Assignment of tasks

Internal Combustion Engine Fundamentals

H 2019

Name: _____

Matriculation number: _____

Signature: _____

120 Points

1. Task (23.5 points)

a) (2 points)

To ensure the complete burn-off of soot in the particle filter of a Diesel engine additional measures must be taken. Please name two active und two passive measures to support the regeneration of a particle filter.

b) (5.5 points)

Sketch the cylinder pressure for a gasoline engine without ignition, in case of glow ignition (before and after ignition) and in case of knocking combustion and label the curves. Describe the causes and consequences as well as the major differences between these abnormal combustion phenomena.
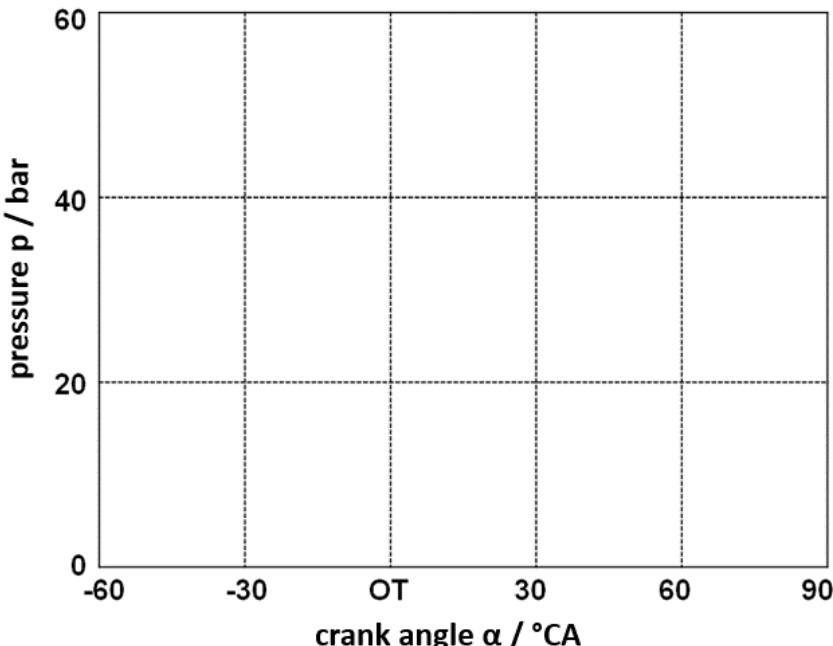

Figure 1.1: diagram for subtask **b)**

c) (2 points)

Please name four boundary conditions that promote a high tendency for engine knock.

d) (3 points)

Define the terms exergy and anergy. Name two examples for pure exergy fluxes in the exergy balance of a combustion engine.

e) (2.5 points)

Mark the type of fuel in the diagram below. Furthermore give examples how an increased 10 %, 50 % and 90 % boiling temperature affects the engine operation (one example per boiling temperature is sufficient).
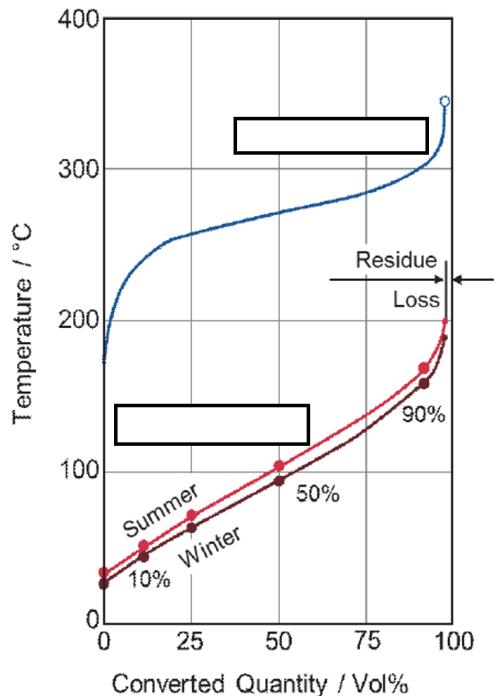

Figure 1.2: diagram for subtask **e)**

f) (2 points)

Name the two phases of combustion in a diesel engine.

g) (5 points)

Name three typical demands on the ignition system. Furthermore explain the terms "hot" and "cold " spark plug.

h) (1.5 points)

Name the three classifications of DI gasoline combustion systems in stratified operation.

2. Task (23 points)

a) (5.5 points)

Plot the real process of the internal combustion engine in the p,V-diagram und plot additionally the valve timings IVO, IVC, EVO, EVC and the ignition timing in the diagram. The direction of the process, TDC and BDC and the ambient pressure p_{amb} has to be made visible.
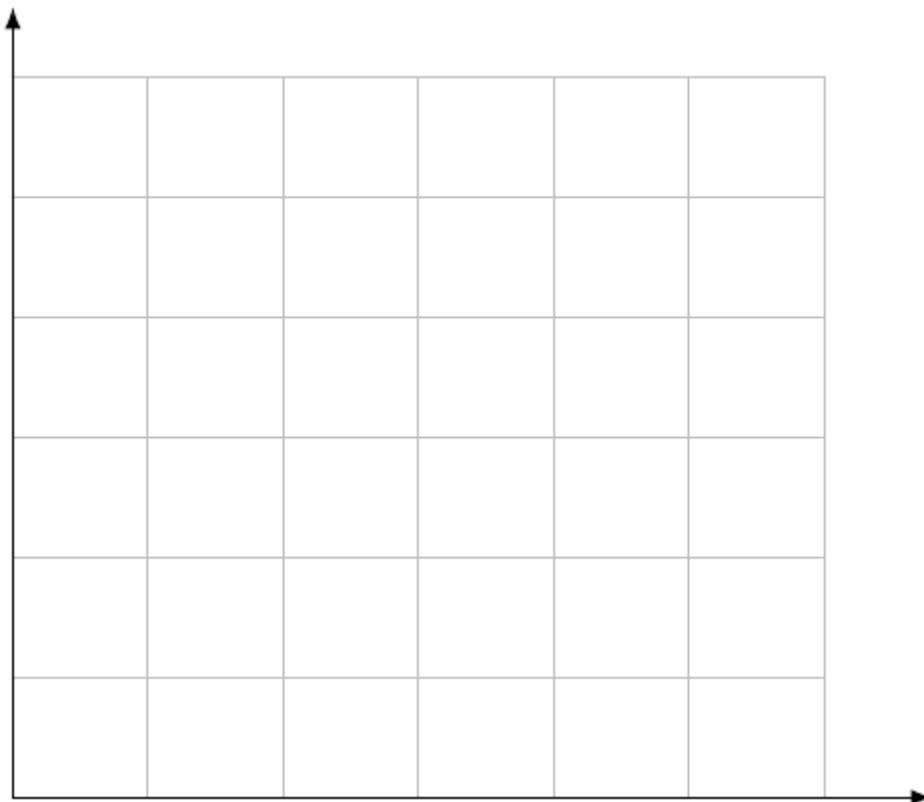
Figure 2.1: diagram for subtask **a)**

From a gasoline engine with peak pressure limit the following data from a part load operating point are known:

General data

maximum pressure of cycle	p_{max}	$=$	100	bar
pressure at start of compression	p_1	$=$	2.5	bar
temperature at start of compression	T_1	$=$	303.15	K
heat input	q_{B}	$=$	980	kJ/kg
compression ratio	ε	$=$	11.5	
isentropic exponent	κ	$=$	1.4	

Air can be modeled as an ideal gas

b) (9.5 points)

Which standard cycle will achieve the highest efficiency with the given boundaries? Justify your answer. Calculate the state variables $(p,\ T,\ v)$ for every state, the heat output q_{A}, as well as the inner efficiency η_{i}. Also calculate the thermodynamic properties of air $(c_{\mathrm{v}}, c_{\mathrm{p}}, R_{\mathrm{L}})$.

Hint to c)

- If you could not solve subtask **b)** compute further with following values
  $\eta_i = 0.55$, $c_p = 1.05\frac{kJ}{kg}$, $c_v = 0.7\frac{kJ}{kg}$ und $v'_3 = 0.055\frac{m^3}{kg}$

c) (4 points)

Calculate the relative change of the inner efficiency, if the engine expands to pressure at start of compression p_1 .

d) (4 points)

Plot in the given T,s - diagram the process from subtask **b)**. Afterwards plot the exergy losses in the T,s - diagram and name them. Consider the anergy of the input heat in the figure.

Figure 2.2: diagram for subtask **d)**

3. Task (25.5 points)

A four-cylinder four-stroke boxer engine is to be investigated with regard to its free mass forces and moments. The sketch below shows the cylinder arrangement and the shape of the crankshaft. Furthermore, the following parameters are known:

