text{ }^\circ\text{C} \rightarrow \Delta t_1 = \mathbf{2\,000 \text{ }^\circ\text{C}}$ → Table V where we find c_{ps} values for all gases contained in the stoichiometric wet flue gas:

	$c_{psi} (2000 \text{ }^\circ\text{C}) \text{ [kJ} \cdot \text{m}^{-3} \cdot \text{K}^{-1}]$
CO ₂	2.445
H ₂ O (g)	1.947
N ₂	1.490

$$Q_{FG1} = \Delta t_1 \cdot \sum c_{psi} \cdot V(FG)_i = 2000 \cdot [(94 \cdot 2.445) + (188 \cdot 1.947) + (713.24 \cdot 1.49)]$$

$$\mathbf{Q_{FG1} = 3\,317\,181.5 \text{ kJ}}$$

$$\mathbf{Q_{FG1} < E \rightarrow \Delta t_{FG} > 2000 \text{ }^\circ\text{C}}$$

$$\Delta t_2 = \mathbf{2\,100 \text{ }^\circ\text{C}}$$

	$c_{psi} (2100 \text{ }^\circ\text{C}) \text{ [kJ} \cdot \text{m}^{-3} \cdot \text{K}^{-1}]$
CO ₂	2.457
H ₂ O (g)	1.968
N ₂	1.498

$$Q_{FG2} = \Delta t_2 \cdot \sum c_{psi} \cdot V(FG)_i = 2100 \cdot [(94 \cdot 2.457) + (188 \cdot 1.968) + (713.24 \cdot 1.498)]$$

$$\mathbf{Q_{FG2} = 3\,505\,657.1 \text{ kJ}}$$

$$\mathbf{Q_{FG1} < E < Q_{FG2}}$$

→ we calculate the temperature using mathematical interpolation of the line:

$$\Delta t_T = \frac{(\Delta t_1 - \Delta t_2)}{(Q_{FG1} - Q_{FG2})} \cdot (E - Q_{FG1}) + \Delta t_1$$

$$\Delta t_T = \frac{(2000 - 2100)}{(3317181.5 - 3505657.1)} \cdot (3369900 - 3314181.5) + 2000$$

$$\Delta t_T = \underline{\underline{2028^\circ\text{C}}}$$

EXERCISE 1.17

Calculate the theoretical adiabatic flame temperature for the combustion process of 100 m³ of gas of composition 25 % v/v H₂, 45 % v/v CH₄, 10 % v/v C₂H₆ and 20 % v/v N₂

$$\Delta t_A = \frac{LHV \cdot V_{fuel}}{1.7 \cdot FG_{SW}}$$

$$LHV_{NG} = \sum x_i \cdot LHV_i = (0.45 \cdot 35\,850) + (0.25 \cdot 10\,752) + (0.1 \cdot 64\,310) = \underline{\underline{25\,251.5 \text{ kJ}\cdot\text{m}^{-3}}}$$

	% w _t	100 m ³ of gas	V(O ₂) [m ³]	V(CO ₂) [m ³]	V(H ₂ O) [m ³]	V(N ₂) [m ³]
CH ₄	45	CH ₄ + 2O ₂ → CO ₂ + 2H ₂ O	90	45	90	---
H ₂	25	H ₂ + ½O ₂ → H ₂ O	12.5	---	25	---
C ₂ H ₆	10	C ₂ H ₆ + 3.5 O ₂ → 2CO ₂ + 3H ₂ O	35	20	30	---
N ₂	20	---	---	---	---	20
Σ			137.5	65	145	20

$$FG_{WD} = V(\text{CO}_2) + V(\text{H}_2\text{O}) + V(\text{N}_2) = 65 + 145 + 537.26 = \underline{\underline{747.26 \text{ m}^3}}$$

$$V(\text{N}_2) = V(\text{N}_2)_{\text{air}} + V(\text{N}_2)_{\text{fuel}} = (0.79 \cdot AR_S) + V(\text{N}_2)_{\text{fuel}} = (0.79 \cdot 654.79) + 20 = \underline{\underline{537.26 \text{ m}^3}}$$

$$AR_S = V(\text{O}_2)/0.21 = 137.5 / 0.21 = \underline{\underline{654.76 \text{ m}^3}}$$

$$\Delta t_A = \frac{LHV \cdot V_{fuel}}{1.7 \cdot FG_{SW}} = \frac{25251.5 \cdot 100}{1.7 \cdot 747.26} = \underline{\underline{1988^\circ\text{C}}}$$

$$E = LHV_{NG} \cdot V(\text{FUEL}) = 25\,251.5 \cdot 100 = \underline{\underline{2\,525\,150 \text{ kJ}}}$$

All supplied energy is transferred to the flue gas $Q_{FG} = \Delta t_{FG} \cdot \sum c_{psi} \cdot V(\text{FG})_i$

$\Delta t_A = 1988^\circ\text{C} \rightarrow \Delta t_1 = 2\,000^\circ\text{C} \rightarrow$ Table V where we find c_{ps} values for all gases contained in the stoichiometric wet flue gas:

	$c_{psi}(2000^\circ\text{C}) [\text{kJ}\cdot\text{m}^{-3}\cdot\text{K}^{-1}]$
CO ₂	2.445
H ₂ O (g)	1.947
N ₂	1.490

$$Q_{FG1} = \Delta t_1 \cdot \sum c_{psi} \cdot V(FG)_i = 2000 \cdot [(45 \cdot 2.445) + (145 \cdot 1.947) + (537.26 \cdot 1.49)]$$

$$Q_{FG1} = 2\,483\,514.8 \text{ kJ}$$

$$Q_{FG1} < E \rightarrow \Delta t_{FG} > 2000 \text{ }^\circ\text{C}$$

$$\Delta t_2 = 2\,100 \text{ }^\circ\text{C}$$

	$c_{psi}(2100 \text{ }^\circ\text{C}) \text{ [kJ}\cdot\text{m}^{-3}\cdot\text{K}^{-1}]$
CO ₂	2.457
H ₂ O (g)	1.968
N ₂	1.498

$$Q_{FG2} = \Delta t_2 \cdot \sum c_{psi} \cdot V(FG)_i = 2100 \cdot [(45 \cdot 2.457) + (145 \cdot 1.968) + (537.26 \cdot 1.498)]$$

$$Q_{FG2} = 2\,624\,749 \text{ kJ}$$

$$Q_{FG1} < E < Q_{FG2}$$

→ we calculate the temperature using mathematical interpolation of the line:

$$\Delta t_T = \frac{(\Delta t_1 - \Delta t_2)}{(Q_{FG1} - Q_{FG2})} \cdot (E - Q_{FG1}) + \Delta t_1$$

$$\Delta t_T = \frac{(2000 - 2100)}{(2484514.8 - 2624749)} \cdot (2525150 - 2484514.8) + 2000$$

$$\Delta t_T = \underline{\underline{2029 \text{ }^\circ\text{C}}}$$

EXERCISE 1.18

Calculate the theoretical adiabatic flame temperature for the combustion process of 1 m³ of CH₄ and 1 m³ H₂.

Results: $\Delta t_T(\text{CH}_4) = 2037 \text{ }^\circ\text{C}$; $\Delta t_T(\text{H}_2) = 2230 \text{ }^\circ\text{C}$

EXERCISE 1.19

Calculate the theoretical adiabatic flame temperature for the combustion process of 100 m³ of gas of composition as in exercise 1.13

Results: $\Delta t_T = 2170 \text{ }^\circ\text{C}$

2. THERMODYNAMICS OF WATER AND WATER STEAM

In technology practice “ice”, “water”, “steam” are the usual terms for solid, liquid and gas phase of H₂O.

Steam diagrams (thermal diagrams h - s , p - V and t - s) and steam tables are used to determine the thermodynamic properties of water and steam and for calculations associated with their state changes. **The reference state** here is the internal energy and entropy of ice at **the triple point** ($p_{tp} = 611.66$ Pa, $T_{tp} = 273.16$ K), the internal energy u' and the entropy s' of the saturated liquid are equal to zero and the enthalpy in this state is then $h_{tp} = 0$ kJ · kg⁻¹.

Pressure or **temperature** are sufficient to determine **the state of saturated steam** and **saturated liquid** (boiling water).

The state of superheated steam is usually indicated by **pressure and temperature**, the temperature is higher than the boiling temperature for corresponding pressure.

The state of wet steam (i.e. a mixture of saturated liquid and saturated steam) cannot be unambiguously defined only by **pressure** and **temperature**, because $p = p(T)$. It is necessary to know another determining variable and that is the specific content of steam x . It therefore indicates the **dryness of the steam**. It is the mass ratio of the amount of steam m'' to the amount of mixture ($m = m' + m''$, where m' is the amount of liquid):

$$x = \frac{m''}{m} = \frac{m''}{m'' + m'}$$

It is a dimensionless quantity and has a value between 0 and 1. The difference $(1 - x)$ is called the steam humidity. Using x , **the specific volume of wet steam** can be determined, i.e. the volume of a mixture with a total weight of 1 kg, if we add the volume of a liquid with weight $(1 - x)$ with the volume of dry steam with a weight of x :

$$v_x = (1 - x) v' + x v'' = v' + x (v'' - v') \quad [\text{m}^3 \cdot \text{kg}^{-1}]$$

and similarly the specific enthalpy or entropy of wet steam:

$$h_x = (1 - x) h' + x h'' = h' + x (h'' - h') \quad [\text{kJ} \cdot \text{kg}^{-1}]$$

$$s_x = (1 - x) s' + x s'' = s' + x (s'' - s') \quad [\text{kJ} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}]$$

EXERCISE 2.01

In a pressure vessel water boils at 150 °C. What is the pressure?

Solution:

When water boils, it means that water is in equilibrium represented by a mixture of saturated steam and saturated liquid, i.e. boiling temperature 150 °C corresponds to the pressure at saturation this pressure can be found in *Table XI* → $p(150^\circ\text{C}) = \underline{\underline{0.4761 \text{ MPa}}}$.

EXERCISE 2.02

Calculate the specific enthalpy h_x of the wet steam if $x = 0.9$ and

a) $p = 1,0026 \text{ MPa}$

b) $t = 200^\circ\text{C}$

Solution: use the equation:

$$h_x = h' + x (h'' - h')$$

values of h' and h'' can be found in Table XI:

a) $h'(p = 1.0026 \text{ MPa}) = 763.2 \text{ kJ}\cdot\text{kg}^{-1}$

$h''(p = 1.0026 \text{ MPa}) = 2778 \text{ kJ}\cdot\text{kg}^{-1}$

$$h_x = 763.2 + 0.9 (2778 - 763.2) = \underline{\underline{2576.5 \text{ kJ}\cdot\text{kg}^{-1}}}$$

b) $h'(t = 200^\circ\text{C}) = 852.4 \text{ kJ}\cdot\text{kg}^{-1}$

$h''(t = 200^\circ\text{C}) = 2792 \text{ kJ}\cdot\text{kg}^{-1}$

$$h_x = 852.4 + 0.9 (2792 - 852.4) = \underline{\underline{2598 \text{ kJ}\cdot\text{kg}^{-1}}}$$

EXERCISE 2.03

1 kg of wet steam has a specific volume $v_x = 333.7$ litres and a temperature 150 °C. Calculate the pressure, the dryness of the steam x and the specific enthalpy h_x .

Solution:

pressure of wet steam when the temperature is 150 °C can be found in the Table XI

$$p(150^\circ\text{C}) = \underline{\underline{0.4761 \text{ MPa}}}$$

the dryness of the steam can be calculated using the equation:

$$v_x = v' + x (v'' - v') \rightarrow x = \frac{v_x - v'}{v'' - v'}$$

values of v' and v'' can be found in Table XI:

$v'(t = 150^\circ\text{C}) = 1.0905 \text{ l}\cdot\text{kg}^{-1}$

$v''(t = 150^\circ\text{C}) = 0.3925 \text{ m}^3\cdot\text{kg}^{-1}$

$$x = \frac{v_x - v'}{v'' - v'} = (333.7 - 1.0905) / (329.5 - 1.0905) = \underline{\underline{0.85}}$$

and the specific enthalpy h_x can be calculated in the same way as in EX 2.02

$$h'(t = 150\text{ °C}) = 632.2 \text{ kJ}\cdot\text{kg}^{-1}$$

$$h''(t = 150\text{ °C}) = 2746 \text{ kJ}\cdot\text{kg}^{-1}$$

$$h_x = h' + x(h'' - h') = 632.2 + 0.85(2746 - 632.2) = \underline{\underline{2428.9 \text{ kJ}\cdot\text{kg}^{-1}}}$$

EXERCISE 2.04

The pressure vessel has a volume $V = 4 \text{ m}^3$ and contains wet steam with dryness of the steam $x = 0.587$; pressure is 270.3 kPa. Calculate the heat Q needed to obtain saturated steam (i.e. $x = 1$).

Solution:

heat can be calculated using equation $Q = m_p \cdot dq$ [kJ]

$$m_p = V / v_x$$

$$v_x = v' + x(v'' - v') = 1.0697 + 0.587(668.1 - 1.0697) = \underline{\underline{392.62 \text{ l}\cdot\text{kg}^{-1}}}$$

$$v'(p = 270.3 \text{ kPa}) = 1.0697 \text{ l}\cdot\text{kg}^{-1}$$

$$v''(p = 270.3 \text{ kPa}) = 0.6681 \text{ m}^3\cdot\text{kg}^{-1}$$

$$m_p = 4 / 0.39262 = \underline{\underline{10.19 \text{ kg}}}$$

$$dq = dh - Vdp$$

$$dh = h_2'' - h_x$$

$$h_x = h' + x(h'' - h') = 546.4 + 0.587(2720 - 546.4) = \underline{\underline{1822.3 \text{ kJ}\cdot\text{kg}^{-1}}}$$

$$h'(p = 270.3 \text{ kPa}) = 546.4 \text{ kJ}\cdot\text{kg}^{-1}$$

$$h''(p = 270.3 \text{ kPa}) = 2720 \text{ kJ}\cdot\text{kg}^{-1}$$

h_2'' and p_2 can be found in Table XI for $v_2 = v_x = v'' = 0.3926 \text{ m}^3\cdot\text{kg}^{-1}$

$$h_2'' = 2746 \text{ kJ}\cdot\text{kg}^{-1}$$

$$p_2 = 476.1 \text{ kPa}$$

$$dq = (2746 - 1822.3) - 0.3926(476.1 - 270.3) = \underline{\underline{842.82 \text{ kJ}\cdot\text{kg}^{-1}}}$$

$$Q = m_p \cdot dq = 10.19 \cdot 842.82 = \underline{\underline{8588.4 \text{ kJ}}}$$

EXERCISE 2.05

Wet steam at constant pressure of 1 MPa and $x = 0.1$ was supplied heat of $1\,200\text{ kJ}\cdot\text{kg}^{-1}$. What was the final state of the steam?

