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INFLUENCE OF SELECTED SYNTHESIS GAS COMPONENT ON INTERNAL PARAMETERS OF COMBUSTION ENGINE

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Abstract: The paper deals with the influence of selected component of synthesis gas on internal parameters of combustion engine that is planned to be used in micro-cogeneration unit. The aim is to better understand the mechanism of combustion of carbon monoxide mixed with methane and as a follow-up to optimize the operation of the Lombardini LGW 702 engine on change of fuel composition. Generally, an increasing proportion of carbon monoxide in methane mixture leads to a decrease in engine performance (mean indicated pressure) and the hourly fuel consumption in each of the operating modes of the engine increases. With growing proportion of CO in mixture with CH_4, the maximum pressure in the cylinder increases together with pressure rise rate up to approximately 10 % vol. of CH_4. With further increasing proportion of CH_4, there is a significant decrease of the before-mentioned engine parameters. The optimum ignition angle for pure methane, or carbon monoxide, does not change significantly and it is about 27° CA BTDC.

KEYWORDS: methane, carbon monoxide, spark ignition engine, combustion analysis

1 Introduction

Nowadays the effective use of mineral resources is at the forefront of interest of the general public. It is also the solution of the issue of energy security of mankind in the future, when conventional energy sources will gradually be depleted and will have to be replaced by new technologies to gain energy for sustainable growth. One of the classic sources of energy is natural gas, which has to be transported from the place of extraction [1] and subsequently it has to be delivered to the place of use.

An important source of energy is also municipal waste of which the energy is efficiently recovered. The recovery runs as gasification freeing synthesis gases, which are used to drive cogeneration units for combined heat and power generation. At present, basically all power units are turbocharged to increase overall efficiency [2]. It is an efficient recovery of the energy bonded in the waste, with a high overall efficiency (over 90%). Depending on the method of production and the feedstock, the synthesis gas may have various composition [3, 4]. Before use the raw synthesis gas has to be purified from unwanted constituents (various tars, hydrogen sulphides, etc.) that may damage the internal combustion engine. Generally, the synthesis gas produced consists of methane, hydrogen, carbon monoxide and non-combustible gases (carbon dioxide and nitrogen).

The presented article deals with a partial study of the influence of carbon monoxide in a mixture with methane on internal parameters of combustion engines. The aim is to learn about the influence of carbon monoxide itself on the overall parameters and on the course of burning in the combustion chamber of the internal combustion engine that operates on synthesis gases.

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The following table (Tab. 1) shows the basic physical-chemical properties of a mixture of methane (CH_4) with carbon monoxide (CO) in varying proportions of individual components. The properties of these mixtures were determined by calculation based on the input tabulated values of the constituent elements.

Tab. 1: Physical and chemical properties of mixture methane (CH_4) with carbon monoxide (CO), NTP – 20°C and 101 325 Pa

Parameter	CH_4 / CO	Molar Mass	Density (NTP)	Lower Heating Value	Air to Fuel Ratio	Heating Value of Mixture	Fuel in Air
Unit	[% vol.]	[g.mol^{-1}]	[kg.m^{-3}]	[kJ.kg^{-1}]	[kg.kg^{-1}]	[kJ.m^{-3}]	[% vol.]
CH_4	100/0	16.04	0.667	50 012	17.12	3 172	9.5
CH4CO25	75/25	19.03	0.791	35 329	11.73	3 201	11.5
CH4CO50	50/50	22.03	0.916	24 638	7.80	3 244	14.4
CH4CO75	25/75	25.02	1.040	16 501	4.81	3 321	19.4
CO	0/100	28.01	1.165	10 103	2.46	3 473	29.5

From the Tab. 1 it can be seen that increasing the proportion of carbon monoxide in the mixture with methane increases the molar mass, which is also related to the increasing density of the mixture, from the original value of 0.667 kg/m^3 to 1.165 kg/m^3. To produce a stoichiometric mixture of methane with air, 9.5 % vol. of methane is needed; vice versa, to produce a stoichiometric mixture of carbon monoxide with air, up to 29.5% vol. of carbon monoxide is needed. By increasing the proportion of carbon monoxide in mixture with methane, the lower calorific value of the fuel decreases from 50.0 MJ / kg for methane to 10.1 MJ / kg for carbon monoxide. Conversely, the volumetric calorific value of the fuel-air mixture is more favourable when combusting carbon monoxide (3 473 kJ/m^3) compared to methane (3 172 kJ/m^3). Therefore, it would seem that a higher engine performance is achieved with CO, since the stoichiometric mixture with air has a higher energy potential. Owing to the cylinder pressure, which is influenced by lower burned-gas volume production, as well as by the energy release rate itself, higher performance parameters are achieved in operation on methane.