Given data

|	
Firing order:	1 - 2 - 3 - 4
Firing interval:	180° crankshaft angle
Piston position of cylinder 1:	TDC
Direction of rotation:	Positive concerning z-axis
Cylinder distance a:	110 mm
Bank offset b:	40 mm
Stroke s:	79 mm
Connecting rod length l:	158 mm
Oscillating mass per cylinder m_h:	630 g
Mass of one balance weight m_{Ag}:	50 g
Balance weight distance to rotational axis r_{Ag}:	15 mm
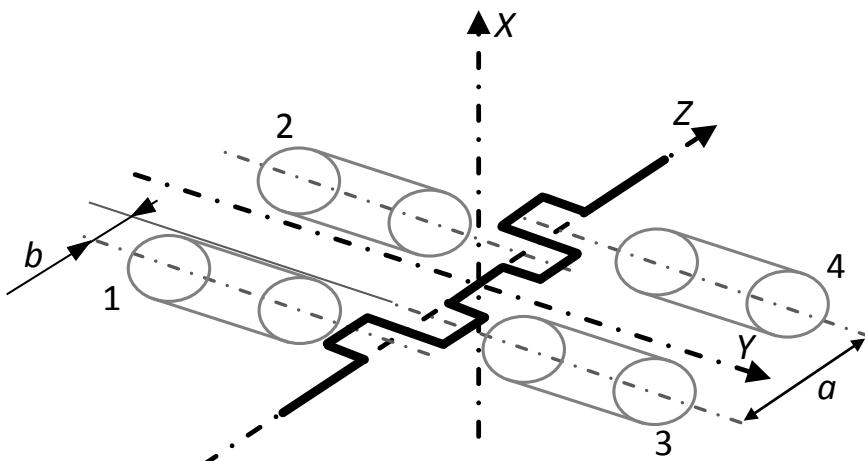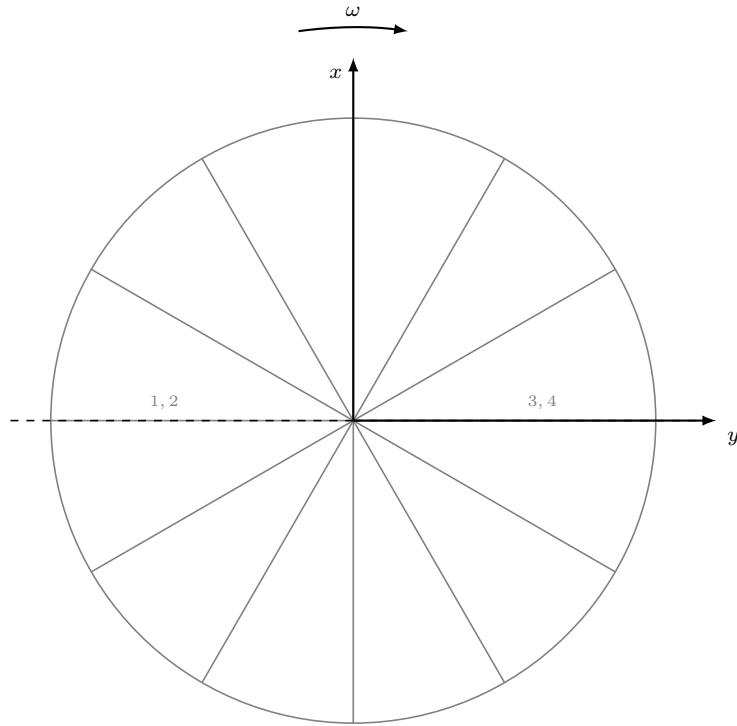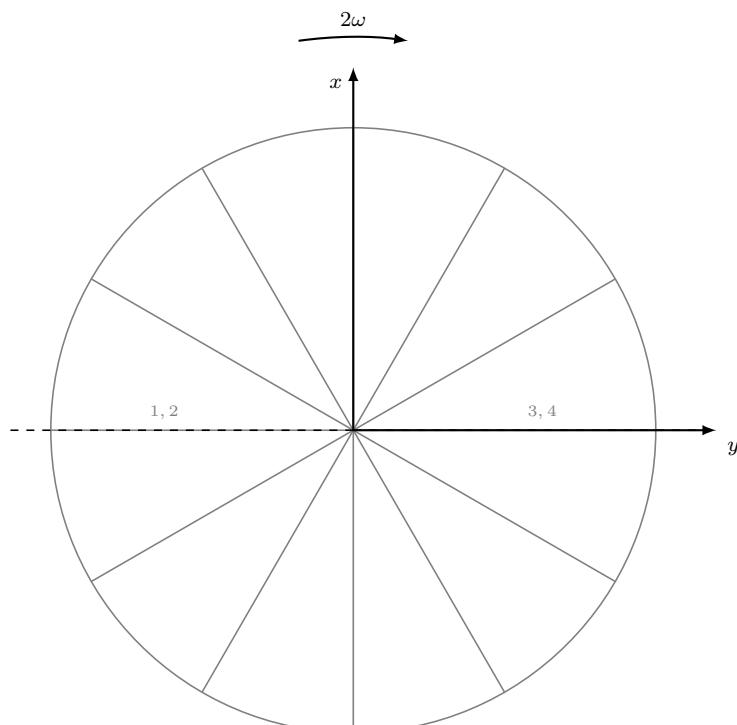
Figure 3.1: cylinder arrangement

Hint

- The origin of the coordinate system corresponds to the center of gravity of the crankshaft.

- The z-axis corresponds to the axis of rotation of the crankshaft
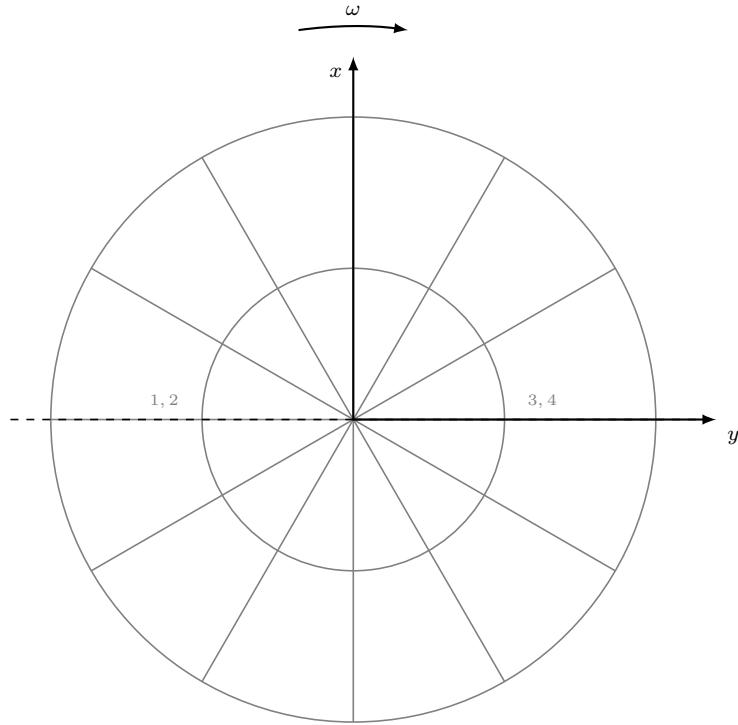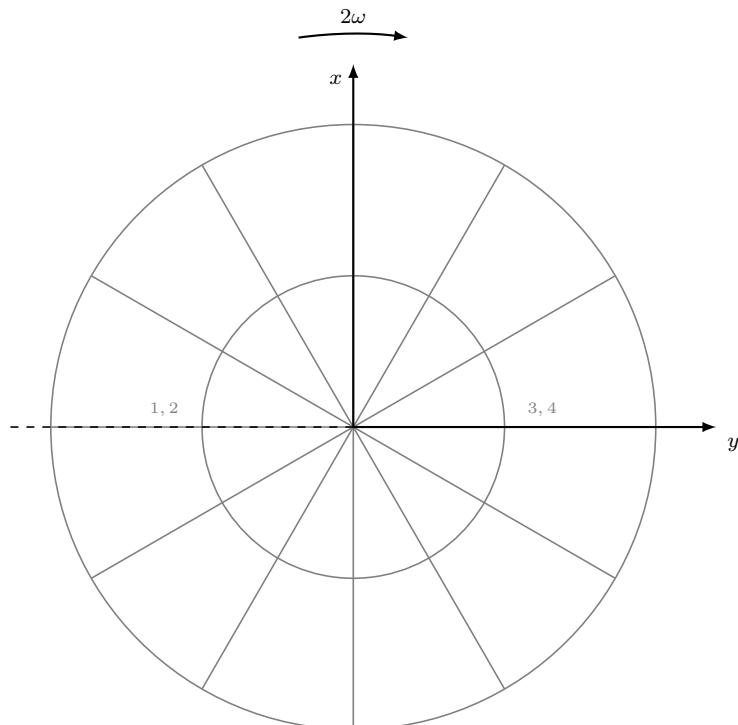
a) (8 points)

Determine <u>graphically</u> the first and second order free positive and negative mass forces in the diagram provided for this purpose on the following page.

**First order mass forces**

Second order mass forces

b) (8 points)

Determine <u>graphically</u> the first and second order free positive and negative mass moments in the diagram provided for this purpose.

First order mass moments

Second order mass moments

c) (3.5 points)

If applicable, please determine <u>mathematically</u> the amount of the resulting free positive and negative rotating mass forces and moments and specify them as multiples of F_{01} and F_{02}. If there is a resultant of 0, please specify which forces and moments compensate each other.

d) (6 points)

In order to satisfy the increased demands for comfort, the 2nd order free mass moments are to be compensated. How many balance shafts are required for the compensation? Determine the length of the balance shaft(s) l_{Ag}. Take into account the given boundary conditions. Note that no additional free mass forces or moments may arise as a result of this measure.

Hint

- The balance masses can be considered as mass points!

4. Task (24 points)

A four-cylinder, four-stroke, port fuel injection gasoline engine will be equiped with a compressor to increase its power output. The engine runs with premium gasoline.

For the baseline, naturally aspirated engine the following values are given:

Bore diameter	D	$=$	91	mm
Stroke	s	$=$	88.4	mm
Compression ratio	ε	$=$	10.4	
Rated engine power	$P_{e,max}$	$=$	110	kW
Rated engine speed	n_p	$=$	5400	1/min

a) (3 points)

Please calculate the engine displacement V_H, the compression volume of <u>one cylinder</u> V_c and the mean piston speed c_m at rated power.

Hint to b)

- If you couldn't solve subtask **a)**, continue using $V_H = 2.2\,l$.

For the baseline, naturally aspirated engine the following values are given at rated power:

Volumetric efficiency	λ_a	$=$	0.93	
Ambient pressure	p_u	$=$	0.95	bar
Ambient temperature	T_u	$=$	298	K
Air fuel ratio	λ	$=$	0.85	
Friction mean effective pressure	p_{mr}	$=$	1.5	bar

b) (9.5 points)

Determine the follwing values at rated power of the engine:

Air mass flowrate	$\dot{m}_L$	kg/h
Fuel mass flowrate	$\dot{m}_B$	kg/h
Brake specific fuel consumption	b_e	g/kWh
Engine thermal efficiency	η_e	
Indicated power	P_i	kW

The baseline engine is now equipped with a compressor. The compressor is driven by the crankshaft by a belt.

Hint to c)

- The supercharged engine has the same rated speed as the baseline engine.

- The friction losses (valvetrain, cranskshaft, etc) remain the same as in the case of the baseline engine.