Result: $h_2 = 2\,164.1\text{ kJ}\cdot\text{kg}^{-1}$ and $x_2 = 0.7$

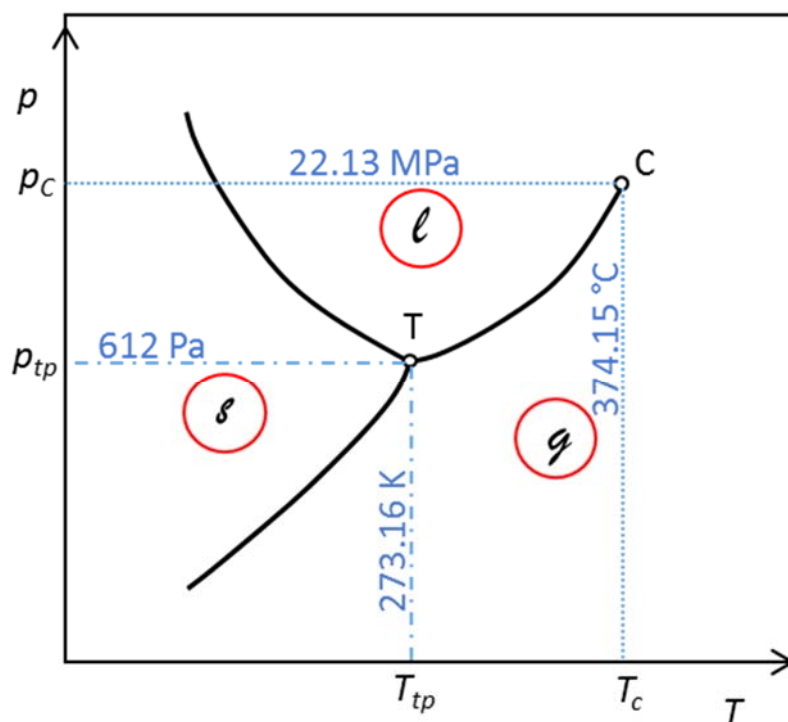
EXERCISE 2.06

Saturated steam of 2.8 MPa is led through a pipeline, where it loses $2\,400\text{ kJ}\cdot\text{m}^{-3}$. Find out the dryness of the steam at the outlet of the pipe.

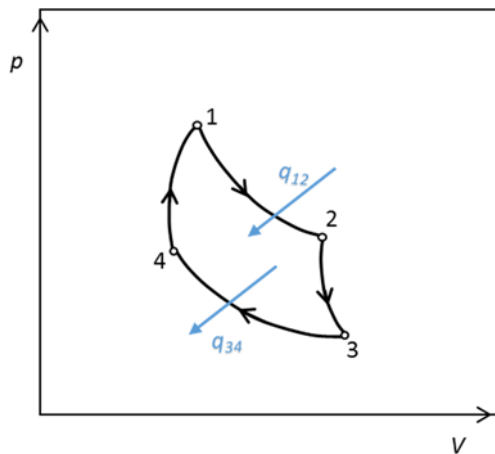
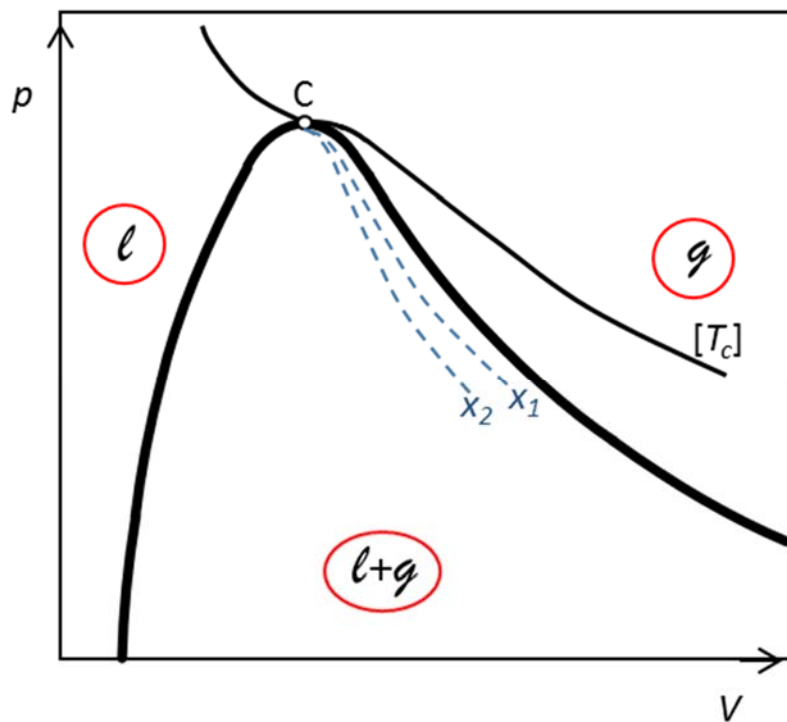
Result: $x_2 = 0.91$

Water state diagrams

Water state p-T diagram



Water state p-V diagram



Carnot cycle

1-2 isothermal expansion

2-3 adiabatic expansion

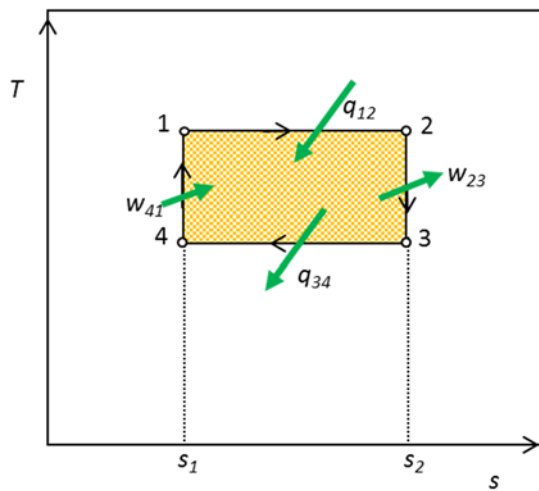
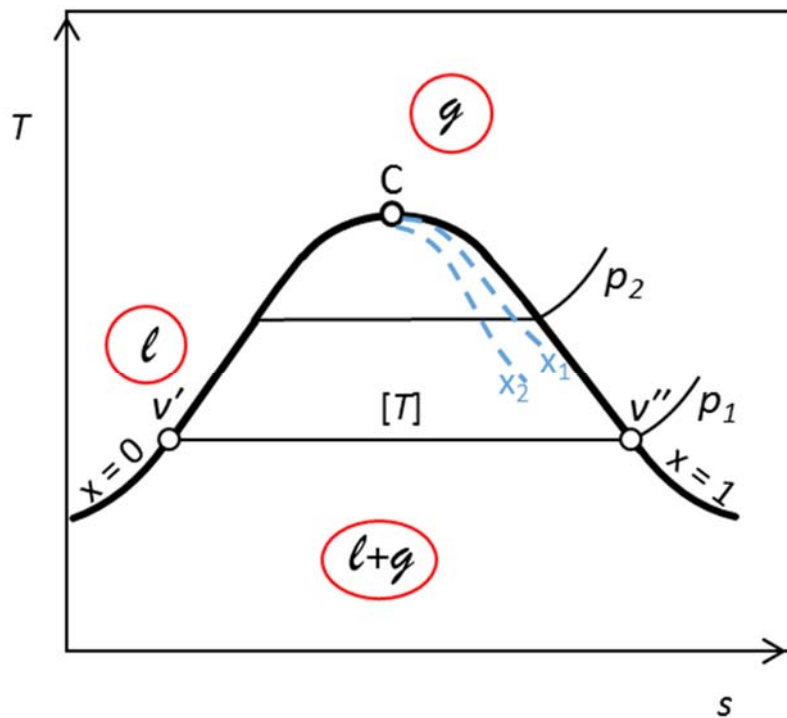
3-4 isothermal compression

4-1 adiabatic compression

Heat is the area under the curve – i.e. q_{12} heat supplied = the area under the curve 1-2 $\rightarrow$ mathematic integration must be used, but we know, that

$$dQ = T \cdot ds$$

Water state T-s diagram



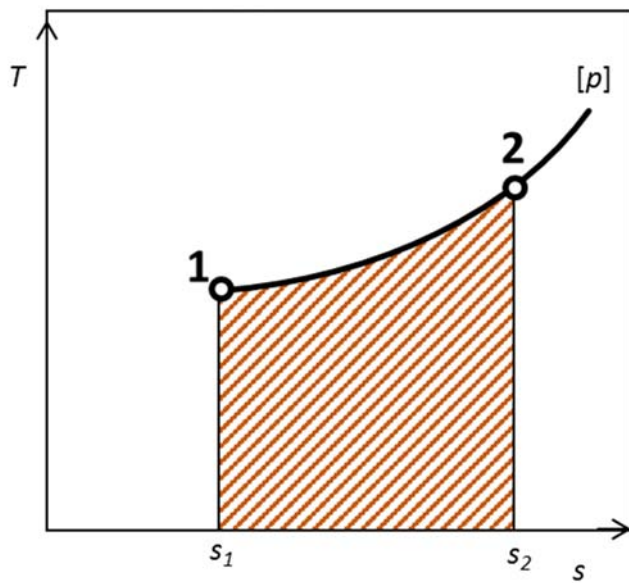
Carnot cycle

- 1-2 isothermal expansion** q_{12} - heat supplied
- 2-3 adiabatic expansion** w_{23} work performed by system
- 3-4 isothermal compression** q_{34} - discharge heat
- 4-1 adiabatic compression** w_{41} work supplied by the compressor

$$w_{12} = q_{34} - q_{12}$$

Thermal efficiency of the Carnot cycle:

$$\eta = w_{12}/q_{12} = (q_{34} - q_{12})/q_{12} = (T_1\Delta s - T_2\Delta s)/T_1\Delta s = (T_1 - T_2)/T_1$$



Isobaric heating

$$[p] \rightarrow w = -p\Delta V$$

$$\Delta U = Q + w$$

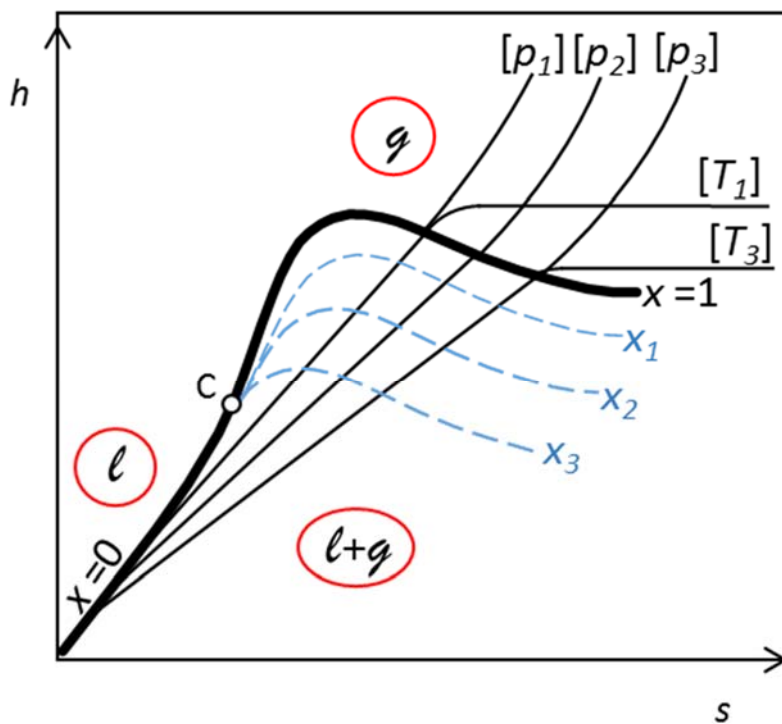
$$\Delta U = Q - p\Delta V = Q - p(V_2 - V_1)$$

$$Q = (U_2 - U_1) + pV_2 - pV_1$$

$$Q = (U_2 + pV_2) - (U_1 + pV_1)$$

$$\mathbf{Q = h_2 - h_1}$$

Water state h-s diagram



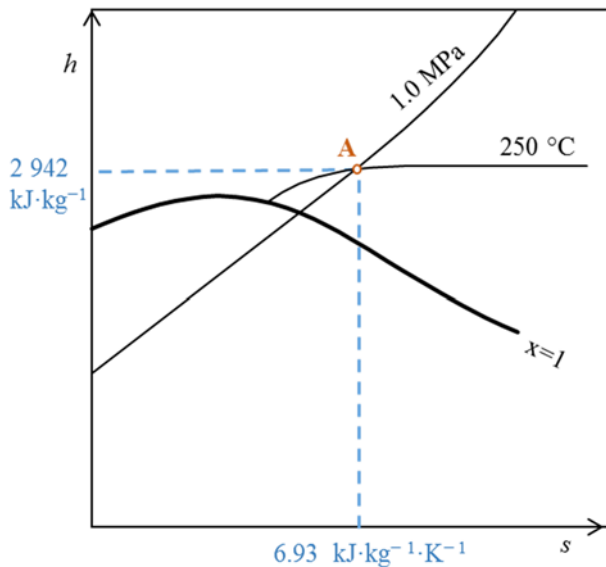
EXERCISE 2.07

Find the state of the steam in the h - s diagram and determine the other quantities in the following cases:

- a) $p = 1 \text{ MPa}$, $t = 250 \text{ }^{\circ}\text{C}$
- b) $p = 0.005 \text{ MPa}$, $t = 50 \text{ }^{\circ}\text{C}$
- c) $p = 8 \text{ MPa}$, $t = 480 \text{ }^{\circ}\text{C}$
- d) $p = 2.8 \text{ MPa}$, $t = 420 \text{ }^{\circ}\text{C}$

Solution:

a) the state of this steam is given by the intersection of the isobar $p = 1.0 \text{ MPa}$ and the isotherm $t = 250 \text{ }^{\circ}\text{C}$ lying in the region of superheated steam (point A in figure).



Enthalpy of the superheated steam is read on the h -axis:

$$h = 2945 \text{ kJ}\cdot\text{kg}^{-1}$$

Entropy on the s -axis:

$$s = 6.93 \text{ kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}.$$

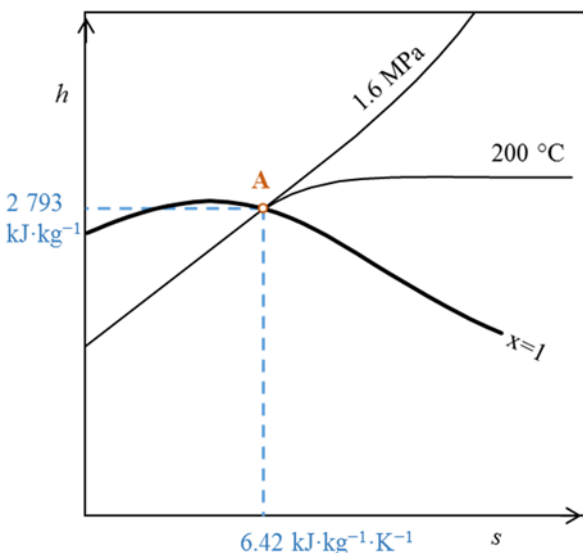
$$\text{b) } h = 2595 \text{ kJ}\cdot\text{kg}^{-1}; \quad s = 8.50 \text{ kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$$

$$\text{c) } h = 3350 \text{ kJ}\cdot\text{kg}^{-1}; \quad s = 6.67 \text{ kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$$

$$\text{d) } h = 3285 \text{ kJ}\cdot\text{kg}^{-1}; \quad s = 7.03 \text{ kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$$

EXERCISE 2.08

Saturated steam has a pressure $p = 1.6 \text{ MPa}$. Find its state in the h - s diagram.