2 Experimental results

The experiments were performed with an internal combustion engine that had been designed for a micro-cogeneration unit [5]. The combustion engine is a non-turbocharged Lombardini LGW 702 engine with basic parameters shown in the following table (Tab. 2).

Tab. 2: Basic parameters of the combustion engine Lombardini LGW 702

Crankshaft throw angle [°]	360
Swept volume [cm^3]	686
Bore/ Stroke [mm]	75 / 77.6
Compression ratio [-]	12.5:1
Valve gear/ Drive	OHC/Belt drive system
Fuel	Natural gas (and alternative gases)
Lubrication system	Pressure circuit, full-flow filtration, oil filling 1.6 l

The following figure (Fig.1) shows a scheme of the measuring bed for the internal combustion engine and the electric induction dynamometer MEZ Vsetín. A low-displacement internal combustion engine (686 cm^3) is used to reduce the operating costs for experimental synthesis gases, as the operation has a high hourly consumption of these gases.

Various combinations of gases had been mixed from pressure bottles. The preparation of air-fuel mixture was performed by a diffuser mixer and the control of stoichiometric mixture was done by means of a feedback control unit. The optimal angle of ignition advance was set manually. All measurements were performed at full load. In order to determine the optimal ignition advance angles at the engine revolutions 1 500 min^{-1}, measurements of regulation characteristics were performed during operation on just methane alone, or just carbon monoxide. Subsequently, under the same number of revolutions, methane was gradually mixed to carbon monoxide, approximately 5 l/min of methane.

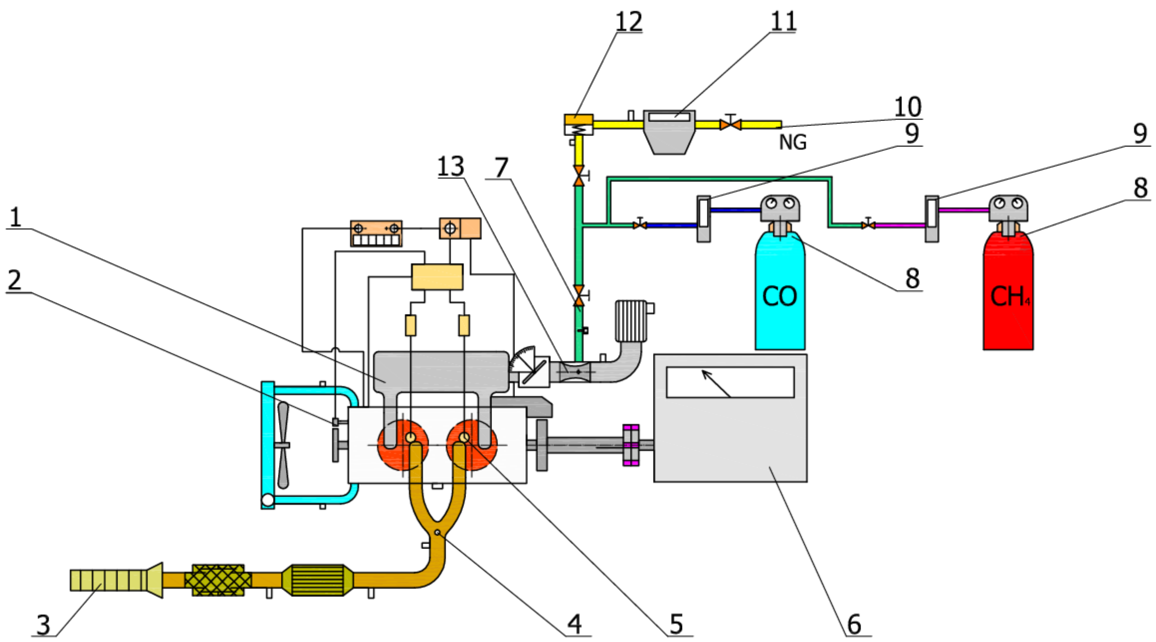


Fig. 1: The basic scheme of the combustion engine LGW 702 (1 - intake manifold, 2 - position sensor of the crankshaft, 3 - exhaust system, 4 - exhaust temperature sensor, 5 - spark plug with integrated pressure sensor, 6 – dynamometer, 7 – mixture richness regulation, 8 – pressure bottle of methane and carbon monoxide , 9 - mass flowmeter of gas, 10 - supply of natural gas, 11 - volumetric flow-meter of natural gas, 12 - zero pressure regulator, 13 - mixer with diffuser)