For the supercharged engine the following values are given at rated power:

Intake manifold pressue	p_{E}	=	1.42	bar
Intake manifold temperature	T_{E}	=	337	K
Air mass flowrate	$\dot{m}_L$	=	560	kg/h
Indicated efficiency	η_{i}	=	0.38	
effective compressor power	$P_{\mathrm{eff,K}}$	=	20	kW
Mixture heating value	H_{G}	=	4730	kJ/m^3

c) (11.5 points)

Determine the following values at the rated power of the engine:

Air fuel ratio	λ	
Fuel mass flowrate	$\dot{m}_{\mathrm{B}}$	kg/h
brake specific fuel consumption	b_{e}	g/kWh
effective power	P_{e}	kW
Volumetric effciency	λ_{a}	

5. Task (24 points)

A four-cylinder four-stroke gasoline engine with a three-way catalyst is investigated on the test bench regarding its catalyst heating.

The following data is given:

Displacement	V_H	$=$	2000	cm^3
Engine speed	n	$=$	1200	$1/\mathrm{min}$
Indicated mean effective pressure	p_mi	$=$	3	bar
Mass fraction carbon in fuel (gasoline regular)	c	$=$	0.84	$-$

a) (2.5 points)

Which exhaust gas components can be significantly reduced with a three-way catalyst? Which requirement regarding the mixture composition has to be fulfilled for an efficiently working system? Sketch the qualitative trace of these raw emissions as a function of the relative air/fuel-ratio λ for a homogeneously operated gasoline engine in the following diagram.
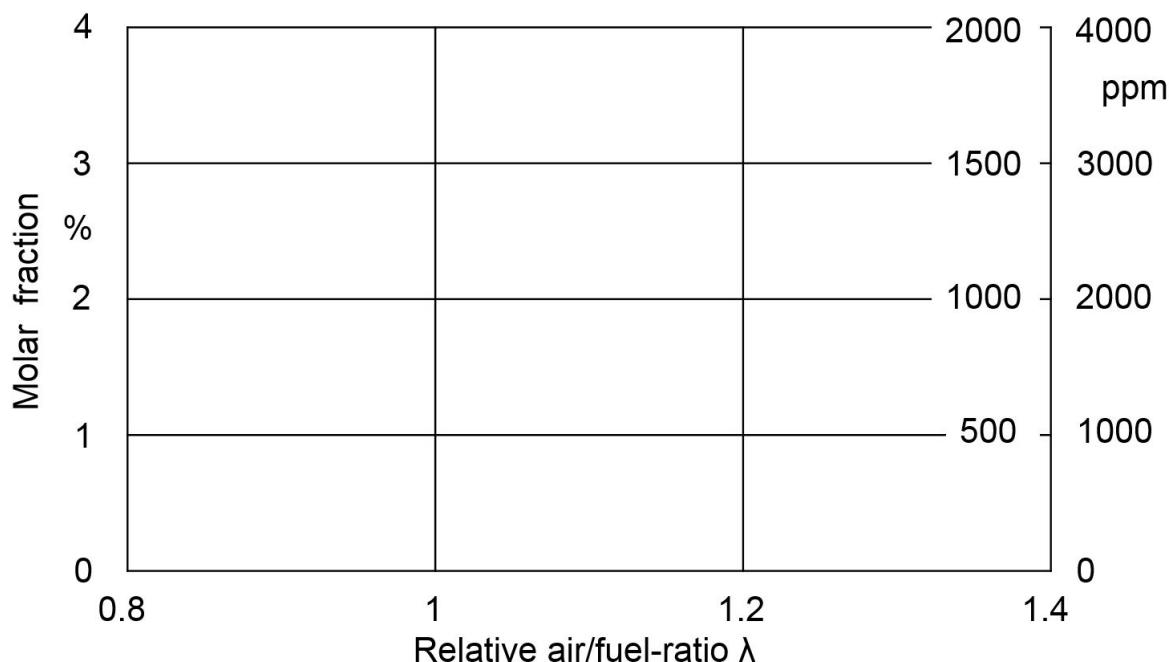

Figure 5.1: diagram for subtask **a)**

Hint to all further subtasks

- The unburned hydrocarbons in the exhaust gas are assumed as C_3H_8

- The molar mass of the exhaust gas can be assumed constant and is $M_A = 28.8$ kg/kmol

- 100 % indicated fuel consumption is equal to $b_i = 300$ g/kWh

- 100 % HC mass flow (engine-out) is equal to $\dot{m}_{HC} = 40$ g/h

At first the engine is operated at optimized efficiency with an ignition timing of 20° CA before top dead center (bTDC).
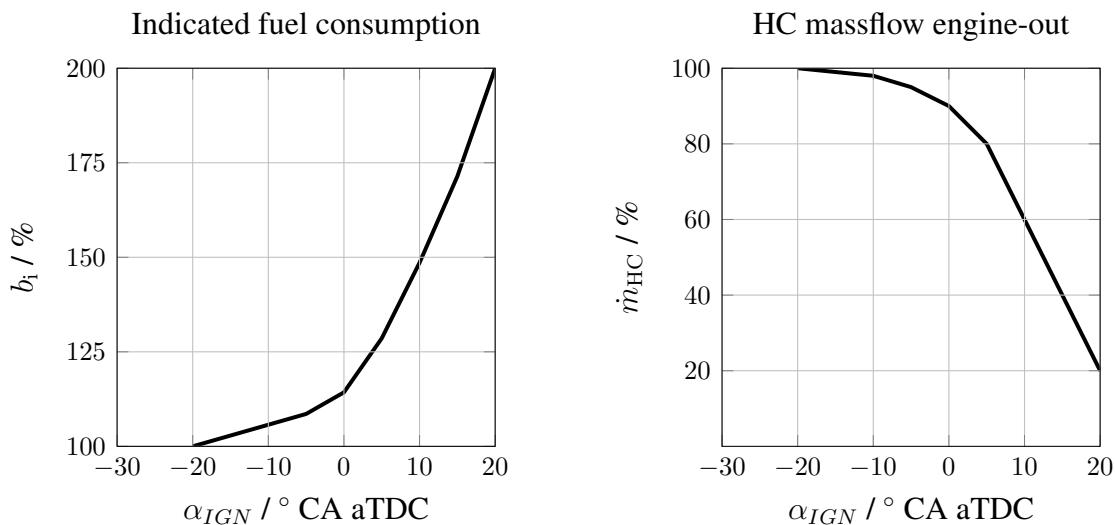

Figure 5.2: diagram for all further subtasks

b) (5.5 points)

Please calculate the following values for the above mentioned operating point:

Indicated power	P_i	kW
Fuel mass flow	$\dot{m}_B$	g/s
Indicated efficiency	η_i	%
Exhaust gas mass flow	$\dot{m}_A$	g/s

Hint to c)

- If you could not solve subtask b) please continue with a fuel mass flow of $\dot{m}_B = 0.5$ g/s

- The CO_2 concentration in the exhaust gas (engine-out) is $\psi_{CO_2} = 12.5$ %

c) (5.5 points)

Please determine the molar fraction of the unburned hydrocarbons ψ_{HC} and carbon monoxide ψ_{CO} in the exhaust gas at engine-out. Furthermore, please determine the specific unburned hydrocarbon consumption b_{HC} based on the indicated power.

Especially at engine cold start/warm-up it is important that the three-way catalyst (TWC) heats up quickly to reach high conversion rates. An indirect measure for a quick heat-up of the catalyst is ignition timing retardation.

Hint to d)

- The exhaust gas temperature T_A is constant in each stationary cold start/warm-up operating point.

- The exhaust gas temperature is $T_A = 400$ °C in the operating point with optimized efficiency and an ignition timing of -20° CA aTDC.
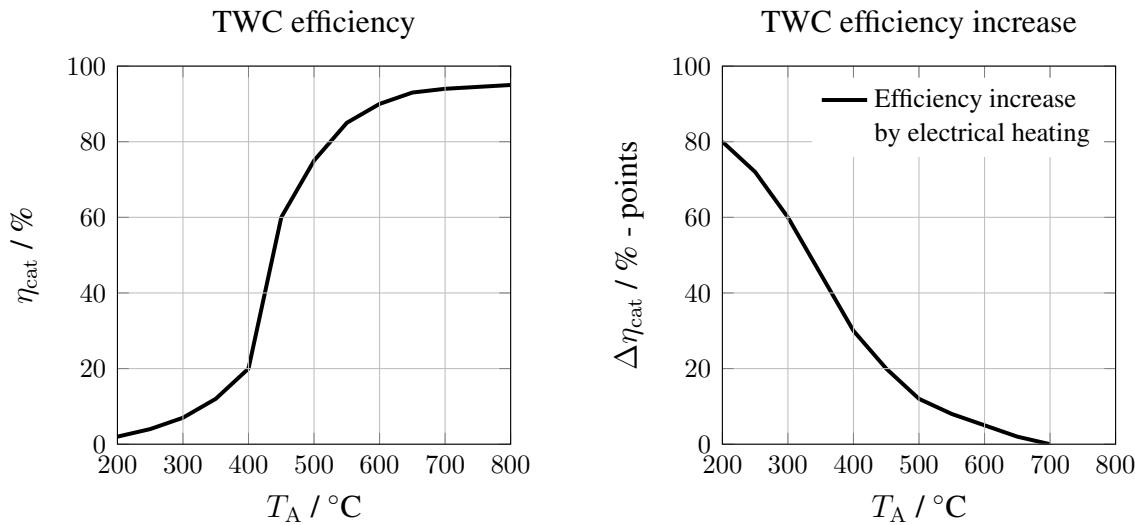

Figure 5.3: diagramm for subtask **d)** and **e)**

d) (4 points)

The ignition timing will be retarded to 10° CA aTDC in order to achieve an exhaust gas temperature increase of 200 °C. Calculate the difference between the HC-emissions after catalyst Δm_{HC} during a 30 s lasting cold start phase if the engine is operated at optimized efficiency and with retarded ignition timing.

e) (4.5 points)

Now the ignition timing will be set to 5° CA aTDC which results in an exhaust gas temperature of 450 °C. Furthermore, the three-way catalyst is electrically heated (E-cat), which increases the three-way catalyst efficiency η_{cat}. Please determine the reduction in HC-emissionens after catalyst Δm_{HC} during a 30 s lasting cold start/warm-up phase if the engine is operated without electrical heating and with electrical heating (E-cat) in the three-way catalyst.

f) (2 points)

Which further measures for a quick heat-up of the three-way catalyst exist besides a retarded ignition timing and an electrically heated catalyst? Name two further indirect and two direct measures.