Solution:

The state is given by the intersection of the isobar $p = 1.6 \text{ MPa}$ with the limit curve $x = 1$ (point A in figure)

$$t = 200 \text{ }^{\circ}\text{C};$$

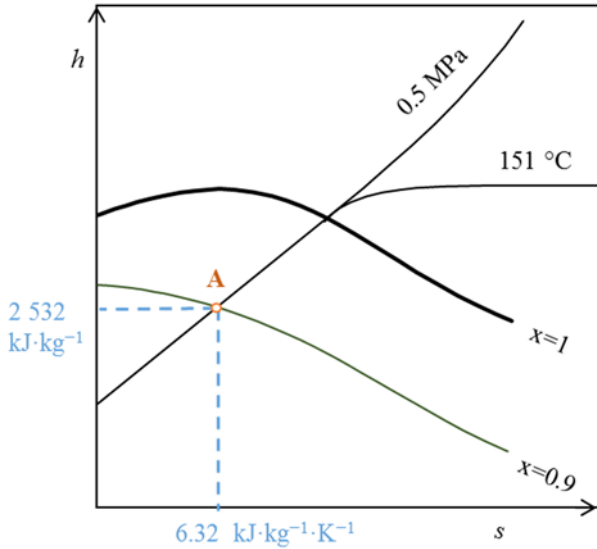
$$h'' = 2795 \text{ kJ}\cdot\text{kg}^{-1};$$

$$s'' = 6.42 \text{ kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$$

EXERCISE 2.09

Determine the state properties of wet steam with the following parameters:

- $p = 0.5 \text{ MPa}$, $x = 0.9$
- $p = 0.004 \text{ MPa}$, $x = 0.95$
- $p = 4 \text{ MPa}$, $x = 0.98$



Solution:

a) In the area of wet steam we find the intersection of the line $x = 0.9$ and the isobar $p = 0.5 \text{ MPa}$ (point A in figure):

$$h = 2540 \text{ kJ} \cdot \text{kg}^{-1};$$

$$s = 6.33 \text{ kJ} \cdot \text{kg}^{-1} \cdot \text{K}^{-1};$$

$$t = 151 \text{ }^{\circ}\text{C}$$

$$\begin{aligned} \text{b) } h &= 2435 \text{ kJ} \cdot \text{kg}^{-1}; \\ t &= 30 \text{ }^{\circ}\text{C}; \\ s &= 8.07 \text{ kJ} \cdot \text{kg}^{-1} \cdot \text{K}^{-1} \end{aligned}$$

$$\begin{aligned} \text{c) } h &= 2770 \text{ kJ} \cdot \text{kg}^{-1}; \\ t &= 250 \text{ }^{\circ}\text{C}; \\ s &= 6.00 \text{ kJ} \cdot \text{kg}^{-1} \cdot \text{K}^{-1} \end{aligned}$$

EXERCISE 2.10

Find the state of the steam in the h - s diagram and determine the properties in the following cases:

- $p = 10 \text{ MPa}$; $t = 320 \text{ }^{\circ}\text{C}$
- $p = 1.5 \text{ MPa}$; $t = 280 \text{ }^{\circ}\text{C}$
- $p = 1 \text{ MPa}$; $x = 0.85$
- $p = 12 \text{ MPa}$; $t = 530 \text{ }^{\circ}\text{C}$
- $p = 5 \text{ MPa}$; $t = 480 \text{ }^{\circ}\text{C}$
- $t = 200 \text{ }^{\circ}\text{C}$; $x = 0.83$
- $p = 0.3 \text{ MPa}$; $h = 2724 \text{ kJ/kg}$
- $p = 2 \text{ MPa}$; $t = 450 \text{ }^{\circ}\text{C}$
- $p = 0.02 \text{ MPa}$; $h = 2420 \text{ kJ/kg}$
- $p = 0.03 \text{ MPa}$; $x = 0.75$

- superheated steam; $h = 2780 \text{ kJ/kg}$; $s = 5.71 \text{ kJ/kgK}$
- superheated steam; $h = 2988 \text{ kJ/kg}$; $s = 6.84 \text{ kJ/kgK}$
- wet steam; $h = 2472 \text{ kJ/kg}$; $s = 5.91 \text{ kJ/kgK}$; $t = 180 \text{ }^{\circ}\text{C}$
- superheated steam; $h = 3428 \text{ kJ/kg}$; $s = 6.59 \text{ kJ/kgK}$
- superheated steam; $h = 3394 \text{ kJ/kg}$; $s = 6.91 \text{ kJ/kgK}$
- wet steam; $h = 2456 \text{ kJ/kg}$; $s = 5.72 \text{ kJ/kgK}$; $p = 1.55 \text{ MPa}$
- Saturated steam; $t = 135 \text{ }^{\circ}\text{C}$; $s = 6.99 \text{ kJ/kgK}$
- superheated steam; $h = 3356 \text{ kJ/kg}$; $s = 7.38 \text{ kJ/kgK}$
- wet steam; $t = 58 \text{ }^{\circ}\text{C}$; $s = 5.71 \text{ kJ/kgK}$; $x = 0.92$
- wet steam; $h = 2038 \text{ kJ/kg}$; $s = 6.06 \text{ kJ/kgK}$; $t = 73 \text{ }^{\circ}\text{C}$

EXERCISE 2.11

Steam with pressure $p_1 = 4 \text{ MPa}$ and temperature $t_1 = 450 \text{ °C}$ expands adiabatically to pressure $p_2 = 0.005 \text{ MPa}$. Find the change in enthalpy, and the state of steam after expansion.

Solution: In the diagram h - s we find the intersection of the isobar 4.0 MPa and the isotherm 450 °C , which corresponds to the superheated steam state (point 1 in figure). Adiabatic expansion takes place from point 1 along the isoentropes to point 2, which is given by the intersection of isoentropes 1-2 and isobars $p_2 = 0.005 \text{ MPa}$. The adiabatic

gradient is then equal to:

$$\Delta h_{ad} = h_1 - h_2$$

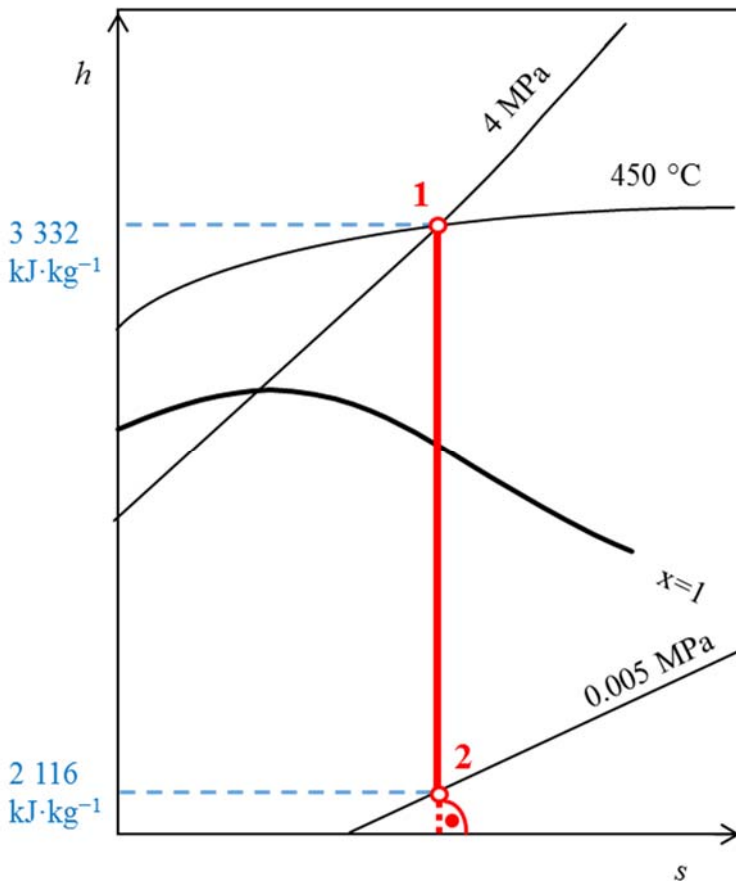
$$\Delta h_{ad} = 3\,335 - 2\,120$$

$$\Delta h_{ad} = \underline{\underline{1\,215 \text{ kJ}\cdot\text{kg}^{-1}}}$$

The state of steam after expansion is determined by pressure and dryness:

$$\underline{\underline{p_2 = 0.005 \text{ MPa}}}$$

$$\underline{\underline{x_2 = 0.82}}$$

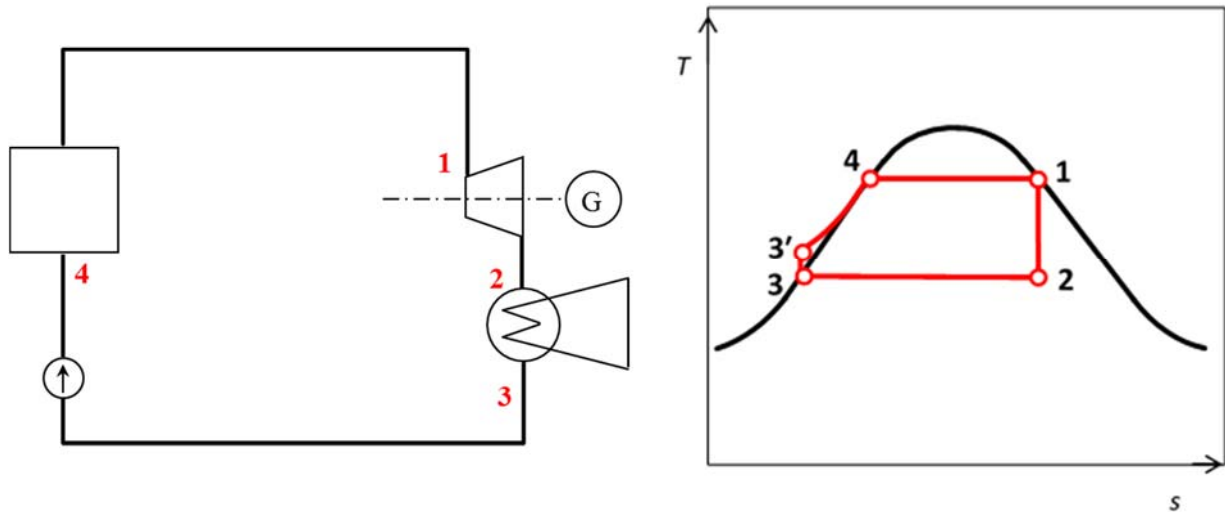
**EXERCISE 2.12**

$5600 \text{ kg}\cdot\text{s}^{-1}$ of steam expands adiabatically from a pressure of $p_1 = 1.6 \text{ MPa}$ and $t_1 = 350 \text{ °C}$ to $p_2 = 0.1 \text{ MPa}$. Calculate the turbine power.

Result: $P = 902 \text{ KW}$

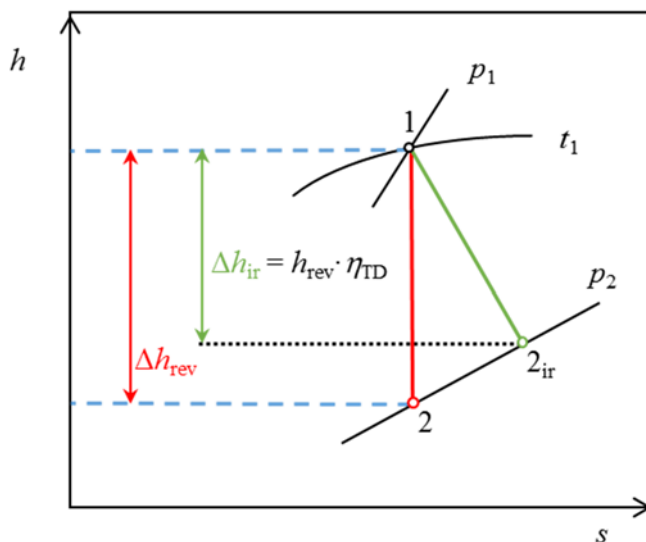
Clausius-Rankine Cycle

The comparative heat cycle, where the working substance is water, is the Clausius-Rankine cycle. The saturated steam produced in the boiler is led to the steam engine, where it expands and produces work, and after subsequent condensation it returns to the boiler.



The thermal efficiency of this cycle is given by the ratio of the heat converted to work to the total heat supplied:

$$\eta_t = \frac{h_1 - h_2}{h_1 - h'_3} = \frac{w}{\lambda}$$



Heat transferred to work is ideally equal to adiabatic/reversible expansion Δh_{rev} , but no machine works ideally, the work of the turbine is equal to the so-called irreversible expansion Δh_{ir} (polytropic process). The relationship between reversible and irreversible expansion is the thermodynamic efficiency:

$$\eta_{TD} = \frac{\Delta h_{ir}}{\Delta h_{rev}} = \frac{w_{real}}{w_{ad}}$$

EXERCISE 2.13

Calculate the thermodynamic efficiency if the superheated steam has a pressure $p_1 = 10$ MPa and a temperature $t_1 = 500$ °C and the wet steam after expansion has a dryness of 0.9 and a pressure $p_2 = 3$ kPa.

Result: $\eta_{TD} = 0.76$

EXERCISE 2.13

The 200 MW turbine has a thermodynamic efficiency of 0.91; coal with a $LHV = 14\,000\text{ kJ}\cdot\text{kg}^{-1}$ is burned in the boiler the efficiency of the boiler is 0.83.

The parameters of the admission steam are $p_1 = 17\text{ MPa}$ and $t_1 = 550\text{ °C}$, the emission steam has a pressure of 4 kPa; the cooling water is heated by 6 °C in the condenser.

Calculate: a) the hourly steam consumption – steam mass flow $\dot{m}_{st}\text{ [t}\cdot\text{h}^{-1}]$

b) hourly cooling water consumption – cooling water mass flow $\dot{m}_{cw}\text{ [t}\cdot\text{h}^{-1}]$

c) hourly fuel consumption – fuel mass flow $\dot{m}_f\text{ [t}\cdot\text{h}^{-1}]$

d) thermal efficiency

Solution:

a) use the equation: $P \cdot \tau = \dot{m}_{st} \cdot w_{real}$

$$w_{real} = \Delta h_{ir} = h_1 - h_{2ir} = \eta_{TD} \cdot (h_1 - h_2)$$

in h-s diagram find the values of enthalpy h_1 and h_2

$$h_1 = 3\,428\text{ kJ}\cdot\text{kg}^{-1} \quad h_2 = 1\,940\text{ kJ}\cdot\text{kg}^{-1}$$

$$\Delta h_{ir} = h_1 - h_{2ir} = \eta_{TD} \cdot (h_1 - h_2) = 0.91 \cdot (3428 - 1940) = \underline{1354.1\text{ kJ}\cdot\text{kg}^{-1}}$$

$$\dot{m}_{st} = \frac{P \cdot \tau}{\Delta h_{ir}} = \frac{200 \cdot 10^3 \cdot 3600}{1354.4} = \underline{531.7\text{ t}\cdot\text{h}^{-1}}$$

b) use the equation: $\dot{m}_{cw} \cdot \Delta t_{cw} \cdot c_p = \dot{m}_{st} \cdot r$

$$r = (h_{2ir} - h'_3)$$

$$h_{2ir} = h_1 - \Delta h_{ir} = 3428 - 1354.1 = 2073.9\text{ kJ}\cdot\text{kg}^{-1}$$

$$h'_3 = \text{enthalpy of saturated water can be found in Table XI} = 121.35\text{ kJ}\cdot\text{kg}^{-1}$$

$$\text{for } c_p \text{ of water use value } 4.19\text{ kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$$

$$\dot{m}_{cw} = \frac{\dot{m}_{st} \cdot r}{\Delta t_{cw} \cdot c_p} = \frac{531.7 \cdot (2073.1 - 121.35)}{6 \cdot 4.19} = \underline{41\,295.65\text{ t}\cdot\text{h}^{-1}}$$

c) use the equation: $\dot{m}_f \cdot LHV \cdot \eta_b = \dot{m}_{st} \cdot \lambda$

$$\text{production heat of steam} \quad \lambda = (h_1 - h'_3)$$

$$\dot{m}_f = \frac{\dot{m}_{st} \cdot \lambda}{LHV \cdot \eta_b} = \frac{531.7 \cdot (3428 - 121.35)}{14\,000 \cdot 0.83} = \underline{151.3\text{ t}\cdot\text{h}^{-1}}$$

d) to calculate thermal efficiency use equation:

$$\eta_t = \frac{w_{real}}{\lambda} = \frac{h_1 - h_{2ir}}{h_1 - h'_3} = \frac{1354.1}{3306.65} = \underline{\underline{40.95 \%}}$$

EXERCISE 2.14

Calculate the specific mass flow of steam and cooling water if the admission steam has $p_1 = 5 \text{ MPa}$ and $t_1 = 320 \text{ }^\circ\text{C}$; $p_2 = 0.01 \text{ MPa}$; $\eta_{TD} = 0.8$ and $\Delta t_{cw} = 8 \text{ }^\circ\text{C}$.