For the analysis of the combustion process, also the pressure courses in the combustion chamber of the engine were recorded. To serve this purpose, a measuring system consisting of an integrated piezoelectric sensor in the KISTLER 6117 BDC15 spark plug, a charge amplifier, and an A / D converter were used. In order to reduce the dynamic course of pressure to the absolute pressure in the cylinder, a piezoresistive pressure sensor was used that monitored the absolute pressure at the time of the suction stroke around the bottom dead centre. The crankshaft position was monitored by the sensor Kistler 2614A. CO and CH_4 gases were measured using the Bronkhorst mass flowmeter and based on the λ probe information, the control unit corrected the richness of the mixture using a stepper motor built into the fuel supply. In the Matlab programming environment, a program was developed to process data from the pressure sensors, the crankshaft position, and the moment of ignition timing.

The process of combustion in the combustion chamber of the engine was evaluated on the basis of single-zone-zero-dimensional thermodynamic model, [6,7]. The model was developed for a closed system, i.e. the intake and exhaust valves were closed, on the principle of energy conservation. The course of the release of heat from the fuel mixture was determined on the basis of analyzed course of pressure in the combustion chamber by Rassweiler-Withrow method. The method is based on the fact that the pressure increase in the combustion chamber comprises both the increase in combustion pressure and the increase in pressure, caused by changed volume as the piston moves in the cylinder (equation (1)). It is based on the general:

$$dU = dQ - dW + \sum_i h_i . dm_i \tag{1}$$

where:

dU - change of internal energy of matter in the system
dQ - heat delivered to the system
dW - the work produced by the system
hi.dmi - *i*-th component of enthalpy of mass flow across system boundaries.

The pressure measured continuously allowed for evaluation of uniformity of combustion engine running, which is characterized by the so-called coefficient of variation (COV). The coefficient of variation is calculated as the ratio of standard deviation to the arithmetic average of the parameter examined, thus:

$$COV = \frac{\sqrt{\frac{1}{n-1}\sum_{i=1}^{n} x_i - \bar{x}}}{\bar{x}}.100 \qquad [\%] \tag{2}$$

Where n is the total number of consecutive cycles, x_i is the i-th value of the tested parameter in a given cycle and and $\bar{x}$ is the average value of the tested parameter from a given number of cycles. The cycle variability has a significant impact on the overall life of the internal combustion engine, as well as on its performance parameters and related fuel consumption.

In the following figure (Fig. 2) introduces courses of pressure in the cylinder around of the top dead centre for the two-component fuel mixture (CH4CO) of CO and CH_4. The lowest value of maximum pressure occurs while combusting carbon monoxide (4.7 MPa). Increasing CH_4 by small amount in the mixture with CO (about 13.9 % vol. CH_4), there occurs a sudden and considerable increase in pressure (7.1 MPa). The maximum pressure for combusted methane is 5.6 MPa. The position of maximum pressure after increasing CH_4 up to 15% gradually approaches the top dead centre (TDC) and then, after further increase of CH_4, it slightly diverges from the TDC. The coefficient of variation (COV) of maximum pressure for CO is 8.8 % and for CH_4 this value is 8.1 %. By gradual increase of CH_4 in the mixture with CO the coefficient drops sharply to 3.4 % at approximately 15% of present CH_4 and then, under gradual increase of CH_4, the coefficient rises up to the value for pure methane.

A similar pattern as maximum pressure can be noticed with pressure rise rate. When combusting pure carbon monoxide, this value is 0.139 MPa/1 °CA and increasing CH_4 to about 8 % vol. increases the pressure rise rate sharply to 0.326 MPa/1 °CA. Subsequently, by further increasing CH_4, the pressure rise rate progressively decreases to 0.191 MPa/1 °CA for pure methane.