Solution

Internal Combustion Engine Fundamentals

H 2019

120 Points

1. Task (23.5 points)

a) (2 points)

To ensure the complete burn-off of soot in the particle filter of a Diesel engine additional measures must be taken. Please name two active und two passive measures to support the regeneration of a particle filter.

> Per measure 0.5 points (max. 1 point for active and 1 point for passive measures)
>
> Active measures:
>
> - Increasing the exhaust gas temperature of the engine by throttling induction air or exhaust gas
>
> - Increasing the exhaust gas temperature of the engine by adjusting the start of injection and/or utilizing post-injection (also external injector)
>
> - Increasing the exhaust gas temperature of the engine by supplying secondary energy to the filter (burner, electric heating)
>
> Passive measures
>
> - Decreasing the particulate ignition temperature by applying a catalytic filter coating
>
> - Decreasing the particulate ignition temperature by using fuel additives
>
> - Decreasing the particulate ignition temperature by adding chemical ignition and combustion improvers into the exhaust gas
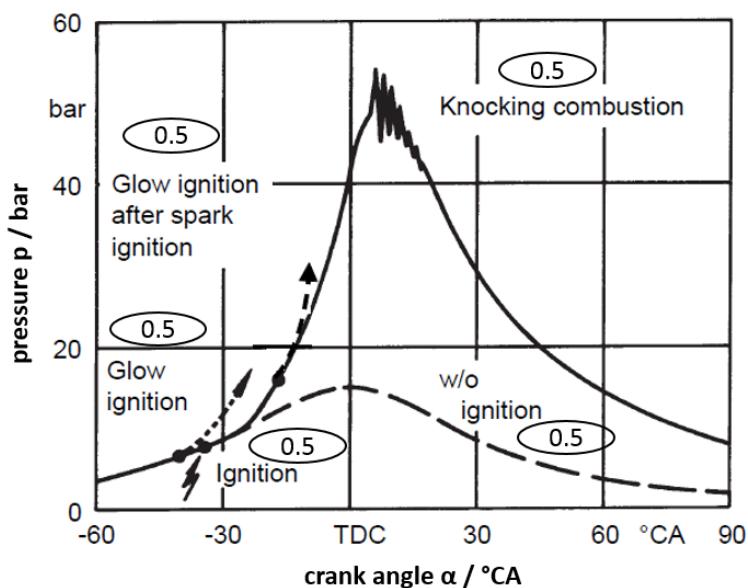
b) (5.5 points)

Sketch the cylinder pressure for a gasoline engine without ignition, in case of glow ignition (before and after ignition) and in case of knocking combustion and label the curves. Describe the causes and consequences as well as the major differences between these abnormal combustion phenomena.

Every bold marked statement 0.5 points

<u>Cause knocking combustion</u>: During normal spark ignition it comes to **self-ignition in the still unburned mixture**. This leads to a **detonation-like propagation of the combustion** in the fresh mixture, which causes high-frequency pressure oscillations and can lead to damage of the engine.

<u>Cause glow ignition</u>: **Ignition of the fuel-air mixture at hot spots** in the combustion chamber. **Faster combustion** at similar pressure pattern as in normal combustion.

<u>Difference</u>: Unlike a knocking combustion at glow ignition initially only a deflagration (faster combustion process) occurs, according to the turbulent flame propagation in spark ignition. **Pressure curves are then similar to a normal combustion with previous ignition timing** (non-knocking glow ignition). **As a result of a glow ignition however, a knocking combustion can occur** (knocking glow ignition).

c) (2 points)

Please name four boundary conditions that promote a high tendency for engine knock.

Every boundary condition 0.5 points (max. 2 points total)

- High pressure and temperature in the unburned mixture

- Approaching the stoichiometric air/fuel ratio ($\lambda = 1$)

- High residual gas fraction (hot residual gas from previous combustion cycle)

- Inhomogenities in the residual gas and fuel distribution.

- Slow processes (causing long pre-reaction times in the residual mixture)

- Low fuel research octane number (RON)

d) (3 points)

Define the terms exergy and anergy. Name two examples for pure exergy fluxes in the exergy balance of a combustion engine.
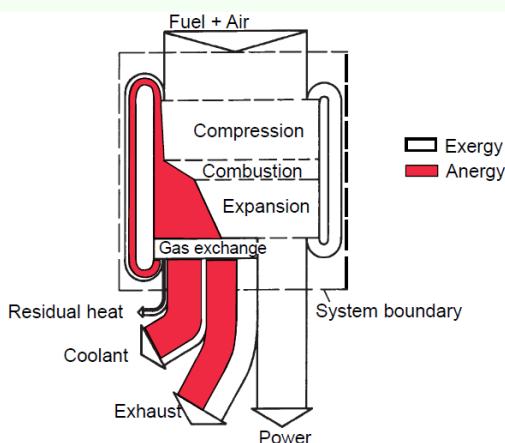
Exergy: Energy that can still be converted into any other energy type.   ①

Anergy: Energy that can not be returned into exergy.   ①

Every example 0.5 points
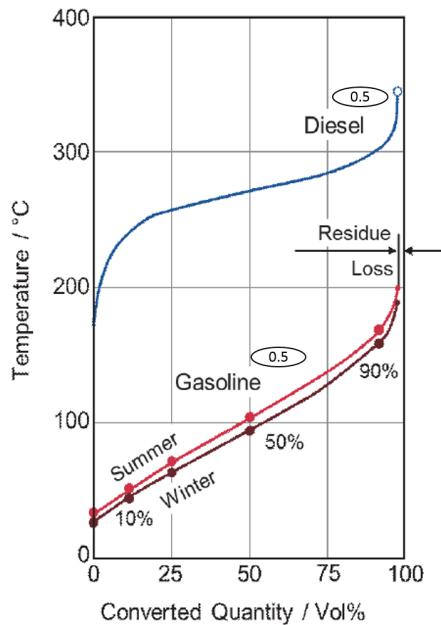
- fuel + air (exergy)   ⓪.⑤

- power (exergy)   ⓪.⑤

e) (2.5 points)

Mark the type of fuel in the diagram below. Furthermore give examples how an increased 10 %, 50 % and 90 % boiling temperature affects the engine operation (one example per boiling temperature is sufficient).

Every statement 0.5 points (max. 0.5 points per 10%-, 50%- and 90%-point)

10 %-point too high:

- poor cold start

50 %-point too high:

- poor transient response at cold engine condition

90 %-point too high:

- engine oil dilution

- residue formation in the combustion chamber (e.g. soot)

f) (2 points)

Name the two phases of combustion in a diesel engine.

- pre-mixed combustion phase　　　　　　　　　　　　　　　　　　　　①

- mixture-controlled combustion phase　　　　　　　　　　　　　　　①

g) (5 points)

Name three typical demands on the ignition system. Furthermore explain the terms "hot" and "cold " spark plug.

Every correct answer one point, max. three points total.

- providing the ignition energy

- generation of the ignition voltage

- control of the ignition timing (ignition point)

- generation of a spark with defined spark duration

hot spark plug: high heat rating index, long insulator nose, large heat receptive surface, minimal thermal load capacity, fast to reach self-cleaning temperature.   ①

cold spark plug: low heat rating index, short insulator nose, small heat receptive surface, high protection against glow ignition, danger of contamination.   ①

h) (1.5 points)

Name the three classifications of DI gasoline combustion systems in stratified operation.

- air-guided   ⓪.⑤

- spray-guided   ⓪.⑤
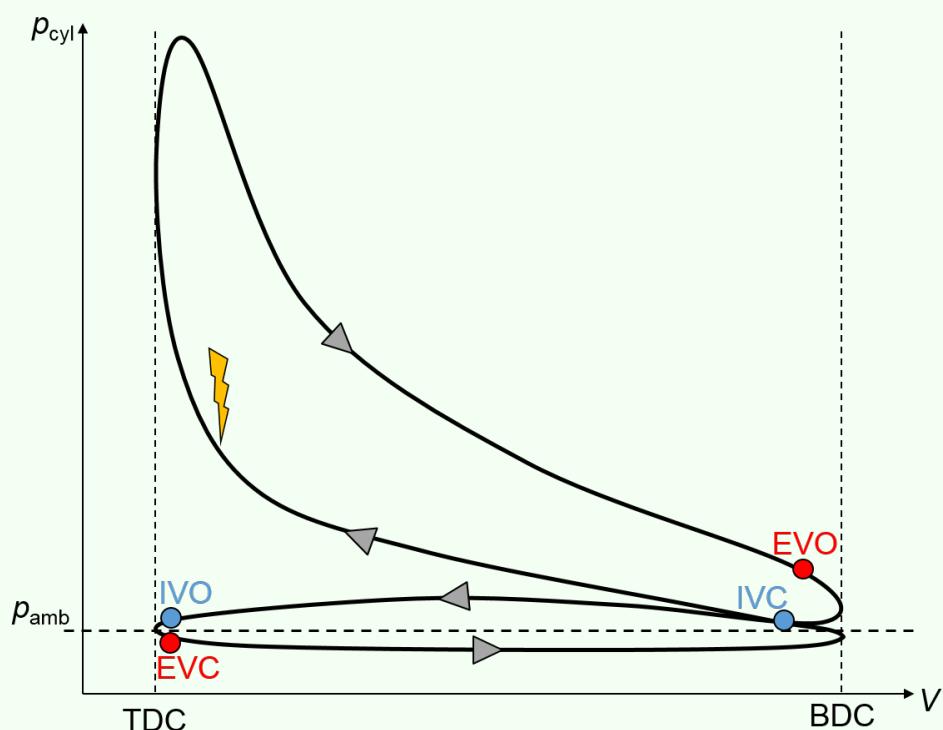
- wall-guided   ⓪.⑤

2. Task (23 points)

a) (5.5 points)

Plot the real process of the internal combustion engine in the p,V-diagram und plot additionally the valve timings IVO, IVC, EVO, EVC and the ignition timing in the diagram. The direction of the process, TDC and BDC and the ambient pressure p_{amb} has to be made visible.