Solution:

- the specific mass flow of steam (adiabatic expansion) $d_{rev} = \frac{3600}{\Delta h_{rev}} \quad [\text{kg} \cdot \text{kWh}^{-1}]$
- the specific mass flow of steam (irreversible expansion) $d_{ir} = \frac{3600}{\Delta h_{ir}} \quad [\text{kg} \cdot \text{kWh}^{-1}]$
- the specific mass flow of cooling water $d_{cw} = \frac{r}{\Delta t_{cw} \cdot c_p} \quad [\text{kg} \cdot \text{kg}^{-1}]$

$$\Delta h_{rev} = h_1 - h_2$$

$$\Delta h_{ir} = h_1 - h_{2ir}$$

$$r = (h_{2ir} - h'_3)$$

in h-s diagram find the values of enthalpy h_1 and h_2

$$h_1 = 2984 \text{ kJ} \cdot \text{kg}^{-1} \quad h_2 = 1984 \text{ kJ} \cdot \text{kg}^{-1}$$

$$\Delta h_{rev} = h_1 - h_2 = 2984 - 1984 = 988 \text{ kJ} \cdot \text{kg}^{-1}$$

$$\Delta h_{ir} = h_1 - h_{2ir} = \eta_{TD} \cdot \Delta h_{rel} = 0.8 \cdot 988 = 790.4 \text{ kJ} \cdot \text{kg}^{-1}$$

$$d_{rev} = \frac{3600}{\Delta h_{rev}} = \frac{3600}{988} = \underline{\underline{3.64 \text{ kg} \cdot \text{kWh}^{-1}}}$$

$$d_{ir} = \frac{3600}{\Delta h_{ir}} = \frac{3600}{790.4} = \underline{\underline{4.56 \text{ kg} \cdot \text{kWh}^{-1}}}$$

$$h_{2ir} = h_1 - \Delta h_{ir} = 2984 - 790.4 = 2193.6 \text{ kJ} \cdot \text{kg}^{-1}$$

h'_3 = enthalpy of saturated water can be found in Table XII = $191.9 \text{ kJ} \cdot \text{kg}^{-1}$

$$d_{cw} = \frac{r}{\Delta t_{cw} \cdot c_p} = \frac{2193.6 - 191.9}{8 \cdot 4.19} = \underline{\underline{59.7 \text{ kg} \cdot \text{kg}^{-1}}}$$

EXERCISE 2.15

A 135 MW turbine has a thermodynamic efficiency of 0.94; coal with a $LHV = 9\,000\text{ kJ}\cdot\text{kg}^{-1}$ is burned in a boiler the efficiency of the boiler is 0.89.

The parameters of the admission steam are $p_1 = 12\text{ MPa}$ and $t_1 = 480\text{ }^\circ\text{C}$, the emission steam has a pressure of 5 kPa; the cooling water is heated by $8\text{ }^\circ\text{C}$ in the condenser.

Calculate: a) the hourly steam consumption – steam flow $\dot{m}_{st}\text{ [t}\cdot\text{h}^{-1}\text{]}$

b) hourly cooling water consumption – cooling water mass flow $\dot{m}_{cw}\text{ [t}\cdot\text{h}^{-1}\text{]}$

c) hourly fuel consumption – fuel mass flow $\dot{m}_f\text{ [t}\cdot\text{h}^{-1}\text{]}$

d) thermal efficiency

Results: $\dot{m}_{st} = 385.84\text{ t}\cdot\text{h}^{-1}$; $\dot{m}_{cw} = 21823.2\text{ t}\cdot\text{h}^{-1}$; $\dot{m}_f = 152\text{ t}\cdot\text{h}^{-1}$; $\eta_t = 39.9\%$

EXERCISE 2.16

A 60 MW turbine has a thermodynamic efficiency of 0.70; coal with a $LHV = 14\,000\text{ kJ}\cdot\text{kg}^{-1}$ is burned in a boiler, the efficiency of the boiler is 0.80. The parameters of the admission steam are $p_1 = 8\text{ MPa}$ and $t_1 = 400\text{ }^\circ\text{C}$, the emission steam has a pressure of 5 kPa; the cooling water is heated by $7\text{ }^\circ\text{C}$ in a condenser.

Calculate: a) the hourly steam consumption – steam flow $\dot{m}_{st}\text{ [t}\cdot\text{h}^{-1}\text{]}$ and the specific mass flow of steam

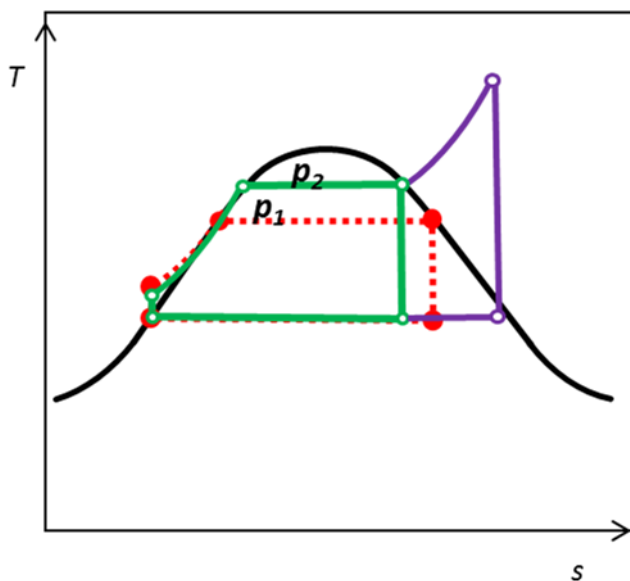
b) hourly cooling water consumption – cooling water mass flow $\dot{m}_{cw}\text{ [t}\cdot\text{h}^{-1}\text{]}$ and specific mass flow of cooling water

c) hourly fuel consumption – fuel mass flow $\dot{m}_f\text{ [t}\cdot\text{h}^{-1}\text{]}$

d) thermal efficiency

Results: $\dot{m}_{st} = 257.1\text{ t}\cdot\text{h}^{-1}$; $d_{ir} = 4.29\text{ kg}\cdot\text{kWh}^{-1}$; $\dot{m}_{cw} = 18929.7\text{ t}\cdot\text{h}^{-1}$; $d_{cw} = 73.6\text{ kg}\cdot\text{kg}^{-1}$; $\dot{m}_f = 68.85\text{ t}\cdot\text{h}^{-1}$; $\eta_t = 28\%$

Increase of thermal efficiency



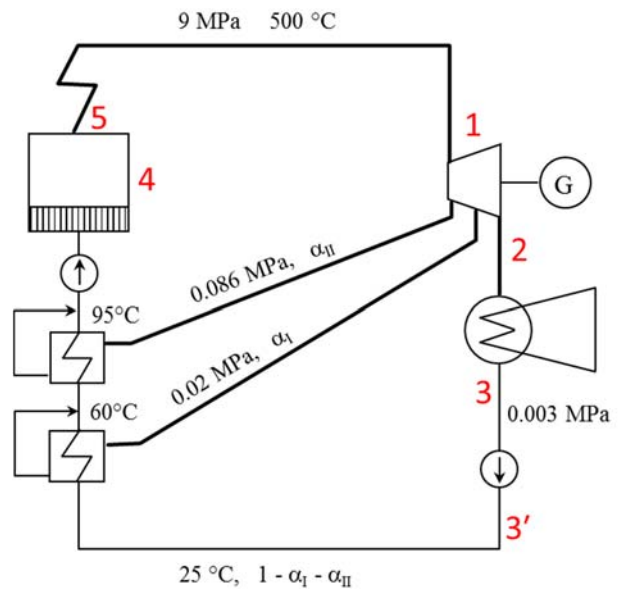
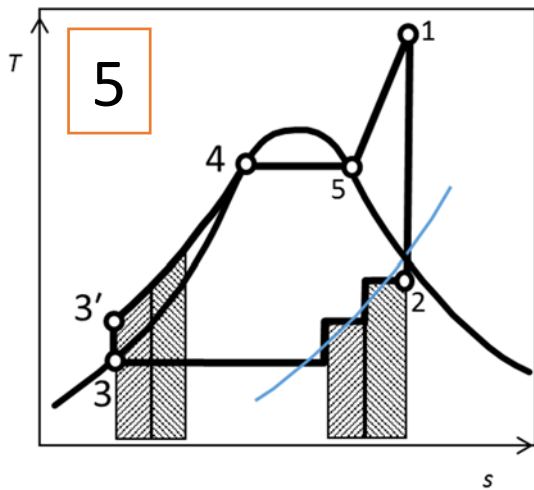
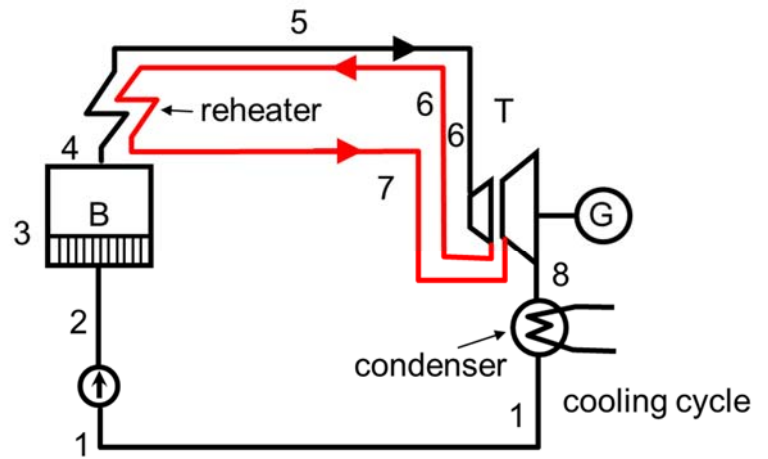
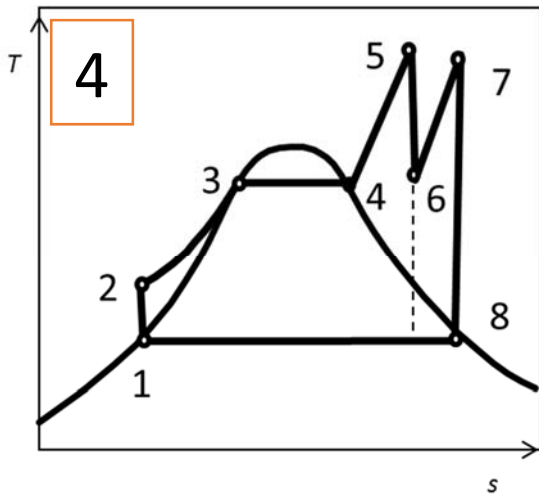
1) increase of pressure or temperature of the admission water steam

2) steam superheating

3) decrease of pressure of condensation

4) steam reheating

5) carnotization of the cycle



EXERCISE 2.17

Calculate the thermal efficiency if $p_1 = 10 \text{ MPa}$ and $p_2 = 4 \text{ kPa}$

a) $t_1 = 400^\circ \text{C}$

b) $t_1 = 500^\circ \text{C}$

bb) at a pressure of 1 MPa, we reheat the steam to a temperature of 400°C

Solution:

$$\eta_t = \frac{w}{\lambda} = \frac{h_1 - h_2}{h_1 - h'_3}$$

a) in h-s diagram find the values of enthalpy h_1 and h_2 ;

$$h_1 = 3096 \text{ kJ} \cdot \text{kg}^{-1}$$

$$h_2 = 1872 \text{ kJ} \cdot \text{kg}^{-1}$$

enthalpy of saturated water can be found in Table XII

$$h'_3 = 121.35 \text{ kJ}\cdot\text{kg}^{-1}$$

$$\eta_t = \frac{h_1 - h_2}{h_1 - h'_3} = \frac{3096 - 1872}{3096 - 121,35} = \underline{\underline{41.15 \%}}$$

b) in h-s diagram find the values of enthalpy h_1 and h_2 ;

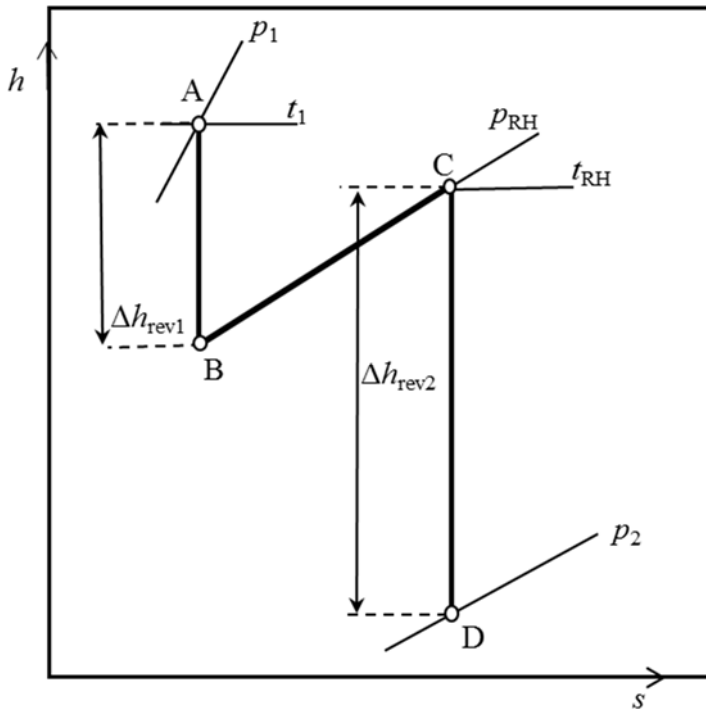
$$h_1 = 3\,372 \text{ kJ}\cdot\text{kg}^{-1} \quad h_2 = 1\,984 \text{ kJ}\cdot\text{kg}^{-1}$$

enthalpy of saturated water can be found in Table XII

$$h'_3 = 121.35 \text{ kJ}\cdot\text{kg}^{-1}$$

$$\eta_t = \frac{h_1 - h_2}{h_1 - h'_3} = \frac{3372 - 1984}{3372 - 121,35} = \underline{\underline{42.70 \%}}$$

bb) in h-s diagram found the values of enthalpy h_A ; h_B ; h_C and h_D



$$h_A = 3\,372 \text{ kJ}\cdot\text{kg}^{-1}$$

$$h_B = 2\,786 \text{ kJ}\cdot\text{kg}^{-1}$$

$$h_C = 3\,264 \text{ kJ}\cdot\text{kg}^{-1}$$

$$h_D = 2\,252 \text{ kJ}\cdot\text{kg}^{-1}$$

$$h'_3 = 121.35 \text{ kJ}\cdot\text{kg}^{-1}$$

$$\eta_t = \frac{\Delta h_{rev1} + \Delta h_{rev2}}{\lambda + (h_C - h_B)} = \frac{(h_A - h_B) + (h_C - h_D)}{(h_A - h'_3) + (h_C - h_B)} = \frac{(3372 - 2786) + (3264 - 2252)}{(3372 - 121,35) + (3264 - 2786)}$$

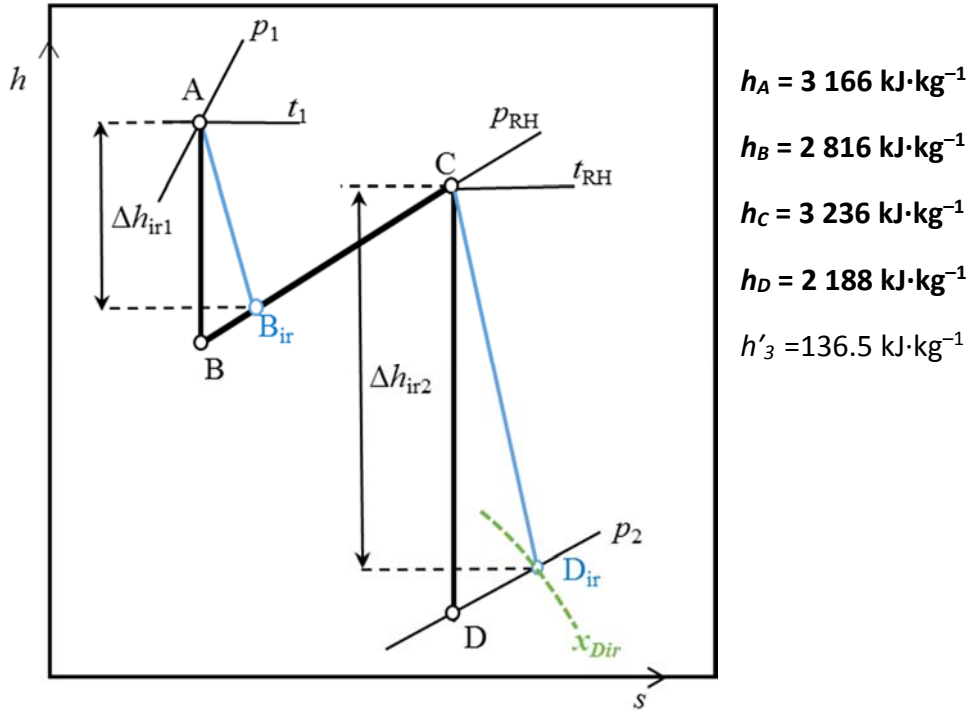
$$\eta_t = \underline{\underline{42.86 \%}}$$

EXERCISE 2.18

Calculate the thermal efficiency if $p_1 = 11 \text{ MPa}$; $t_1 = 430 \text{ }^\circ\text{C}$, and at a pressure of 2.6 MPa , we reheat the steam to a temperature of $400 \text{ }^\circ\text{C}$, and $p_2 = 5 \text{ kPa}$. The turbine has a thermodynamic efficiency of 0.90 . Find out the dryness of the steam at the outlet of the turbine.