- correct named axis   (0.5)
- firing cycle qualitively plotted correctly   (0.5)
- load cycle qualitively plotted correctly   (0.5)
- TDC and BDC recorded correctly   (0.5)
- p_{amb} plotted correctly   (0.5)
- realistic valve timings recorded 4 x   (0.5)
- ignition timing recorded correctly   (0.5)
- direction of the cycle recorded correctly   (0.5)

b) (9.5 points)

Which standard cycle will achieve the highest efficiency with the given boundaries? Justify your answer. Calculate the state variables (p, T, v) for every state, the heat output q_A, as well as the inner efficiency η_i. Also calculate the thermodynamic properties of air (c_v, c_p, R_L).

- $R_L = \frac{R_m}{M_L} = 0.287 \frac{kJ}{kgK}$ (0.5)

- $c_v = \frac{R_L}{\kappa-1} = 0.718 \frac{kJ}{kgK}$ (0.5)

- $c_p = R_L + c_v = 1.005 \frac{kJ}{kgK}$ (0.5)

- $v_1 = v_4 = \frac{R_L \cdot T_1}{p_1} = 0.3481 \frac{m^3}{kg}$ (1)

- $v_2 = \frac{v_1}{\epsilon} = 0.03027 \frac{m^3}{kg}$ (0.5)

- $T_2 = T_1 \epsilon^{\kappa-1} = 805.261 K$ (0.5)

- $p_2 = \frac{p_1}{(\frac{1}{\epsilon})^\kappa} = 76.369 bar$ (0.5)

- $T_3^* = \frac{q_B}{c_v} + T_2 = 2170.16 K$
  $p_3^* = p_2 \cdot \frac{T_3^*}{T_2} = 205.81 bar > p_{max}$ (0.5)

- $p_2 < p_{max} < p_3^* \rightarrow Seiliger$ (0.5)

- $p_3 = p_{max} = p_3'$ (1)

- $T_3 = T_2 \cdot \frac{p_3}{p_2} = 1054.435 K$ (0.5)

- $T_3' = T_3 + \frac{q_B - c_v(T_3 - T_2)}{c_p} = 1851.853 K$ (0.5)

- $v_3' = \frac{RT_3'}{p_3'} = 0.05316 \frac{m^3}{kg}$ (0.5)

- $T_4 = T_3' (\frac{v_3'}{v_4})^{\kappa-1} = 873.297 K$ (0.5)

- $p_4 = p_3' (\frac{v_3'}{v_4})^\kappa = 7.202 bar$ (0.5)

- $q_A = c_v(T_1 - T_4) = -409.169 \frac{kJ}{kg}$ (0.5)

- $\eta_i = 1 - \frac{-q_A}{q_B} = 0.582$ (0.5)
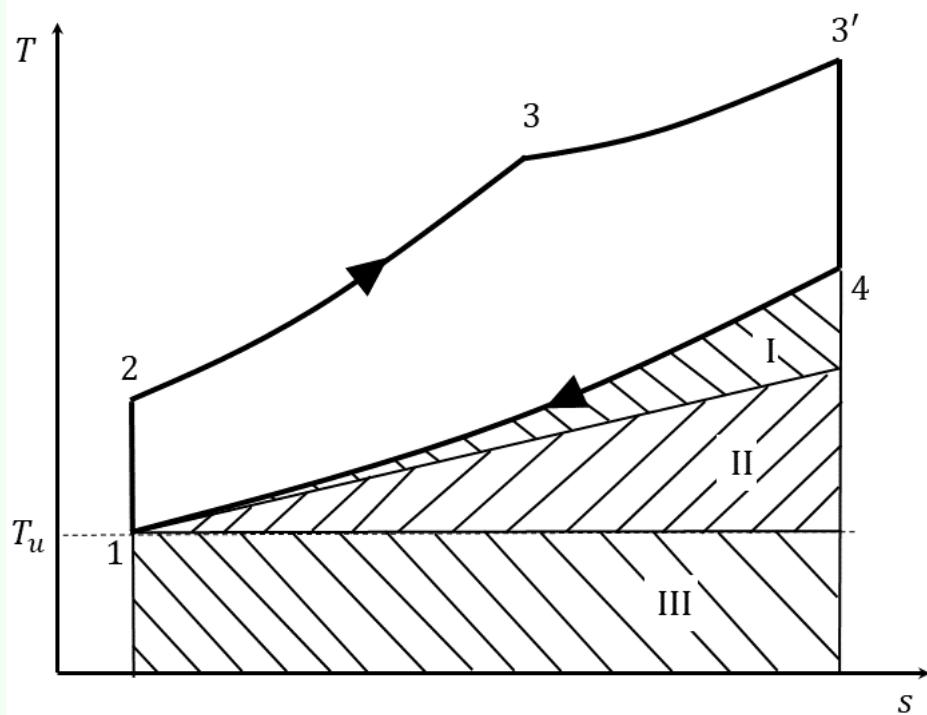
c) (4 points)

Calculate the relative change of the inner efficiency, if the engine expands to pressure at start of compression p_1 .

- $p'_4 = p_1$ (0.5)

- $v'_4 = v'_3 (\frac{p'_3}{p'_4})^{(\frac{1}{\kappa})} = 0.741 \frac{m^3}{kg}$ (1)

- $T'_4 = T'_3 (\frac{v'_3}{v'_4})^{(\kappa-1)} = 645.469 K$ (1)

- $q'_A = c_p(T_1 - T'_4) = -343.933 \frac{kJ}{kg}$ (0.5)

- $\eta'_i = 1 - \frac{-q'_A}{q_B} = 0.649$ (0.5)

- $\Delta \eta'_i = \frac{\eta'_i - \eta_i}{\eta_i} * 100 = 11.428\%$ (0.5)

d) (4 points)

Plot in the given T,s - diagram the process from subtask **b)**. Afterwards plot the exergy losses in the T,s - diagram and name them. Consider the anergy of the input heat in the figure.

- states of Seiliger process plotted correctly   (0.5)

- relation between status changes correct   (0.5)

- area of the exergy losses plotted correctly per area   (0.5) → (1.5)

- I: exergy loss, because no expanse till starting pressure   (0.5)

- II: exergy loss, because no expanse till starting temperature   (0.5)

- III: anergy of input heat   (0.5)
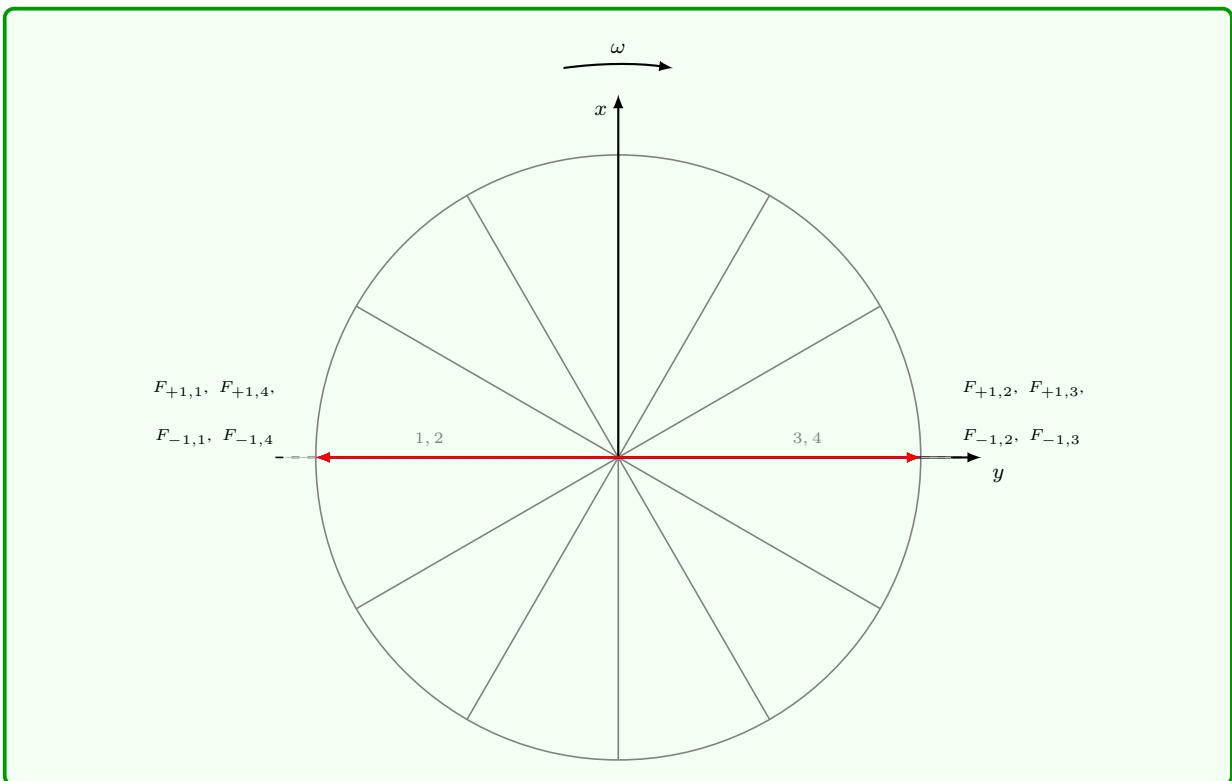
3. Task (25.5 points)