Solution:

$$\eta_t = \frac{\Delta h_{ir1} + \Delta h_{ir2}}{\lambda + (h_C - h_{Bir})} = \frac{[(h_A - h_B) + (h_C - h_D)] \cdot \eta_{TD}}{(h_A - h'_3) + (h_C - h_{Bir})}$$



$$h_{Bir} = h_A - \Delta h_{ir1} = 3166 - 315 = 2\,851 \text{ kJ}\cdot\text{kg}^{-1}$$

$$\Delta h_{ir1} = \eta_{TD} \cdot \Delta h_{rel1} = 0.9 \cdot (3166 - 2816) = 315 \text{ kJ} \cdot \text{kg}^{-1}$$

$$\eta_t = \frac{[(h_A - h_B) + (h_C - h_D)] \cdot \eta_{TD}}{(h_A - h'_3) + (h_C - h_{Bir})}$$

$$\eta_t = \frac{[(3166-2816)+(3236-2188)] \cdot 0.9}{(3166-136,5)+(3236-2851)} = \underline{\underline{36.85\%}}$$

in h-s diagram find the values of the dryness of the steam at the intersection of pressure $p_2 = 5 \text{ kPa}$ and enthalpy h_{Dir}

$$h_{Dir} = h_C - \Delta h_{ir2} = 3236 - 943.2 = 2\,292.8 \text{ kJ}\cdot\text{kg}^{-1}$$

$$\Delta h_{ir2} = \eta_{TD} \cdot \Delta h_{rel2} = 0.9 \cdot (3236 - 2188) = 943.2 \text{ kJ} \cdot \text{kg}^{-1}$$

$X_{Dir} = 0.89$

3. MASS AND HEAT BALANCE

Mass balance of a technological process or system is a calculation, by which it is estimated how much of each constituent enters, accumulates, is created or lost within this process or system during a given time, during which the process takes place. In other words, mass balance is a mathematical application of the mass conservation law.

Mass balance allows to estimate the mass of those constituents of the system, for which it is either difficult or even impossible to measure their mass in the system experimentally.

The general principles of a mass balance described in this section apply to fuel combustion (e.g. in a boiler or furnace) as well as to gasification of fuel or waste in generators, owing to the fact that gasification may be considered an incomplete combustion. Because chemical reactions take place during combustion or gasification processes in which chemical compounds are transformed into others, it is convenient to base the mass balance on partial balances of individual chemical elements (i.e. not chemical compounds) because they do not undergo any changes during the process, nor can they be created or lost.

The basic components of the mass balance of combustion and gasification processes are as follows:

- | | |
|----------------|--|
| <u>Input:</u> | <ol style="list-style-type: none">1. mass of fuel2. mass of dry air3. mass of humidity present in air |
| <u>Output:</u> | <ol style="list-style-type: none">1. mass of dry gaseous flue gas2. mass of water vapour (humidity) present in flue gas3. mass of slag (i.e. the solid residue left after complete combustion or gasification) |

In real systems, other components may be present, such as fly ash, tar and soot leaving with the outcoming gas, or water vapour used at inlet of a gasification process. These components must be estimated by measurement.

The following are the partial mass balances that constitute the mass balance of a system:

1. **c a r b o n b a l a n c e** , by which the **mass of dry gaseous flue gas** is estimated from the known amount of carbon present in the fuel, slag and flue gas
2. **n i t r o g e n b a l a n c e** , by which the **mass of total dry air** is estimated from the known amount of nitrogen present in the fuel slag and flue gas
3. **h y d r o g e n b a l a n c e** (or water balance), by which the **mass of water vapour (humidity) in the flue gas** is estimated from the known amount of humidity present in the air, and the known amounts of hydrogen and humidity present in the fuel.

Input data necessary to perform the mass and heat balances (more about heat balance below) are usually the average of several measurements taken in given intervals, e.g. 12 or 24 hours), at steady-state operation. The following are the typical data measured and collected:

1. mass of fuel consumed and its temperature
2. proximate (combustible, ash, water) and ultimate (elemental – carbon, hydrogen, nitrogen, oxygen, etc.) analysis of fuel and its heat of combustion
3. composition and temperature of gaseous flue gas as well as all other outcoming substances
4. temperature and composition of slag, i.e. ash and unburned carbon; the mass of slag is either measured directly or calculated from the known amount of ash in slag and fuel
5. temperature, pressure and humidity of air at inlet to the system
6. mass and state of incoming steam or humidity of outcoming gas (during gasification)

It is not necessary to consider steam produced in the system when performing the balance, because equal amount of steam is produced from incoming feedwater and hence the same number would be present on both sides of the balance.

The mas balance is typically calculated on the basis of 100 kg of consumed fuel.

Enthalpy balance (also heat balance) is the mathematical expression of the energy conservation law. Enthalpy balance may be considered a form of energy balance, where the changes in kinetic and potential energies and performed work may be neglected. Enthalpy balance comprises of the heat of combustion of fuel and gaseous flue gas and with the enthalpy of water vapour present in air and flue gas. If the enthalpy balance is based on its low heat value (fuel efficiency), then only the heat capacity of water vapour in air and flue gas is considered. The reference temperature for the enthalpy balance is typically 0 °C or the lowest temperature of one of the system's components (usually fuel).

- Input:
1. enthalpy of all components entering the system relative to the reference temperature
 2. heat of combustion of the fuel
 3. heat produced by all exothermal reactions that take place in the system other than the combustion or gasification in question
 4. heat from other sources that enters the system

- Output:
1. enthalpy of all components leaving the system relative to the reference temperature
 2. heat of combustion of products of incomplete combustion (or products of gasification)

3. heat of possible endothermal reactions, in case it is absorbed within the system
4. heat taken from the system and used for other purposes, e.g. heat used in a steam generator to produce steam or heat transferred during cooling
5. thermal losses to the environment

Thermal efficiency η_{SG} of a steam generator (boiler) is expressed as the ratio of heat used for the intended purpose and total amount of heat supplied to the system. It can be expressed as the fraction of supplied heat or as percentage, where the remaining part represents heat losses. Procedure of calculating thermal efficiency of steam generators and boilers is given in detail by the Czech standard ČSN 07 0302 called “Steam generator acceptance tests”, which uses the heat balance based on heats of combustion as described above, and the standard ČSN 07 0305 called “Evaluation of boiler losses”.

Considering that the most significant part of the supplied heat originates in the fuel, steam generator thermal efficiency may simply be calculated as the ratio of utilized heat to the low heat value (*LHV*) of the fuel.

In the case of gasification units, two values of efficiency are distinguished: the hot efficiency, in which case the utilized heat contains heat of the hot gas including all products of gasification directly coming out from the gasification chamber; this value is important in the specific case when the produced gas is burnt directly at outlet of the gasification chamber. The second efficiency is the cold efficiency, where the produced gas is cold and cleaned and the utilized heat is its low or high heat value.

EXERCISE 3.01

Calculate the enthalpy balance and thermal efficiency of a steam generator, where the following characteristics coming from steady-state operation are available:

Length of measurement: 12 hours

Mass of burnt coal: 260 t

Mass of produced steam: 980 t

Analyses and measurements were performed in one-hour intervals and the following mean values were obtained:

Coal: C 50.20 % w_t ; H 2.80 % w_t ; S 1.19 % w_t ; O 6.51 % w_t ; N 1.00 % w_t ;
ash matter 8.20 % w_t ; water 30.10 % w_t .

HHV 16 886 kJ·kg⁻¹; temperature 15 °C, ($c = 0.8$ kJ·kg⁻¹·K⁻¹).

Slag: ash 80.9 % w_t ; C 19.1 % w_t ; temperature 100 °C ($c = 1.0$ kJ·kg⁻¹·K⁻¹).

Air: temperature 22 °C; relative humidity 60 %;
atmospheric pressure 99 kPa.

Dry flue gas: (CO₂ + SO₂) 15.38 % v/v; CO 0.04 % v/v; N₂ 81.05 % v/v; O₂ 3.53 % v/v
temperature 300.5 °C.

Steam: pressure 3 MPa temperature 400 °C

Feed water: temperature 105 °C

Solution:

Schematic drawing of the balance is shown in Fig. 3.01.

Mass balance

The balance is calculated for 100 kg of burnt coal.

1. Carbon balance:

slag: the mass of slag is not available from analyses, therefore, we shall calculate it from the data available for ash. If we consider no or negligible fly-ash is lost from the system, all ash present in fuel is transformed into slag.

Slag is comprised of ash (100 kg coal contains 8.2% w_t of ash matter, i.e. 8.2 kg, which is transformed in ash representing 80.9 % w_t of slag) and unburned carbon (represented by carbon level of 19.1 % w_t)

$$\text{Mass of slag: } \frac{8.2}{80.9} \cdot 100 = \underline{\underline{10.1 \text{ kg}}}$$

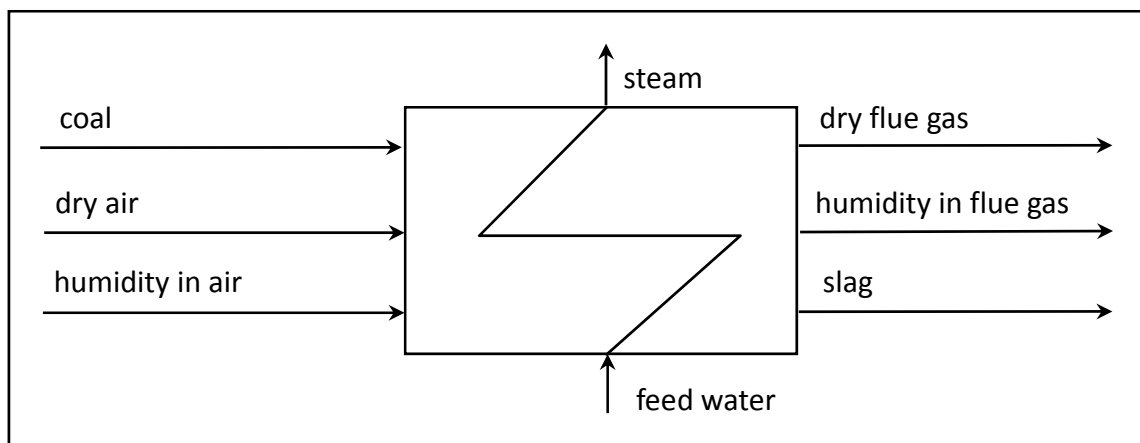


Fig. 3.01: Scheme of steam generator balance

dry flue gas:

inlet: C in coal	50.20 kg
S in coal	1.19 kg
outlet: C in slag	$10.1 \cdot 0.191 = 1.93 \text{ kg}$
in dry flue gas	$50.20 - 1.93 = 48.27 \text{ kg}$

Burning 48.27 kg of C will generate one-carbon gases $\text{CO}_2 + \text{CO}$ in the following quantity:

$$48.27 \cdot \frac{22.4}{12} = 90.10 \text{ m}^3$$

Burning of 1.19 kg of S in coal will generate SO₂ in the following quantity:

$$1.19 \cdot \frac{22.4}{32} = 0.83 \text{ m}^3$$

The total volume of (CO₂ + SO₂ + CO) = 90.93 m³ in dry flue gas represents the following fraction:

$$15.38 + 0.04 = 15.42 \% \text{ v/v}$$

The total volume of dry flue gas (100%) is then as follows:

$$\frac{90.93}{15.42} \cdot 100 = 589.7 \text{ m}^3$$

The mass of dry flue gas generated by burning 100 kg of coal is the sum of the masses of all of its constituents, hence it is calculated as the product of each constituent's volume (relative to the total flue gas volume of 589.7 m³) and its density:

SO ₂ :	0.83	· 2.927	= 2,43 kg
CO:	589.7 · 0.0004	· 1,250	= 0,29 kg
CO ₂ :	(90.1 – 589.7 · 0.0004)	· 1,976	= 177,57 kg
N ₂ :	589,7 · 0,8105	· 1,251	= 597,92 kg
O ₂ :	589,7 · 0,0353	· 1,429	= <u>29,75 kg</u>
Mass of dry flue gas:			<u>807,96 kg</u>

2. Nitrogen balance:

Nitrogen transfers into flue gas from the incoming air and from coal (1 kg N). The composition of dry air is 23.1 % w_t O₂ and 76.9 % w_t N₂.

$$\text{Mass of dry air: } \frac{597.92 - 1}{0.769} = \underline{\underline{776.2 \text{ kg}}}$$

3. Water balance:

Humidity in air:

Temperature of air is 22 °C, relative humidity 60 %. Atmospheric pressure is 99kPa. Saturated vapour pressure at temperature of 22 °C is 2.643 kPa (see Tab. XIII)

Volume of water vapour in air:

$$V(H_2O)_{AR} = \frac{p_{H_2O}(\Delta t_{AR}) \cdot \varphi}{p_b - p_{H_2O}(\Delta t_{AR}) \cdot \varphi} \cdot AR_{real} = \frac{2.643 \cdot 0.6}{99 - 2.643 \cdot 0.6} \cdot \frac{776.2}{1.293} = 9.80 \text{ m}^3$$

$$\text{Mass of water vapour in air: } 9.80 \cdot 0.8038 = \underline{\underline{7.9 \text{ kg}}}$$

Humidity in flue gas:

Inlet: water in coal	30.1 kg
water generated by burning hydrogen in coal $2.8 \cdot 9$	25.2 kg
humidity coming in air	<u>7.9 kg</u>
Mass of water vapour in flue gas:	<u>63.2 kg</u>

Total mass balance

<u>inlet</u>		<u>outlet</u>	
coal	100.0 kg	dry flue gas	808.0 kg
dry air	776.2 kg	humidity in flue gas	63.2 kg
humidity in air	<u>7.9 kg</u>	slag	<u>10.1 kg</u>
Total	884.1 kg	Total	881.3 kg

In this mass balance, the difference found between inlet and outlet is 0,3%, which is a satisfactory correlation, often difficult to achieve in practice due to long time intervals between individual measurements, use of averaged values and varying accuracy of the instrumental methods.

Enthalpy balance

The basis of the enthalpy balance constitute the results provided by the mass balance above and it is related to temperature of 0 °C.

Inlet:

1. Coal:	heat generated by burning coal	$100 \cdot 16\,886 = 1\,688\,600 \text{ kJ}$
	heat capacity of coal	$100 \cdot 0.8 \cdot 15 = \underline{1\,200 \text{ kJ}}$
total heat inlet in coal:		1 689 800 kJ

2. Air: enthalpy of steam in air (22 °C, 1.56 kPa) must be first related to 0 °C:

enthalpy of stem	$7.9 (2\,541 - 0) = 20\,074 \text{ kJ}$
heat capacity of dry air	$776.3 \cdot 1,005 \cdot 22 = \underline{17\,160 \text{ kJ}}$
total heat inlet in air:	37 234 kJ

Total inlet: **1 727 034 kJ**

Outlet:

1. Dry flue gas: heat capacity of gases composing dry flue gas (mean specific heat capacity of gases relative to 1 kg of gas are given in Tab.VI):

SO ₂ :	2.43 · 0.687	=	1.67
CO :	0.29 · 1.054	=	0.31
CO ₂ :	177.57 · 0.949	=	168.51
N ₂ :	597.92 · 1.049	=	627.22
O ₂ :	29.75 · 0.950	=	<u>28.26</u>
			825.97 · 300.5 = 248 200 kJ

combustion heat of CO: 0.29 · 10 216 = 2 963 kJ

Dry flue gas contains total amount of heat (leaving the system): 251 163 kJ

2. Humidity in flue gas: due to the low partial pressure of steam in flue gas, its state lies in a region where its enthalpy is a function of temperature only, hence it can be obtained by reading enthalpy at 300.5 °C in the *h-s* diagram, which lies at 3 075 kJ·kg⁻¹ and the enthalpy of water at the reference state (at 0 °C) equal to 0 kJ·kg⁻¹ is subtracted:

$$63.2 \cdot (3\,075 - 0) = \mathbf{194\,340\,kJ}$$

3. Slag:

heat capacity	10.1 · 1 · 100	= 1 010 kJ
combustion heat of C present in slag	1.93 · 33 520	= <u>64 695 kJ</u>
total heat carried in slag		65 705 kJ

4. Produced steam:

burning of 100 kg coal produces $\frac{98}{260} \cdot 100 = 376.9$ kg of steam

production heat of steam $\lambda = 3\,230 - 440 = 2\,790$ kJ·kg⁻¹

total production heat 376.9 · 2 790 = **1 051 551 kJ**

5. Undetermined losses: the difference between heat introduced to the system (inlet heat) and heat leaving the system (sum of values calculated in points 1 to 3 above) represents undetermined losses, which comprise losses to the environment and errors that occur during measurements of input data.

inlet heat	1 727 034 kJ
outlet heat (points 1 to 3)	<u>- 1 562 275 kJ</u>
undetermined losses:	164 275 kJ

Total heat balance

inlet		outlet	
coal	1 689 800 kJ	wet flue gas	445 503 kJ
air	37 234 kJ	slag	65 705 kJ
		produced steam	1 051 551 kJ
		<u>undetermined losses</u>	<u>164 275 kJ</u>
total inlet	1 727 034 kJ	total outlet	1 727 034 kJ

The thermal efficiency of the steam generator is represented by the percentage of the total heat that was used to produce steam:

$$\underline{\eta_K = 60.9 \%}$$

EXERCISE 3.02

Calculate the heat balance of a boiler on the basis of the following data acquired during a 12-hour long operation:

Coal: C 46.5 % w_t ; H 2.7 % w_t ; S 1.0 % w_t ; O 11 % w_t ; N 1.0 % w_t ;
ash matter 15.4 % w_t ; water 22.6 % w_t .
HHV 14 040 kJ·kg⁻¹; temperature 20 °C, ($c = 0.8$ kJ·kg⁻¹·K⁻¹).
mass of burnt coal: 91.2 t

Slag: ash 96 % w_t ; C 4.0 % w_t ; temperature 100 °C ($c = 1.0$ kJ·kg⁻¹·K⁻¹).

Air: temperature 30 °C; relative humidity 70 %;
atmospheric pressure 97.3 kPa.

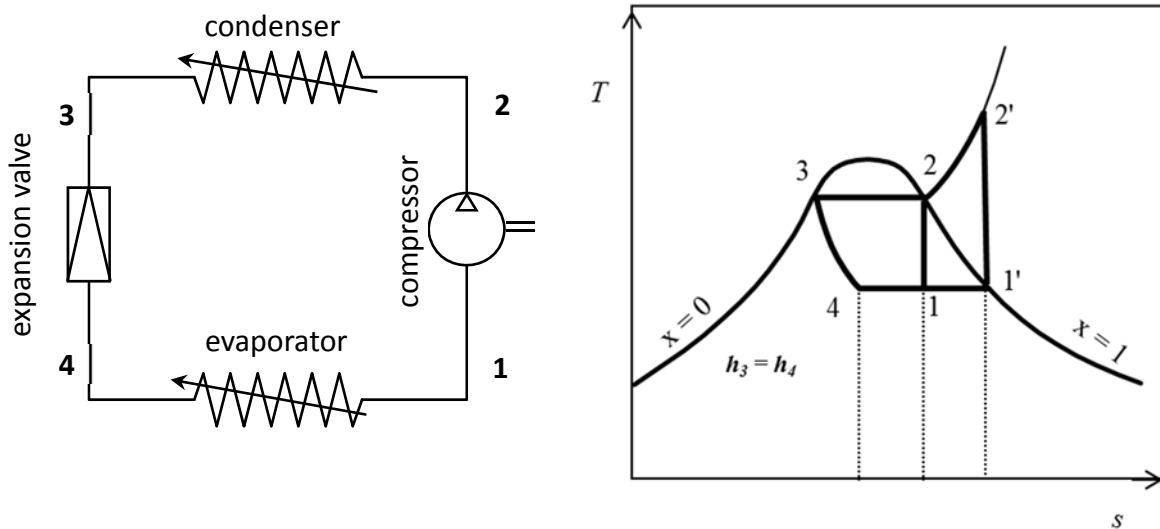
Dry flue gas: (CO₂ + SO₂) 12.66 % v/v; N₂ 80.3 % v/v; O₂ 7.04 % v/v
temperature 280 °C.

Steam: pressure 4 MPa temperature 425 °C
mass of produced steam: 353 kg

Feed water: temperature 150 °C

R e s u l t: thermal efficiency of the boiler $\eta_K = 63.3 \%$

4. VAPOUR-COMPRESSION REFRIGERATION



Refrigerating medium – NH₃ (b.p. –34 °C); SO₂ (b.p. –10 °C); CH₃Cl (b.p. –23 °C);

CO₂ (b.p. –78 °C), freons (b.p. –30 °C)

Refrigerating capacity – heat removed from each kilogram of refrigerating medium in the evaporator

$$q_0 = r \cdot (x_1 - x_4) = h_1 - h_4 \quad [\text{kJ/kg}]$$

Work of compressor – work delivered to the compressor during adiabatic compression

$$w = h_2 - h_1 \quad [\text{kJ/kg}]$$

Specific cooling rate

$$\varepsilon = q_0/w$$

Refrigerating rate – the amount of heat that the circulating refrigerating medium removes from the cooled substance in the evaporator per unit time

$$Q_0 = \dot{m} \cdot q_0 \quad [\text{kJ/h}]$$

Theoretical power of compressor

$$P = \dot{m} \cdot w = Q_0/\varepsilon \quad [\text{kJ/h}]$$

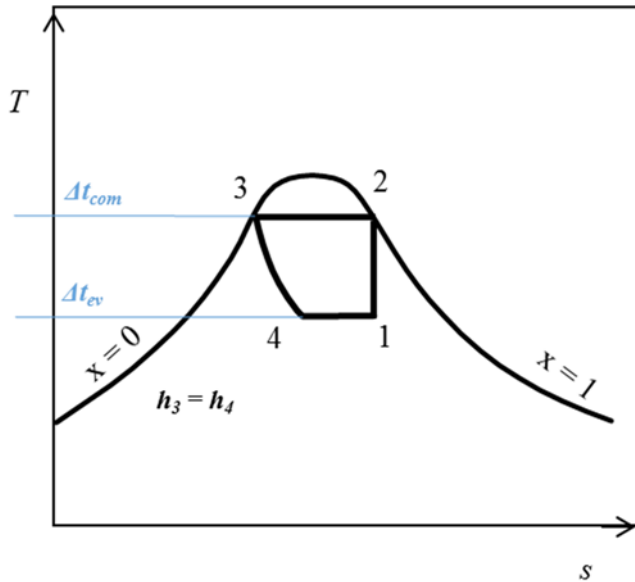
Real power of compressor

$$P_{real} = \frac{\dot{m} \cdot w}{3600 \cdot \eta_m} \quad [\text{kW}]$$

η_m mechanical efficiency of compressor (0.85-0.92)

EXERCISE 4.01

Vapour-compression refrigeration working in wet cycle, refrigerating medium is NH_3 . The temperature in evaporator (Δt_{ev}) is -30°C , the temperature in condenser (Δt_{con}) is 60°C , $\dot{m} = 440 \text{ kg/h}$; $\eta_m = 0.9$. Calculate: P_{real} ; Q_0 ; q_0 and ε



Solution:

read enthalpies in T-s diagram of NH_3

$$h_1 = 1375 \text{ kJ/kg}$$

$$h_2 = 1700 \text{ kJ/kg}$$

$$h_3 = h_4 = 710 \text{ kJ/kg}$$

$$q_0 = r \cdot (x_1 - x_4) = h_1 - h_4 = 1375 - 710 = \underline{665 \text{ kJ/kg}}$$

$$w = h_2 - h_1 = 1700 - 1375 = \underline{325 \text{ kJ/kg}}$$

$$\varepsilon = q_0 / w = 665 / 325 = \underline{2.05}$$

$$Q_0 = \dot{m} \cdot q_0 = 440 \cdot 665 = \underline{292.6 \text{ MJ/h}}$$

$$P_{real} = \frac{\dot{m} \cdot w}{3600 \cdot \eta_m} = \frac{440 \cdot 325}{3600 \cdot 0.9} = \underline{44.12 \text{ kW}}$$

EXERCISE 4.02

Vapour-compression refrigeration working in wet cycle, refrigerating medium is NH_3 and has $P_{real} = 50 \text{ kW}$. The temperature in evaporator (Δt_{ev}) is -5°C , the temperature in condenser (Δt_{con}) is 25°C . Calculate: Q_0 and q_0

Solution: read enthalpies in T-s diagram of NH_3

$$h_1 = 1580 \text{ kJ/kg}$$

$$h_2 = 1700 \text{ kJ/kg}$$

$$h_3 = h_4 = 550 \text{ kJ/kg}$$

$$q_0 = r \cdot (x_1 - x_4) = h_1 - h_4 = 1580 - 550 = \underline{1030 \text{ kJ/kg}}$$

$$Q_0 = \dot{m} \cdot q_0$$

$$\dot{m} = \frac{P_{real} \cdot 3600 \cdot \eta_m}{w} = \frac{50 \cdot 3600 \cdot 1}{120} = \underline{1500 \text{ kg/h}}$$

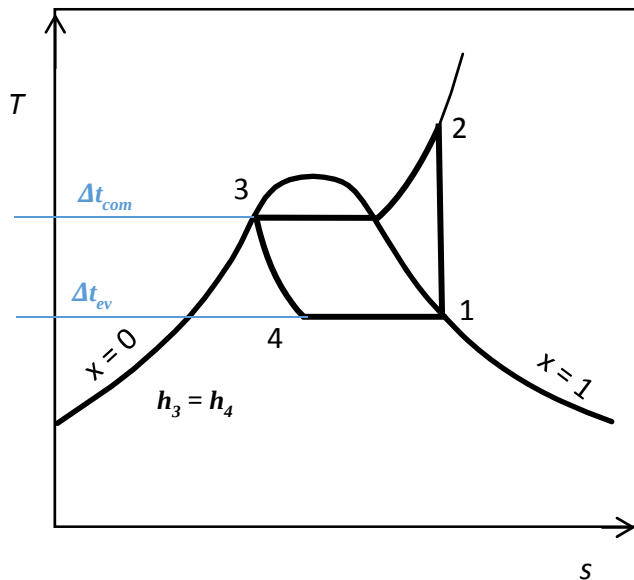
$$w = h_2 - h_1 = 1700 - 580 = \underline{120 \text{ kJ/kg}}$$

$$Q_0 = \dot{m} \cdot q_0 = 1500 \cdot 1030 = \underline{1545 \text{ MJ/h}}$$

EXERCISE 4.03

Vapour-compression refrigeration working in dry cycle, refrigerating medium is NH_3 and has refrigerating effect $Q_0 = 420 \text{ MJ/h}$. The temperature in evaporator (Δt_{ev}) is -15°C , the temperature in condenser (Δt_{con}) is 30°C .

Calculate: P_{real} ; $\dot{m}$; ε and q_0



Solution:

read enthalpies in T-s diagram of NH_3

$$h_1 = 1650 \text{ kJ/kg}$$

$$h_2 = 1890 \text{ kJ/kg}$$

$$h_3 = h_4 = 560 \text{ kJ/kg}$$

$$q_0 = r \cdot (x_1 - x_4) = h_1 - h_4 = 1650 - 560 = \underline{1010 \text{ kJ/kg}}$$

$$\dot{m} = Q_0 / q_0 = 420 \cdot 10^3 / 1010 = \underline{415.8 \text{ kg/h}}$$

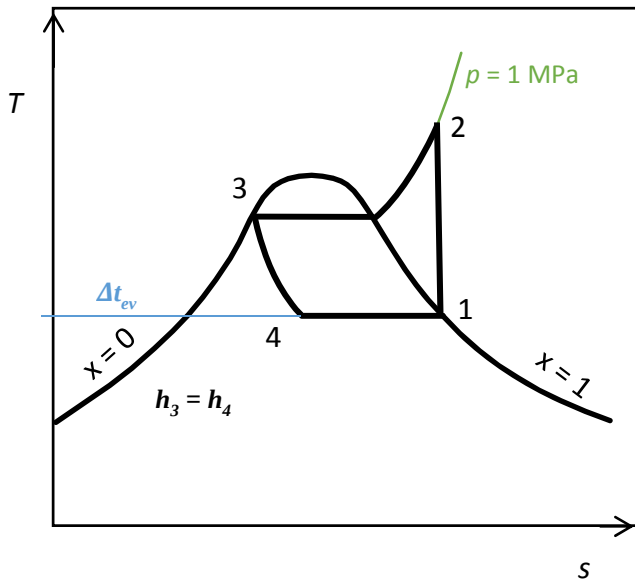
$$\varepsilon = q_0 / w = q_0 / (h_2 - h_1) = 1010 / (1890 - 1650) = \underline{4.2}$$

$$P_{real} = \frac{\dot{m} \cdot w}{3600 \cdot \eta_m} = \frac{415.8 \cdot 240}{3600 \cdot 1} = \underline{27.72 \text{ kW}}$$

EXERCISE 4.04

Vapour-compression refrigeration working in dry cycle, refrigerating medium is NH_3 and has $P_{real} = 30 \text{ kW}$; $\eta_m = 0.85$. The temperature in evaporator (Δt_{ev}) is -20°C , and in compressor the vapour NH_3 is compressed to $p = 1 \text{ MPa}$.

Calculate: Q_0 ; $\dot{m}$; ε and q_0



Solution:

read enthalpies in T-s diagram of NH₃

$$h_1 = 1640 \text{ kJ/kg}$$

$$h_2 = 1895 \text{ kJ/kg}$$

$$h_3 = h_4 = 540 \text{ kJ/kg}$$

$$q_0 = r \cdot (x_1 - x_4) = h_1 - h_4 = 1640 - 540 = \underline{1100 \text{ kJ/kg}}$$

$$\dot{m} = \frac{P_{real} \cdot 3600 \cdot \eta_m}{w} = \frac{30 \cdot 3600 \cdot 0.85}{1895 - 1640} = \underline{360 \text{ kg/h}}$$

$$\varepsilon = q_0 / w = q_0 / (h_2 - h_1) = 1100 / 255 = \underline{4.34}$$

$$Q_0 = \dot{m} \cdot q_0 = 360 \cdot 1100 = \underline{396 \text{ MJ/h}}$$

EXERCISE 4.05

Vapour-compression refrigeration working in dry cycle, refrigerating medium is NH₃ and has $\dot{m} = 820 \text{ kg/h}$. The temperature in evaporator $\Delta t_{ev} = -20^\circ\text{C}$, and in compressor the vapour NH₃ is compressed to $p = 1.2 \text{ MPa}$.