a) (8 points)
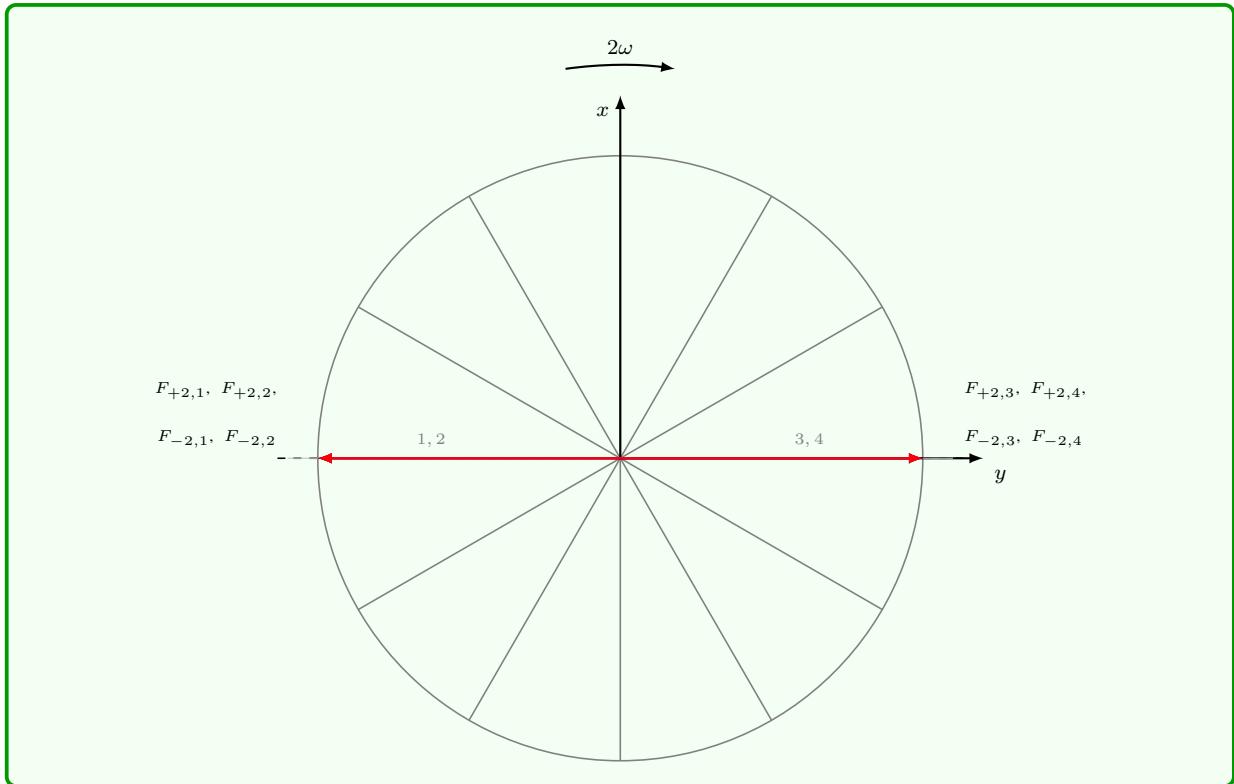
Determine graphically the first and second order free positive and negative mass forces in the diagram provided for this purpose on the following page.

> 0.5 points per vector

First order mass forces
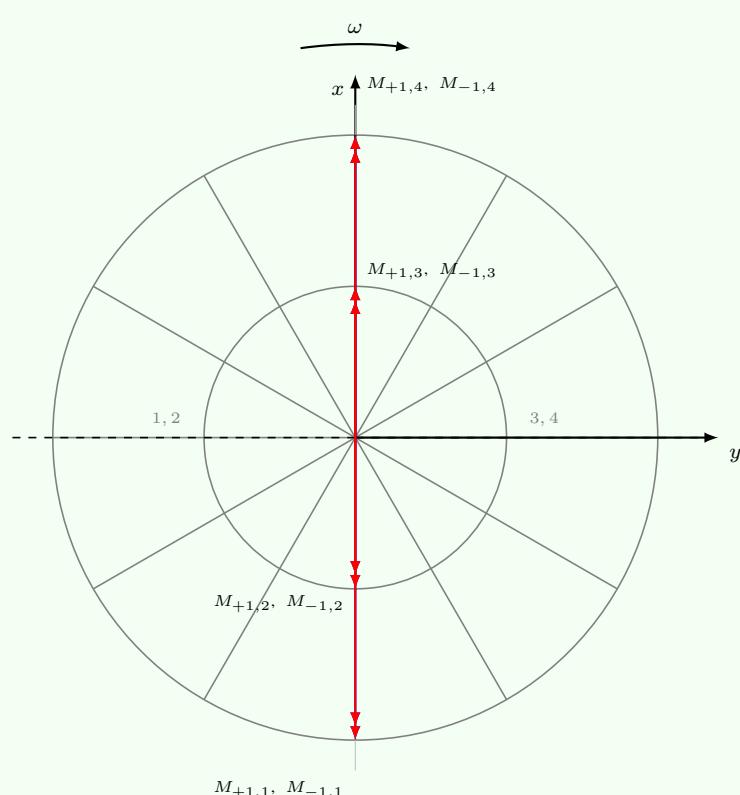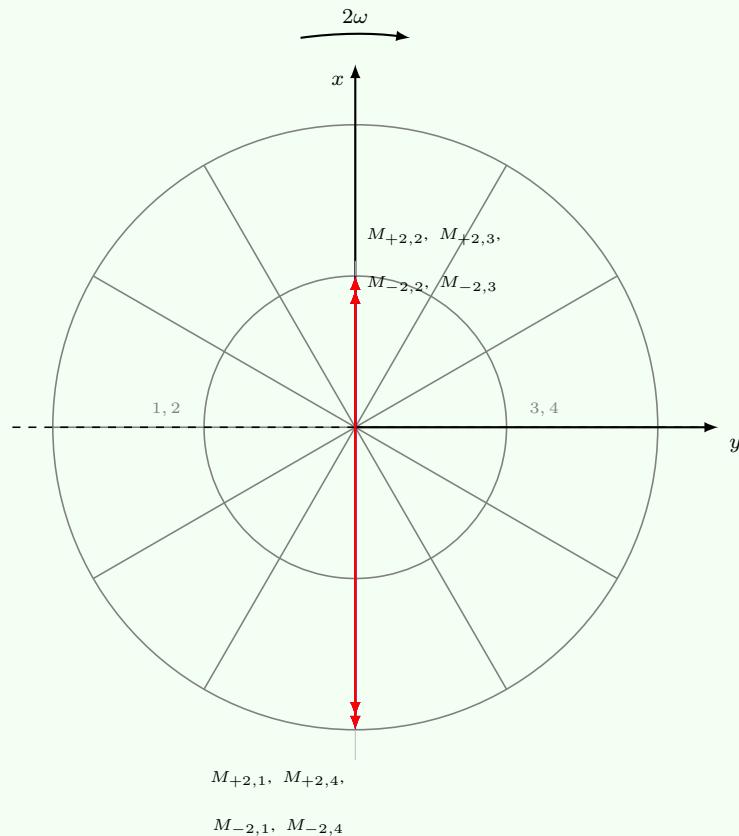
Second order mass forces

## b) (8 points)

Determine <u>graphically</u> the first and second order free positive and negative mass moments in the diagram provided for this purpose.

> 0.5 points per vector

First order mass moments

Second order mass moments

The diagram shows a polar/wheel layout with axes x (vertical) and y (horizontal), with 2ω rotation at top. Labels: $M_{+2,2}$, $M_{+2,3}$, $M_{-2,2}$, $M_{-2,3}$ near top; $1,2$ on left; $3,4$ on right; $M_{+2,1}$, $M_{+2,4}$, $M_{-2,1}$, $M_{-2,4}$ at bottom.

c) (3.5 points)

If applicable, please determine <u>mathematically</u> the amount of the resulting free positive and negative rotating mass forces and moments and specify them as multiples of F_{01} and F_{02}. If there is a resultant of 0, please specify which forces and moments compensate each other.

$\sum F_1 = 0$ as $\sum \vec{F}_{+1,i} = 0$ and $\sum \vec{F}_{-1,i} = 0$ (0.5)

$\sum M_1 = 0$ as $\sum \vec{M}_{+1,i} = 0$ and $\sum \vec{M}_{-1,i} = 0$ (0.5)

$\sum F_2 = 0$ as $\sum \vec{F}_{+2,i} = 0$ and $\sum \vec{F}_{-2,i} = 0$ (0.5)

$\sum M_2 = \sum M_{+2,i} + \sum M_{-2,i}$

$\sum M_{+2,i} = M_{+2,2} + M_{+2,3} - M_{+2,1} - M_{+2,4}$ (0.5)

$= F_{+2,2} \cdot \dfrac{a-b}{2} + F_{+2,3} \cdot \dfrac{a-b}{2} - F_{+2,1} \cdot (\dfrac{a-b}{2} + b) - F_{+2,4} \cdot (\dfrac{a-b}{2} + b)$

$= F_{+2} \cdot (a - b) - F_{+2} \cdot (a - b + 2 \cdot b)$

$= F_{+2} \cdot 2 \cdot (-b)$ (0.5)

$\sum M_{-2,i} = F_{-2} \cdot 2 \cdot (-b)$ (0.5)

$\Rightarrow \sum M_2 = F_{02} \cdot 2 \cdot (-b)$ (0.5)

d) (6 points)

In order to satisfy the increased demands for comfort, the 2nd order free mass moments are to be compensated. How many balance shafts are required for the compensation? Determine the length of the balance shaft(s) l_{Ag}. Take into account the given boundary conditions. Note that no additional free mass forces or moments may arise as a result of this measure.

Hint

- The balance masses can be considered as mass points!