Calculate: Q_0 ; ε ; q_0 and P_{real} ($\eta_m = 0.89$)

Results: $q_0 = 1070 \text{ kJ/kg}$; $Q_0 = 877.4 \text{ MJ/h}$; $\varepsilon = 8.82$; $P_{real} = 71.7 \text{ kW}$

Heat Pump

EXERCISE 4.06

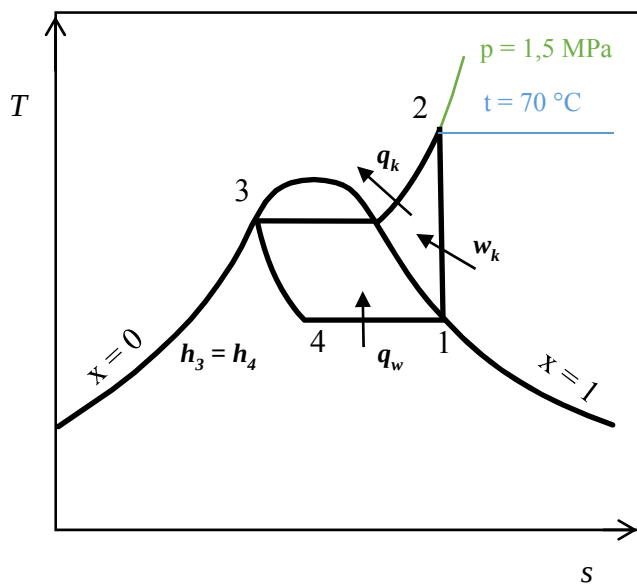
Calculate the theoretic power of compressor of heat pump working in dry cycle, working medium is NH₃. The temperature after the compressor is 70°C and $p = 1.5 \text{ MPa}$. The heat pump system is heating 2500 kg/h of water from 60 to 65°C .

Solution:

$$P_{real} = \dot{m}_{NH_3} \cdot w_c$$

$$w_c = h_2 - h_1$$

$$\dot{m}_{NH_3} = Q / q_{2,3}$$



read enthalpies in T-s diagram of NH₃

$$h_1 = 1700 \text{ kJ/kg}$$

$$h_2 = 1810 \text{ kJ/kg}$$

$$h_3 = h_4 = 600 \text{ kJ/kg}$$

$$w_c = h_2 - h_1 = 1810 - 1700 = 110 \text{ kJ/kg}$$

$$\dot{m}_{NH_3} = Q / q_{2,3}$$

$$Q = \dot{m}_{H_2O} \cdot \Delta t \cdot c_p = 2500 \cdot 5 \cdot 4.18 = 52\,250 \text{ kJ/h}$$

$$q_{2,3} = h_2 - h_3 = 1810 - 600 = 1210 \text{ kJ/kg}$$

$$\dot{m}_{NH_3} = Q / q_{2,3} = 52\,250 / 1210 = 43.18 \text{ kJ/h}$$

$$P_{real} = \dot{m}_{NH_3} \cdot w_c = 43.18 \cdot 110 = \underline{\underline{1.32 \text{ kW}}}$$

5. TABLES

Table I Multiples and parts of units

Multiples of units	prefix		Part of units	prefix	
	designation	sympol		designation	symbol
10^{18}	exa-	E-	10^{-1}	deci-	d-
10^{15}	peta-	P-	10^{-2}	centi-	c-
10^{12}	tera-	T-	10^{-3}	mili-	m-
10^9	giga-	G-	10^{-6}	mikro-	μ -
10^6	mega-	M-	10^{-9}	nano-	n-
10^3	kilo-	k-	10^{-12}	piko-	p-
10^2	hekto-	h-	10^{-15}	femto-	f-
10	deka-	da-	10^{-18}	atto-	a-

Table II Physical and thermodynamic quantities and their units

quantity	SI and auxiliary units	Practical units	Relations
force F	newton N	MN, kN	1 N = 1 kg·m·s ⁻² = 1 W·s·m ⁻¹ 1 kp = 9,81 N 1 dyn = 10 ⁻⁵ N
pressure p	pascal Pa	N·m ⁻² , N·mm ⁻² bar, mbar MPa, kPa	1 Pa = 1 N·m ⁻² 1 MPa = 10 bar = 1 N·mm ⁻² 1 at = 1 kp·cm ⁻² = 0,981 bar 1 atm = 760 torr = 1,013 bar 1 torr = 1,33 mbar 1 bar = 750 torr = 1,02 at = 0,1 MPa
output power P	watt W	GW, MW, kW	1 W = 1 J·s ⁻¹ = 1 N·m·s ⁻¹ = 1 VA
heat flux q	W·m ⁻²		1 kcal·m ⁻² ·h ⁻¹ = 1,16 W·m ⁻² = 1,16 J·m ⁻² ·s ⁻¹
work W energy E	joule J	GJ, MJ, kJ MWh, kWh, Ws	1 kcal = 4,19 kJ = 1,16 Wh 1 kW h = 3600 kJ = 860 kcal
combustion heat HHV	J·kg ⁻¹	MJ·kg ⁻¹ , kJ·kg ⁻¹ , MJ·m ⁻³ , kJ·m ⁻³	1 kcal·kg ⁻¹ = 4,19 kJ·kg ⁻¹ 1 kcal·m ⁻³ = 4,19 kJ·m ⁻³
fuel efficiency LHV	J·kg ⁻¹	MJ·kg ⁻¹ , kJ·kg ⁻¹ , MJ·m ⁻³ , kJ·m ⁻³	1 kcal·kg ⁻¹ = 4,19 kJ·kg ⁻¹ 1 kcal·m ⁻³ = 4,19 kJ·m ⁻³
temperature T t	kelvin K degree Celsius °C		0 °C = 273,15 K Δt 1 °C = 1 K

Table III Combustion heat and fuel efficiency of gases and vapours

		HVV [kJ·m ⁻³]	LHV [kJ·m ⁻³]	HHV [kJ·kg ⁻¹]	LHV [kJ·kg ⁻¹]
Acetylene	C ₂ H ₂	58 990	56 940	50 367	48 650
Ammoniac	NH ₃	17 250	14 193	22 357	18 422
Benzene(vapours)	C ₆ H ₆	146 370	140 340	41 993	40 277
n-butane	C ₄ H ₁₀	134 020	123 552	49 572	45 720
Butten	C ₄ H ₈	121 877	113 840	48 692	45 468
Ethan	C ₂ H ₆	69 250	64 310	51 690	48 020
Ethen	C ₂ H ₄	64 016	59 955	50 785	47 562
Methane	CH ₄	39 888	35 850	55 760	50 116
Carbon monoxide	CO	12 700	12 700	10 216	10 216
Propane	C ₃ H ₈	101 820	93 575	50 410	46 348
Propene	C ₃ H ₆	94 370	88 215	49 278	46 055
Sulfane to SO ₂		25 707	23 697	16 705	15 407
Sulfane to SO ₃		30 145	28 135	19 594	18 254
Hydrogen	H ₂	12 790	10 752	142 443	119 742

Table IV Physical constants of gases and vapours

	molecular mass	density 0°C 101kPa	gas constant	Specific heat capacity of gas 0°C a 0,101 MPa			critical condition	
	[g·mol ⁻¹]	[kg·m ⁻³]	<i>R</i>	<i>c_p</i>	<i>c_v</i>	$\frac{c_p}{c_v}$	<i>t_k</i>	<i>p_k</i>
			[kJ·kg ⁻¹ ·K ⁻¹]	[kJ·kg ⁻¹ ·K ⁻¹]		$\frac{c_p}{c_v}$	[°C]	[MPa]
C ₂ H ₂	26.04	1.171	0.3196	1.683	1.352	1.25	35.7	6.24
NH ₃	17.03	0.771	0.4883	2.219	1.680	1.37	132.4	11.3
C ₄ H ₁₀	58.12	2.673	0.1432	1.917	1.733	1.11	152.0	3.8
N ₂	28.02	1.251	0.2967	1.047	0.746	1.40	-147.0	3.4
C ₂ H ₆	30.06	1.357	0.2767	1.729	1.445	1.20	32.1	4.95
C ₂ H ₄	28.05	1.261	0.2966	1.528	1.222	1.25	9.7	5.14
SO ₂	64.06	2.927	0.1298	0.633	0.503	1.25	157.5	7.88
CO	28.01	1.250	0.2970	1.047	0.854	1.40	-140.2	3.5
CO ₂	44.01	1.976	0.1890	0.837	0.653	1.30	31.1	7.4
O ₂	32.00	1.429	0.2599	0.913	0.653	1.40	-118.8	5.04
CH ₄	16.03	0.717	0.5188	2.225	1.700	1.31	-82.1	4.62
C ₃ H ₈	44.06	2.020	0.1888	1.863	1.650	1.13	95.6	4.36
H ₂ S	34.09	1.539	0.2442	1.059	0.804	1.30	100.4	19.14
H ₂	2.016	0.0898	4.1250	14.266	10.13	1.40	-239.9	1.3
H ₂ O(p)	18.02	0.8038	0.4792	1.859	1.398	1.33	374.1	22.55
air (dry)	28.95	1.293	0.2870	1.010	0.720	1.40	-140.7	3.77

Table V Mean specific heat capacities of gases c_{ps} [kJ·m⁻³·K⁻¹] at different temperatures and const. pressure 0.1 MPa

t [°C]	H ₂	N ₂	O ₂	CO	H ₂ O(p)	CO ₂	SO ₂	air
0	1.281	1.303	1.306	1.299	1.490	1.620	1.779	1.298
100	1.293	1.304	1.318	1.302	1.498	1.725	1.863	1.302
200	1.297	1.310	1.335	1.307	1.519	1.817	1.942	1.310
300	1.302	1.314	1.356	1.317	1.536	1.892	2.010	1.319
400	1.304	1.325	1.381	1.329	1.557	1.955	2.072	1.331
500	1.306	1.335	1.402	1.343	1.582	2.022	2.123	1.344
600	1.308	1.348	1.419	1.357	1.607	2.076	2.169	1.356
700	1.310	1.360	1.436	1.372	1.634	2.122	2.206	1.373
800	1.318	1.373	1.452	1.386	1.662	2.164	2.240	1.386
900	1.323	1.385	1.469	1.400	1.691	2.202	2.273	1.398
1000	1.327	1.398	1.482	1.413	1.716	2.236	2.294	1.411
1100	1.335	1.411	1.490	1.425	1.741	2.265	2.319	1.426
1200	1.343	1.423	1.503	1.436	1.767	2.294	2.340	1.436
1300	1.352	1.432	1.515	1.447	1.792	2.315	2.357	1.444
1400	1.360	1.444	1.523	1.457	1.817	2.340	2.374	1.453
1500	1.364	1.453	1.532	1.466	1.838	2.361	2.386	1.465
1600	1.373	1.461	1.540	1.475	1.863	2.382	2.399	1.474
1700	1.381	1.469	1.549	1.483	1.884	2.399	2.412	1.482
1800	1.390	1.478	1.557	1.490	1.905	2.416	2.424	1.486
1900	1.384	1.482	1.566	1.497	1.926	2.428	2.433	1.495
2000	1.406	1.490	1.574	1.504	1.947	2.445	2.441	1.499
2100	1.410	1.498	1.578	1.510	1.968	2.457	2.449	1.507
2200	1.423	1.503	1.586	1.516	1.984	2.470	2.457	1.511
2300	1.431	1.511	1.595	1.521	2.001	2.482	2.466	1.516
2400	1.436	1.515	1.599	1.527	2.018	2.491	2.474	1.520
2500	1.444	1.519	1.607	1.532	2.030	2.499	2.478	1.528
2600	1.452	1.528	1.611	1.540	2.047	2.508	2.483	1.532
2700	1.457	1.532	1.617	1.545	2.060	2.520	2.491	1.537
2800	1.465	1.536	1.624	1.549	2.076	2.525	2.495	1.541
2900	1.473	1.540	1.629	1.553	2.089	2.537	2.499	1.545
3000	1.477	1.545	1.637	1.557	2.097	2.541	2.504	1.549

Table VI Mean specific heat capacities of gases c_{ps} [$\text{kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$] at different temperatures and const. pressure 0.1 MPa

t [°C]	H ₂	N ₂	O ₂	CO	H ₂ O(p)	CO ₂	SO ₂	air
0	14.248	1.039	0.915	1.040	1.859	0.815	0.607	1.005
100	14.353	1.040	0.923	1.042	1.893	0.866	0.636	1.005
200	14.421	1.043	0.935	1.046	1.894	0.910	0.662	1.013
300	14.446	1.049	0.950	1.054	1.919	0.949	0.687	1.022
400	14.477	1.057	0.965	1.063	1.948	0.983	0.708	1.030
500	14.509	1.066	0.979	1.075	1.978	1.013	0.724	1.042
600	14.542	1.076	0.993	1.086	2.009	1.040	0.737	1.051
700	14.587	1.087	1.005	1.098	2.042	1.064	0.754	1.059
800	14.641	1.097	1.016	1.109	2.075	1.085	0.762	1.072
900	14.706	1.108	1.026	1.120	2.110	1.104	0.775	1.084
1000	14.776	1.118	1.035	1.130	2.114	1.122	0.783	1.093
1100	14.853	1.127	1.043	1.140	2.177	1.138	0.791	1.101
1200	14.934	1.136	1.051	1.149	2.211	1.153	0.795	1.109
1300	15.023	1.145	1.058	1.158	2.243	1.166	0.803	1.118
1400	15.113	1.153	1.065	1.166	2.274	1.178	0.812	1.126
1500	15.202	1.160	1.071	1.173	2.305	1.189	0.816	1.135
1600	15.294	1.167	1.077	1.180	2.335	1.200	0.820	1.139
1700	15.383	1.174	1.083	1.187	2.363	1.209	0.825	1.143
1800	15.472	1.180	1.089	1.192	2.391	1.218	0.829	1.151
1900	15.561	1.186	1.094	1.198	2.417	1.226	0.831	1.157
2000	15.649	1.191	1.099	1.203	2.442	1.233	0.833	1.160
2100	15.736	1.197	1.104	1.208	2.466	1.241	0.837	1.164
2200	15.819	1.201	1.109	1.213	2.489	1.247	0.841	1.168
2300	15.902	1.206	1.114	1.218	2.512	1.253	0.843	1.172
2400	15.983	1.210	1.118	1.222	2.533	1.259	0.846	1.176
2500	16.064	1.214	1.123	1.226	2.554	1.264	0.849	1.181
2600	16.141	1.222	1.127	1.231	2.574	1.268	0.850	1.185
2700	16.215	1.224	1.131	1.235	2.594	1.273	0.852	1.189
2800	16.308	1.227	1.134	1.238	2.612	1.277	0.854	1.193
2900	16.388	1.231	1.143	1.240	2.621	1.281	0.854	1.196
3000	16.451	1.235	1.147	1.243	2.630	1.285	0.854	1.197

Table VII Mean specific heat capacities of gases c_{ps} [$\text{kJ}\cdot\text{m}^{-3}\cdot\text{K}^{-1}$] at different temperatures and const. pressure 0.1 MPa

t (°C)	CH ₄	C ₂ H ₂	C ₂ H ₄	C ₂ H ₆	C ₆ H ₆	NH ₃	H ₂ S
0	1.545	1.909	1.888	2.227	3.894	1.612	1.583
100	1.620	2.072	2.123	2.525	4.396	1.645	1.595
200	1.758	2.198	2.345	2.807	4.857	1.687	1.624
300	1.892	2.307	2.537	3.077	5.317	1.737	1.671
400	2.018	2.395	2.742	3.333	5.820	1.796	-
500	2.135	2.470	2.914	3.496	-	1.255	-
600	2.252	2.532	3.073	3.793	-	1.922	-
700	2.361	2.600	3.215	4.002	-	-	-
800	2.466	2.659	3.370	4.199	-	-	-
900	2.562	2.713	3.475	4.380	-	-	-
1000	2.654	2.763	3.592	4.543	-	-	-

Table VIII Mean specific heat capacities of gases c_{ps} [$\text{kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$] at different temperatures and const. pressure 0.1 MPa

t (°C)	CH ₄	C ₂ H ₂	C ₂ H ₄	C ₂ H ₆	C ₆ H ₆	NH ₃	H ₂ S
0	2.152	1.629	1.495	1.662	1.114	2.089	1.030
100	2.261	1.767	1.683	1.884	1.260	2.135	1.038
200	2.454	1.876	1.859	2.093	1.394	2.185	1.055
300	2.638	2.968	2.022	2.294	1.528	2.253	1.084
400	2.809	2.043	2.173	2.487	1.671	2.328	-
500	2.977	2.106	2.311	2.663	-	2.403	-
600	3.140	2.164	2.437	2.830	-	2.491	-
700	3.295	2.219	2.550	2.985	-	-	-
800	3.437	2.269	2.671	3.132	-	-	-
900	3.571	2.315	2.755	3.266	-	-	-
1000	3.697	2.357	2.847	3.382	-	-	-

Table IX Degree of carbon dioxide dissociation $\alpha \cdot 10^2$

t[°C]	Partial pressure CO ₂ [kPa]										
	4	6	8	10	12	14	16	18	20	25	30
1500	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.4
1600	2.0	1.8	1.8	1.6	1.45	1.4	1.35	1.3	1.3	1.2	1.1
1700	3.8	3.3	3.0	2.8	2.6	2.5	2.4	2.3	2.2	2.0	1.9
1800	6.3	5.5	5.0	4.6	4.4	4.2	4.0	3.8	3.7	3.5	3.3
1900	10.1	8.9	8.1	7.6	7.2	6.8	6.5	6.3	6.1	5.6	5.3
2000	16.5	14.6	13.4	12.5	11.8	11.2	10.8	10.4	10.0	9.4	8.8
2100	23.9	21.3	19.6	18.3	17.3	16.6	15.9	15.3	14.9	13.9	13.1
2200	35.1	31.5	29.2	27.5	26.1	25.0	24.1	23.3	22.3	21.2	20.1
2300	44.7	40.7	37.9	35.9	34.3	32.9	31.8	30.9	30.0	28.2	26.9
2400	56.0	51.8	48.8	46.5	44.6	43.1	41.8	40.6	39.6	37.5	35.8
2500	66.3	62.2	59.3	56.9	55.0	53.4	52.0	50.7	49.7	47.3	45.4
2600	75.2	71.6	68.9	66.7	64.9	63.4	62.0	60.8	59.7	57.4	55.5
2700	82.5	79.8	77.6	75.7	74.1	72.8	71.6	70.5	69.4	67.3	65.5
2800	88.3	86.1	84.4	83.0	81.7	80.6	79.6	78.7	77.9	76.1	74.5
2900	92.2	90.6	89.4	88.3	87.4	86.5	85.8	85.1	84.5	83.0	81.8
3000	94.9	93.9	93.1	92.3	91.7	91.1	90.6	90.1	89.6	88.5	87.6

Table X Degree of water vapour dissociation $\alpha \cdot 10^2$

t[°C]	Water vapour partial pressure [kPa]										
	4	6	8	10	12	14	16	18	20	25	30
1600	0.85	0.75	0.65	0.60	0.58	0.56	0.54	0.52	0.50	0.48	0.46
1700	1.45	1.27	1.16	1.08	1.02	0.95	0.90	0.85	0.80	0.76	0.73
1800	2.40	2.10	1.90	1.80	1.70	1.60	1.53	1.46	1.40	1.30	1.25
1900	4.05	3.60	3.25	3.00	2.85	2.70	2.60	2.50	2.40	2.20	2.10
2000	5.75	5.05	4.60	4.30	4.00	3.80	3.55	3.50	3.40	3.15	2.95
2100	8.55	7.50	6.80	6.35	6.0	5.70	5.45	5.25	5.10	4.80	4.55
2200	12.3	10.8	9.90	9.30	8.80	8.35	7.95	7.65	7.40	6.90	6.50
2300	16.0	15.0	13.57	12.9	12.2	11.6	11.10	10.75	10.40	9.65	9.10
2400	22.5	20.0	18.4	17.2	16.3	15.6	15.0	14.4	13.9	13.0	12.25
2500	28.5	25.6	23.5	22.1	20.9	20.0	19.3	18.6	18.0	16.8	15.9
2600	37.1	33.5	31.0	29.2	27.8	26.7	25.7	24.8	24.1	22.6	21.5
2700	44.7	40.7	37.9	35.9	34.2	33.0	31.8	30.8	29.9	28.2	26.8
2800	54.5	50.3	47.3	45.0	43.2	41.6	40.4	39.3	38.3	36.2	34.6
2900	62.8	58.6	55.5	53.2	51.3	49.7	48.3	47.1	46.0	43.7	41.9
3000	70.6	66.7	63.8	61.6	59.6	58.0	56.6	55.4	54.3	51.9	50.0

Table XI Water and steam at saturation

Temperature	pressure	Specific volume		Entropy		Enthalpy	
t [°C]	p [MPa]	water $v' \cdot 10^3$ [m ³ ·kg ⁻¹]	steam v'' [m ³ ·kg ⁻¹]	water s' [kJ·kg ⁻¹ ·K ⁻¹]	steam s'' [kJ·kg ⁻¹ ·K ⁻¹]	water h' [kJ·kg ⁻¹]	steam h'' [kJ·kg ⁻¹]
0.01	0.0006	1.0002	206.1	0	9.1555	0	2501
10	0.0012	1.0003	106.3	0.1511	8.8998	42.02	2519
20	0.0023	1.0018	57.76	0.2965	8.6661	83.92	2537
30	0.0042	1.0044	32.88	0.4368	8.4521	125.75	2556
40	0.0073	1.0079	19.52	0.5724	8.2557	167.54	2574
50	0.0124	1.0121	12.03	0.7038	8.0749	209.34	2392
60	0.0199	1.0171	7.668	0.8312	7.9082	251.15	2609
70	0.0312	1.0228	5.040	0.9550	7.7540	293.0	2626
80	0.0474	1.0290	3.405	1.0754	7.6110	334.9	2643
90	0.0702	1.0359	2.359	1.1927	7.4781	377.0	2659
100	0.1014	1.0435	1.672	1.3070	7.3541	419.1	2676
110	0.1434	1.0515	1.209	1.4187	7.2380	461.4	2691
120	0.1986	1.0603	0.8913	1.5278	7.1291	503.8	2706
130	0.2703	1.0697	0.6681	1.6346	7.0264	546.4	2720
140	0.3615	1.0798	0.5085	1.7393	6.9293	589.0	2733
150	0.4761	1.0905	0.3925	1.8420	6.8370	632.2	2746
160	0.6181	1.1020	0.3068	1.9428	6.7491	675.5	2758
170	0.7921	1.1143	0.2426	2.0419	6.6649	719.2	2768
180	1.0026	1.1274	0.1939	2.1395	6.5841	763.2	2778
190	1.2550	1.1414	0.1564	2.2358	6.5060	807.6	2786
200	1.5547	1.1565	0.1272	2.3308	6.4303	852.4	2792
210	1.9074	1.1727	0.1043	2.4248	6.3565	897.7	2798
220	2.3193	1.1902	0.08610	2.5178	6.2842	943.7	2801
230	2.7968	1.2090	0.07151	2.6102	6.2131	990.2	2803
240	3.3467	1.2295	0.05971	2.7019	6.1425	1037.5	2803
250	3.976	1.2517	0.05009	2.7934	6.0722	1085.7	2801
260	4.692	1.2761	0.04218	2.8847	6.0017	1134.8	2796
270	5.503	1.3030	0.03562	2.9762	5.9304	1185.1	2790
280	6.417	1.3328	0.03015	3.0681	5.8578	1236.7	2780
290	7.442	1.3666	0.02556	3.1608	5.7832	1290.0	2767
300	8.588	1.4042	0.02166	3.2547	5.7058	1344.8	2749
310	9.865	1.4479	0.01834	3.3506	5.6243	1402.0	2728
320	11.284	1.4991	0.01548	3.4491	5.5373	1462.1	2701
330	12.858	1.5606	0.01298	3.5516	5.4425	1525.7	2666
340	14.600	1.6375	0.01078	3.6599	5.3359	1594.5	2622
350	16.529	1.7401	0.00880	3.7783	5.2109	1670.9	2564
360	18.666	1.8945	0.00694	3.9164	5.0528	1762.0	2481
370	21.043	2.2222	0.00495	4.1142	4.7998	1892.7	2334
373.95	22.064	3.2600	0.00326	4.412		2087.6	

Table XII Water and steam at saturation

pressure	temper ature	Specific volume		Entropy		Enthalpy	
p [MPa]	t [°C]	water $v' \cdot 10^3$ [m ³ ·kg ⁻¹]	steam v'' [m ³ ·kg ⁻¹]	water s' [kJ·kg ⁻¹ ·K ⁻¹]	steam s'' [kJ·kg ⁻¹ ·K ⁻¹]	water h' [kJ·kg ⁻¹]	steam h'' [kJ·kg ⁻¹]
0.001	6.92	1.0001	129.208	0.1054	8.975	29.32	2513
0.01	45.83	1.0102	14.676	0.6492	8.149	191.9	2584
0.05	81.35	1.0317	2.9648	1.0910	7.593	340.6	2645
0.1	99.63	1.0434	1.6946	1.3026	7.360	417.4	2675
0.2	120.23	1.0608	0.88592	1.5302	7.127	504.8	2707
0.3	133.54	1.0735	0.60586	1.672	6.992	561.4	2725
0.4	143.62	1.0839	0.46242	1.777	6.897	604.7	2738
0.5	151.85	1.0928	0.37481	1.860	6.822	640.1	2749
0.6	158.84	1.1009	0.31556	1.931	6.761	670.5	2757
0.7	164.96	1.1082	0.27274	1.992	6.709	697.2	2764
0.8	170.42	1.1150	0.24030	2.046	6.663	720.9	2769
0.9	175.36	1.1213	0.21484	2.094	6.623	742.8	2774
1.0	179.88	1.1274	0.19430	2.138	6.587	762.7	2778
1.2	187.96	1.1386	0.16320	2.216	6.523	798.3	2785
1.4	195.04	1.1489	0.14072	2.284	6.469	830.0	2790
1.6	201.37	1.1586	0.12368	2.344	6.422	858.3	2793
1.8	207.10	1.1678	0.11031	2.397	6.379	884.4	2796
2.0	212.37	1.1766	0.09953	2.447	6.340	908.5	2799
2.6	226.03	1.2012	0.07988	2.573	6.242	971.7	2803
3.0	233.84	1.2163	0.06662	2.646	6.186	1008.3	2804
3.5	242.54	1.2345	0.05702	2.725	6.125	1049.8	2803
4.0	250.33	1.2521	0.04974	2.796	6.070	1087.5	2801
4.5	257.41	1.2691	0.04402	2.859	6.022	1120.9	2798
5.0	263.92	1.2858	0.03941	2.921	5.973	1154.4	2794
6.0	275.56	1.3187	0.03241	3.027	5.890	1213.9	2785
7.0	285.80	1.3514	0.02734	3.122	5.814	1267.4	2772
8.0	294.98	1.3838	0.02352	3.208	5.745	1317.0	2758
9.0	303.32	1.4174	0.02048	3.287	5.678	1363.7	2743
10.0	310.96	1.4521	0.01803	3.360	5.615	1407.7	2725
11.0	318.04	1.4890	0.01598	3.430	5.553	1450.2	2705
12.0	324.63	1.5270	0.01426	3.496	5.492	1491.1	2685
13.0	330.81	1.5670	0.01277	3.561	5.432	1531.5	2662
14.0	336.63	1.6110	0.01149	3.623	5.372	1570.8	2638
15.0	342.12	1.6580	0.01035	3.685	5.310	1610.2	2611
16.0	347.32	1.7101	0.009318	3.746	5.247	1650	2582
17.0	352.26	1.7690	0.008401	3.809	5.177	1690	2550
18.0	356.96	1.8380	0.007504	3.871	5.107	1732	2510
19.0	361.44	1.9231	0.006700	3.943	5.018	1767	2466
20.0	365.71	2.038	0.005850	4.015	4.928	1827	2410
21.0	369.79	2.218	0.005006	4.159	4.760	1890	2330
22.0	373.70	2.730	0.003467	4.303	4.591	2016	2168

Table XIII Saturated water vapour pressure [kPa]

°C	0	1	2	3	4	5	6	7	8	9
0	0.611	0.656	0.705	0.757	0.813	0.872	0.935	1.001	1.072	1.147
10	1.227	1.312	1.402	1.497	1.597	1.704	1.817	1.936	2.062	2.196
20	2.337	2.486	2.643	2.808	2.982	3.167	3.360	3.564	3.779	4.004
30	4.241	4.491	4.753	5.029	5.318	5.622	5.940	6.274	6.624	6.991
40	7.375	7.778	8.198	8.639	9.099	9.852	10.08	10.61	11.16	11.74
50	12.33	12.96	13.61	14.29	15.00	15.74	16.51	17.31	18.15	19.01
60	19.92	20.86	21.84	22.85	23.91	25.01	26.14	27.33	28.56	29.84
70	31.16	32.54	33.96	35.43	36.96	38.54	40.19	41.89	43.65	45.47
80	47.36	49.31	51.33	53.42	55.57	57.80	60.10	62.49	64.95	67.49
90	70.11	72.80	75.61	78.49	81.46	84.52	87.69	90.95	94.30	97.78

Table XIV Ammoniac

	pressure	Specific volume		Entropy		Enthalpy	
t	p	liquid	steam	liquid	steam	liquid	steam
[°C]	[MPa]	$v' \cdot 10^3$	v''	s'	s''	h'	h''
		[m ³ ·kg ⁻¹]	[m ³ ·kg ⁻¹]	[kJ·kg ⁻¹ ·K ⁻¹]	[kJ·kg ⁻¹ ·K ⁻¹]	[kJ·kg ⁻¹]	[kJ·kg ⁻¹]
-50	0.0409	1.425	2.62	3.279	9.620	193	1608
-45	0.0546	1.437	2.01	3.377	9.520	216	1617
-40	0.0718	1.449	1.55	3.473	9.424	238	1625
-35	0.0933	1.462	1.22	3.567	9.334	260	1633
-30	0.1195	1.476	0.963	3.660	9.249	282	1641
-25	0.1516	1.490	0.772	3.751	9.167	304	1641
-20	0.1903	1.504	0.624	3.841	9.090	327	1648
-15	0.2363	1.519	0.509	3.926	9.015	350	1656
-10	0.2909	1.534	0.419	4.016	8.944	373	1663
-5	0.3549	1.550	0.347	4.102	8.876	396	1669
0	0.4294	1.566	0.290	4.187	8.809	419	1675
5	0.5157	1.583	0.244	4.271	8.746	442	1681
10	0.6150	1.601	0.206	4.353	8.684	465	1686
15	0.7283	1.619	0.175	4.435	8.624	489	1691
20	0.8572	1.639	0.149	4.515	8.586	513	1696
25	1.0032	1.659	0.128	4.595	8.509	536	1699
30	1.1670	1.680	0.111	4.675	8.454	560	1703
35	1.3504	1.702	0.0959	4.753	8.399	585	1706
40	1.5544	1.726	0.0833	4.831	8.346	609	1708