For the compensation of an oscillating moment, two balance shafts ⓪⑤ with opposite direction of rotation are required. Consequently, half of the amount of the resultant is compensated by each shaft. ATTENTION: The balance shafts for the compensation of 2nd order mass moments rotate at twice the angular velocity: $\omega_{Ag} = 2 \cdot \omega$ ⓪⑤

Moment to be compensated per shaft:

$$\Rightarrow M_{Soll} = \frac{1}{2} \cdot M_2 = F_{02} \cdot (-b) = \frac{s}{2 \cdot l} \cdot m_h \cdot \frac{s}{2} \cdot \omega^2 \cdot (-b) \quad ①$$

$$= \frac{39,5mm}{158mm} \cdot 0,63kg \cdot 39,5mm \cdot (-40mm) \cdot \omega^2 = -248,85 \cdot \omega^2 \cdot kg \cdot mm^2 \quad ①$$

Resulting moment per balance saft:

$$M_{Ag} = m_{Ag} \cdot r_{Ag} \cdot \omega_{Ag}^2 \cdot \frac{l_{Ag}}{2} \cdot 2 = m_{Ag} \cdot r_{Ag} \cdot (2 \cdot \omega)^2 \cdot l_{Ag} \quad ①$$

$$= 0,05kg \cdot 15mm \cdot 4 \cdot \omega^2 \cdot l_{Ag} = 3 \cdot \omega^2 \cdot l_{Ag} \cdot kg \cdot mm \quad ①$$

$$M_{Soll} = M_{Ag} \Rightarrow l_{Ag} = \frac{248,85 \cdot \omega^2 kg \cdot mm^2}{3 \cdot \omega^2 kg \cdot mm} = 82,95mm \quad ①$$

4. Task (24 points)

a) (3 points)

Please calculate the engine displacement V_H, the compression volume of <u>one cylinder</u> V_c and the mean piston speed c_m at rated power.

$$V_\mathrm{H} = \frac{\pi \cdot D^2}{4} \cdot s \cdot z \quad \text{(0.5)}$$

$$V_\mathrm{H} = 2.31 \,\mathrm{l} \quad \text{(0.5)}$$

$$\varepsilon = \frac{V_\mathrm{h} + V_\mathrm{c}}{V_\mathrm{c}}$$

$$V_\mathrm{c} = \frac{V_\mathrm{H}}{(\varepsilon - 1) \cdot z} \quad \text{(0.5)}$$

$$V_\mathrm{c} = 0.0611 \,\mathrm{l} \quad \text{(0.5)}$$

$$c_\mathrm{m} = 2 \cdot s \cdot n \quad \text{(0.5)}$$

$$c_\mathrm{m} = 15.9 \,\mathrm{m/s} \quad \text{(0.5)}$$

b) (9.5 points)

Determine the follwing values at rated power of the engine:

Air mass flowrate	$\dot{m}_\mathrm{L}$	kg/h
Fuel mass flowrate	$\dot{m}_\mathrm{B}$	kg/h
Brake specific fuel consumption	b_e	g/kWh
Engine thermal efficiency	η_e	
Indicated power	P_i	kW

$$\dot{m}_\mathrm{G} = \lambda_\mathrm{a} \cdot i \cdot n \cdot V_\mathrm{H} \cdot \rho_\mathrm{G} \quad \text{(0.5)}$$

$$\rho_\mathrm{G} = \frac{p_\mathrm{E}}{R_\mathrm{G} \cdot T_\mathrm{E}} \quad \text{(0.5)}$$

$$R_\mathrm{L} = \frac{R}{M_\mathrm{L}} = 0.287 \,\mathrm{kJ/kgK} \quad \text{(0.5)}$$

$$R_\mathrm{B} = \frac{R}{M_\mathrm{B}} = 0.085 \,\mathrm{kJ/kgK} \quad \text{(0.5)}$$

$$R_{\mathrm{G}} = \xi_{\mathrm{L}} \cdot R_{\mathrm{L}} + \xi_{\mathrm{B}} \cdot R_{\mathrm{B}} \quad \text{(0.5)}$$

$$\xi_{\mathrm{B}} = \frac{\dot{m}_{\mathrm{B}}}{\dot{m}_{\mathrm{B}} + \dot{m}_{\mathrm{L}}} \quad \text{(0.5)}$$

$$\xi_{\mathrm{B}} = 0.075 \quad \text{(0.5)}$$

$$\xi_{\mathrm{L}} = 1 - \xi_{\mathrm{B}} = 0.925 \quad \text{(0.5)}$$

$$R_{\mathrm{G}} = 0.272 \, \mathrm{kJ/kgK} \quad \text{(0.5)}$$

$$\rho_{\mathrm{G}} = 1.17 \mathrm{kg/m}^3 \quad \text{(0.5)}$$

$$\dot{m}_{\mathrm{G}} = 405.4 \mathrm{kg/h} \quad \text{(0.5)}$$

$$\dot{m}_{\mathrm{L}} = \dot{m}_{\mathrm{G}} \cdot \xi_{\mathrm{L}} = 375 \mathrm{kg/h} \quad \text{(0.5)}$$

$$\dot{m}_{\mathrm{B}} = \dot{m}_{\mathrm{G}} \cdot \xi_{\mathrm{B}} = 30.4 \mathrm{kg/h} \quad \text{(0.5)}$$

$$b_{\mathrm{e}} = \frac{\dot{m}_{\mathrm{B}}}{P_{\mathrm{e}}} \quad \text{(0.5)}$$

$$b_{\mathrm{e}} = 276.4 \mathrm{g/kWh} \quad \text{(0.5)}$$

$$\eta_{\mathrm{e}} = \frac{P_{\mathrm{e}}}{\dot{m}_{\mathrm{B}} \cdot H_{\mathrm{u,B}}} \quad \text{(0.5)}$$

$$\eta_{\mathrm{e}} = 0.31 \quad \text{(0.5)}$$

$$P_{\mathrm{i}} = P_{\mathrm{e}} + i \cdot n \cdot V_{\mathrm{H}} \cdot p_{\mathrm{mr}} \quad \text{(0.5)}$$

$$P_{\mathrm{i}} = 125.5 \, \mathrm{kW} \quad \text{(0.5)}$$

c) (11.5 points)

Determine the following values at the rated power of the engine:

Air fuel ratio	λ	
Fuel mass flowrate	$\dot{m}_{\mathrm{B}}$	kg/h
brake specific fuel consumption	b_{e}	g/kWh
effective power	P_{e}	kW
Volumetric effciency	λ_{a}	

$$\rho_{\mathrm{G}} = \frac{p_{\mathrm{E}}}{R_{\mathrm{G}} \cdot T_{\mathrm{E}}} \quad \text{(0.5)}$$

$$R_{\mathrm{L}} = \frac{R}{M_{\mathrm{L}}} = 0.287 \, \mathrm{kJ/kgK}$$

$$R_{\text{B}} = \frac{R}{M_{\text{B}}} = 0.085\,\text{kJ/kgK}$$

$$R_{\text{G}} = \xi_{\text{L}} \cdot R_{\text{L}} + \xi_{\text{B}} \cdot R_{\text{B}} \quad \text{(0.5)}$$

$$\xi_{\text{B}} = \frac{\dot{m}_{\text{B}}}{\dot{m}_{\text{B}} + \dot{m}_{\text{L}}} = \frac{1}{1 + L_{\text{st,B}} \cdot \lambda} \quad \text{(0.5)}$$

$$\xi_{\text{L}} = \frac{\dot{m}_{\text{L}}}{\dot{m}_{\text{B}} + \dot{m}_{\text{L}}} = \frac{L_{\text{st,B}} \cdot \lambda}{1 + L_{\text{st,B}} \cdot \lambda} \quad \text{(0.5)}$$

$$\rho_{\text{G}} = \frac{p_{\text{E}}}{T_{\text{E}}} \cdot \frac{1 + L_{\text{st,B}} \cdot \lambda}{\lambda \cdot L_{\text{st,B}} \cdot R_{\text{L}} + R_{\text{B}}} \quad \text{(1)}$$

$$H_{\text{G}} = \frac{\rho_{\text{G}} \cdot H_{\text{u}}}{\lambda \cdot L_{\text{st}} + 1}$$

$$\rho_{\text{G}} = \frac{H_{\text{G}} \cdot (1 + L_{\text{st,B}} \cdot \lambda)}{H_{\text{u}}} \quad \text{(1)}$$

$$\frac{H_{\text{G}} \cdot (1 + L_{\text{st,B}} \cdot \lambda)}{H_{\text{u}}} = \frac{p_{\text{E}}}{T_{\text{E}}} \cdot \frac{1 + L_{\text{st,B}} \cdot \lambda}{\lambda \cdot L_{\text{st,B}} \cdot R_{\text{L}} + R_{\text{B}}} \quad \text{(1)}$$

$$\lambda = \frac{1}{L_{\text{st,B}} \cdot R_{\text{L}}} \cdot \left(\frac{p_{\text{E}} \cdot H_{\text{u}}}{T_{\text{E}} \cdot H_{\text{G}}} - R_{\text{B}} \right) \quad \text{(1)}$$

$$\lambda = 0.88 \quad \text{(0.5)}$$

$$\dot{m}_{\text{B}} = \frac{\dot{m}_{\text{L}}}{L_{\text{st,B}} \cdot \lambda} \quad \text{(0.5)}$$

$$\dot{m}_{\text{B}} = 43.89\text{kg/h} \quad \text{(0.5)}$$

$$\lambda_{\text{a}} = \frac{\dot{m}_{\text{L}} + \dot{m}_{\text{B}}}{i \cdot n \cdot V_{\text{H}} \cdot \rho_{\text{G}}} \quad \text{(0.5)}$$

$$\rho_{\text{G}} = 1.55\text{kg/m}^3 \quad \text{(0.5)}$$

$$\lambda_{\text{a}} = 1.04 \quad \text{(0.5)}$$

$$P_{\text{e}} = (\eta_{\text{i}} \cdot \dot{m}_{\text{B}} \cdot H_{\text{u,B}}) - (i \cdot n \cdot V_{\text{H}} \cdot p_{\text{mr}}) - P_{\text{eff,K}} \quad \text{(1)}$$

$$P_{\text{e}} = 159\,\text{kW} \quad \text{(0.5)}$$
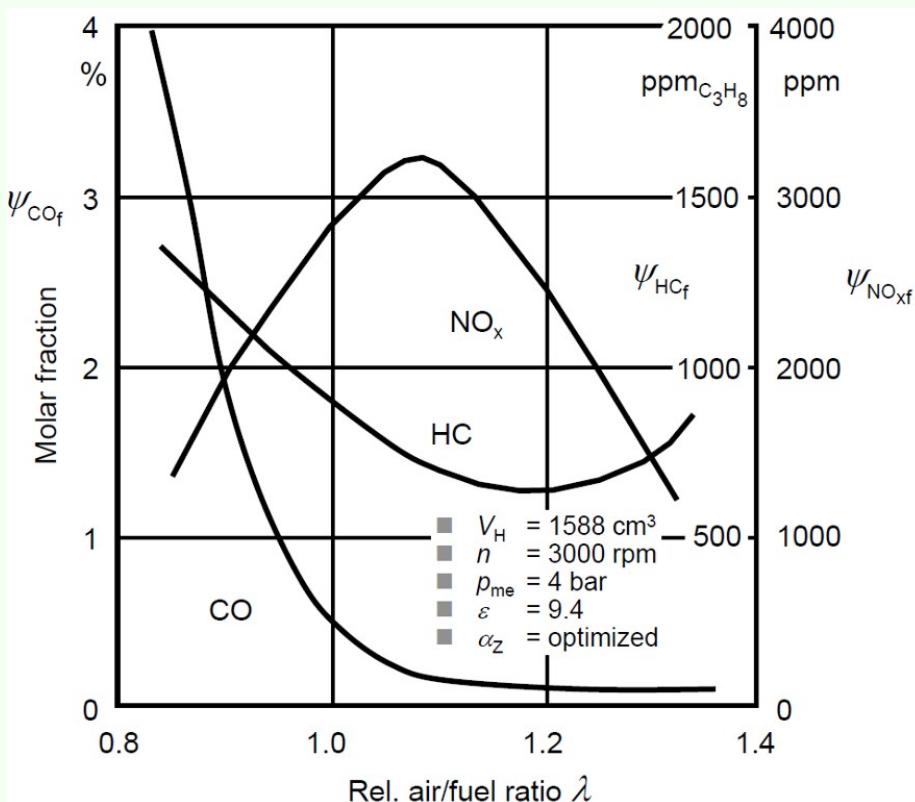
$$b_{\text{e}} = \frac{\dot{m}_{\text{B}}}{P_{\text{e}}} \quad \text{(0.5)}$$

$$b_{\text{e}} = 276\text{g/kWh} \quad \text{(0.5)}$$

5. Task (24 points)

a) (2.5 points)

Which exhaust gas components can be significantly reduced with a three-way catalyst? Which requirement regarding the mixture composition has to be fulfilled for an efficiently working system? Sketch the qualitative trace of these raw emissions as a function of the relative air/fuel-ratio λ for a homogeneously operated gasoline engine in the following diagram.

- correct naming of exhaust gas components (NO_X, HC and CO) (1x ⓪.⑤)   ⓪.⑤

- Air/fuel-ratio $\lambda = 1$ (between 0.99 and 1.01) (1x ⓪.⑤)   ⓪.⑤

- correct curves NO_X, HC and CO (3x ⓪.⑤)   ①.⑤

b) (5.5 points)

$P_i = i \cdot n \cdot V_h \cdot z \cdot p_{mi}$ (0.5)

$P_i = 6 \text{ kW}$ (0.5)

Read from given data: $b_i = 300 \frac{g}{kWh}$ (0.5)

$\dot{m}_B = b_i \cdot P_i$ (0.5)

$\dot{m}_B = 0.5 \frac{g}{s}$ (0.5)

$\eta_i = \frac{P_i}{\dot{m}_B \cdot H_u}$ (0.5)

$\eta_i = 28.57 \%$ (0.5)

$\dot{m}_L = \lambda \cdot L_{St} \cdot \dot{m}_B$ (0.5)

$\dot{m}_L = 7.25 \frac{g}{s}$ (0.5)

$\dot{m}_A = \dot{m}_B + \dot{m}_L$ (0.5)

$\dot{m}_A = 7.75 \frac{g}{s}$ (0.5)

c) (5.5 points)

Please determine the molar fraction of the unburned hydrocarbons ψ_{HC} and carbon monoxide ψ_{CO} in the exhaust gas at engine-out. Furthermore, please determine the specific unburned hydrocarbon consumption b_{HC} based on the indicated power.

Read from given data: $\dot{m}_{HC} = 40 \frac{g}{h}$ (0.5)

In general: $\dot{n} = \frac{\dot{m}}{M}$ and $\Psi_i = \frac{\dot{n}_i}{\dot{n}_A}$ (0.5)

$M_{HC} = M_{C_3H_8} = 3 \cdot M_C + 8 \cdot M_H = 44.097 \frac{g}{mol}$ (0.5)

$\Psi_{HC} = \frac{\dot{n}_{HC}}{\dot{n}_A} = \frac{\dot{m}_{HC} \cdot M_A}{\dot{m}_A \cdot M_{HC}}$ (0.5)

$\Psi_{HC} = 936.35 \text{ ppm}$ (0.5)

$b_{HC} = \frac{\dot{m}_{HC}}{P_i}$ (0.5)

$b_{HC} = 6.67 \frac{g}{kWh}$ (0.5)

Carbon balance to detemine Ψ_{CO} in the exhaust gas before catalyst:

$\dot{n}_C = \dot{n}_{CO_2} + \dot{n}_{CO} + 3 \cdot \dot{n}_{HC}$ ①

$\frac{c \cdot \dot{m}_B}{M_C} = \frac{\dot{m}_A}{M_A} \cdot (\Psi_{CO_2} + \Psi_{CO} + 3 \cdot \Psi_{HC})$

$\Psi_{CO} = \frac{c \cdot \dot{m}_B \cdot M_A}{M_C \cdot \dot{m}_A} - \Psi_{CO_2} - 3 \cdot \Psi_{HC}$ (0.5)

$\Psi_{CO} = 2139.59 \text{ ppm}$ (0.5)

d) (4 points)

The ignition timing will be retarded to 10° CA aTDC in order to achieve an exhaust gas temperature increase of 200 °C. Calculate the difference between the HC-emissions after catalyst Δm_{HC} during a 30 s lasting cold start phase if the engine is operated at optimized efficiency and with retarded ignition timing.

$\Delta m_{\mathrm{HC}} = m_{\mathrm{HC,IGN\ opt}} - m_{\mathrm{HC,IGN\ 10CAaTDC}}$ (0.5)

$m_{\mathrm{HC}} = \dot{m}_{\mathrm{HC}} \cdot \Delta \mathrm{t}$ (0.5)

$\dot{m}_{\mathrm{HC,after\ cat}} = (1 - \eta_{\mathrm{cat}}) \cdot \dot{m}_{\mathrm{HC,before\ cat}}$ (0.5)

Ignition timing at optimized efficiency (-20° CA aTDC):

Read from diagram $\eta_{\mathrm{cat}} = 20\%$ (0.5)

$\dot{m}_{\mathrm{HC,after\ cat\ IGN\ opt}} = 32\ \frac{\mathrm{g}}{\mathrm{h}}$ (0.5)

Retarded ignition (10° CA aTDC):

Read from diagram $\eta_{\mathrm{cat}} = 90\%$ (0.5)

$\dot{m}_{\mathrm{HC,after\ cat\ IGN\ retarded}} = 2.4\ \frac{\mathrm{g}}{\mathrm{h}}$ (0.5)

$\Delta m_{\mathrm{HC}} = (32\frac{\mathrm{g}}{\mathrm{h}} - 2.4\frac{\mathrm{g}}{\mathrm{h}}) \cdot 30\mathrm{s} = 0.25\mathrm{g}$ (0.5)

e) (4.5 points)

Now the ignition timing will be set to 5° CA aTDC which results in an exhaust gas temperature of 450 °C. Furthermore, the three-way catalyst is electrically heated (E-cat), which increases the three-way catalyst efficiency η_{cat}. Please determine the reduction in HC-emissionens after catalyst Δm_{HC} during a 30 s lasting cold start/warm-up phase if the engine is operated without electrical heating and with electrical heating (E-cat) in the three-way catalyst.

$\Delta m_{\mathrm{HC}} = m_{\mathrm{HC,IGN\ 5CAaTDC}} - m_{\mathrm{HC,E-cat}}$

Without E-cat retarded ignition timing (5° CA aTDC):

Read from diagram $\eta_{\mathrm{cat}} = 60\%$ (0.5)

$\dot{m}_{\mathrm{HC,before\ cat}} = 0.8 \cdot 40 = 32\ \frac{\mathrm{g}}{\mathrm{h}}$ (0.5)

$\dot{m}_{\mathrm{HC,after\ cat}} = (1 - \eta_{\mathrm{cat}}) \cdot \dot{m}_{\mathrm{HC,before\ cat}}$ (0.5)

$\dot{m}_{\mathrm{HC,after\ cat}} = (1 - 0.6) \cdot 32 = 12.8\ \frac{\mathrm{g}}{\mathrm{h}}$ (0.5)

With E-cat

Read from diagram $\eta_{\mathrm{E-cat}} = 60\% + 20\% = 80\%$ (0.5)

$\dot{m}_{\mathrm{HC,beforeE-cat}} = 0.8 \cdot 40 = 32\ \frac{\mathrm{g}}{\mathrm{h}}$ (0.5)

$$\dot{m}_{\text{HC,after E-cat}} = (1 - \eta_{\text{E-cat}}) \cdot \dot{m}_{\text{HC,before E-cat}} \quad \text{(0.5)}$$
$$\dot{m}_{\text{HC,after E-cat}} = (1 - 0.8) \cdot 32 = 6.4 \tfrac{\text{g}}{\text{h}} \quad \text{(0.5)}$$
$$\Delta m_{\text{HC}} = (12.8 \tfrac{\text{g}}{\text{h}} - 6.4 \tfrac{\text{g}}{\text{h}}) \cdot 30 \text{s} = 0.053 \text{g} \quad \text{(0.5)}$$

f) (2 points)

Which further measures for a quick heat-up of the three-way catalyst exist besides a retarded ignition timing and an electrically heated catalyst? Name two further indirect and two direct measures.

Indirect measures:

Enrichment   (0.5)

Secondary air injection   (0.5)

Direct measures:

Closely coupled catalytic converter   (0.5)

Starter catalytic converter   (0.5)

(Gradient coating)