The methane in the mixture with carbon monoxide will also influence the course of combustion. Figure (Fig.3) shows the mass fraction burned (MFB) of the fuel and the fuel combustion rate (dMFB/dα) as dependence on the angle of crankshaft rotation for various compositions of the CH4CO mixture. The period between the start of ignition (SOI) and burning of 5 % of carbon monoxide is approximately 20.6 °CA, compared to burning methane, in which case that time is 19.9 °CA. A greater difference can be observed with the mixture containing 13.9 % CH_4, in which case the period decreases to 14.6 °CA. A similar pattern has been recorded with 50 % of fuel burned, in which case heat (363 °CA) is fastest released from fuel at 13.9 % proportion of CH_4 in the CH4CO mixture. For CO combustion, the angle at which the 50 % mass fraction has been burned is approximately 374 °CA, or for methane it is 371 °CA. The duration of the main combustion (10 % mass fraction burned – 90 % mass fraction burned) is 30.8 °CA for CO, or 24.7 °CA for methane. A considerably short burning period (23.2 °CA) has been measured for the proportion of 13.9 % vol. of CH_4. The coefficient of variation (COV) for 5 % of mass fraction burned is 0.36 % for both CO and for CH4. The lowest COV value is for 13.9 % proportion of CH_4 and is 0.24 %. Greater differences in scattering have been recorded at the position in which 50 % of the fuel has been burned. Specifically, for CO it is 0.68 % and for CH_4 it is 0.58 %. Once again, the lowest COV value (0.41%) is at 13.9 % proportion of CH_4 in the mixture with CO. The greatest differences in COV are recorded for fuel reduction (90 % MFB) when this value is for CO 1.10% and for CH_4 0.86 %. The slightest difference between the individual cycles in which 90 % fuel has been burned is found for the position 13.9 % vol. of CH_4. Its value is 0.29 %.

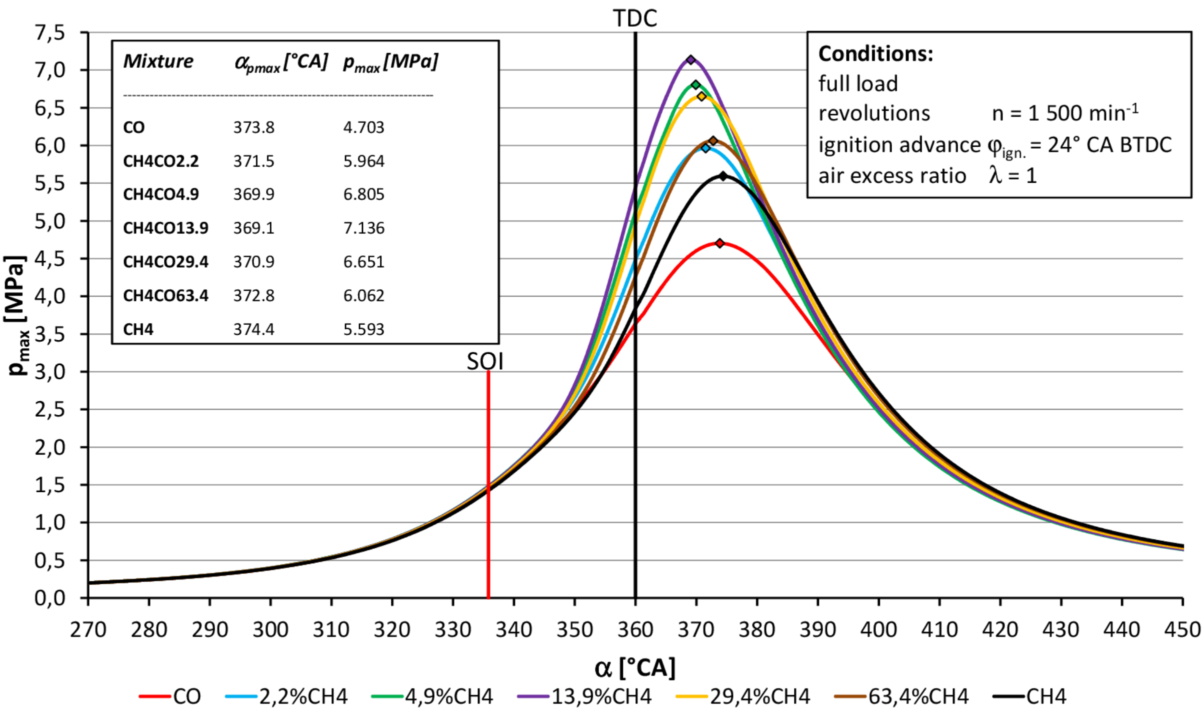


Fig. 2: Course of pressure in the combustion chamber as dependent on the crank angle, for various mixtures of carbon monoxide with methane (SOI – start of ignition, TDC – top dead centre)

In general, the presence of a small amount (from 5 to 15%) of CH_4 in CH4CO mixture significantly increases the rate of oxidation reactions. This is due to the H-containing species enhancing the oxidation reactions of CO with O_2 by providing H-bearing radicals such as HO_2, H, and especially OH during their own oxidation reactions with oxygen, which accelerate the oxidation reaction rates of CO in air [8, 9].

The foregoing results indicate the need to optimize the ignition angle for each composition of mixture, even under constant operating conditions of the internal combustion engine. The following figure (Fig. 4) shows the fuel burn-up curves for different CH4CO mixtures at optimum ignition angles, where the highest performance parameters are achieved.

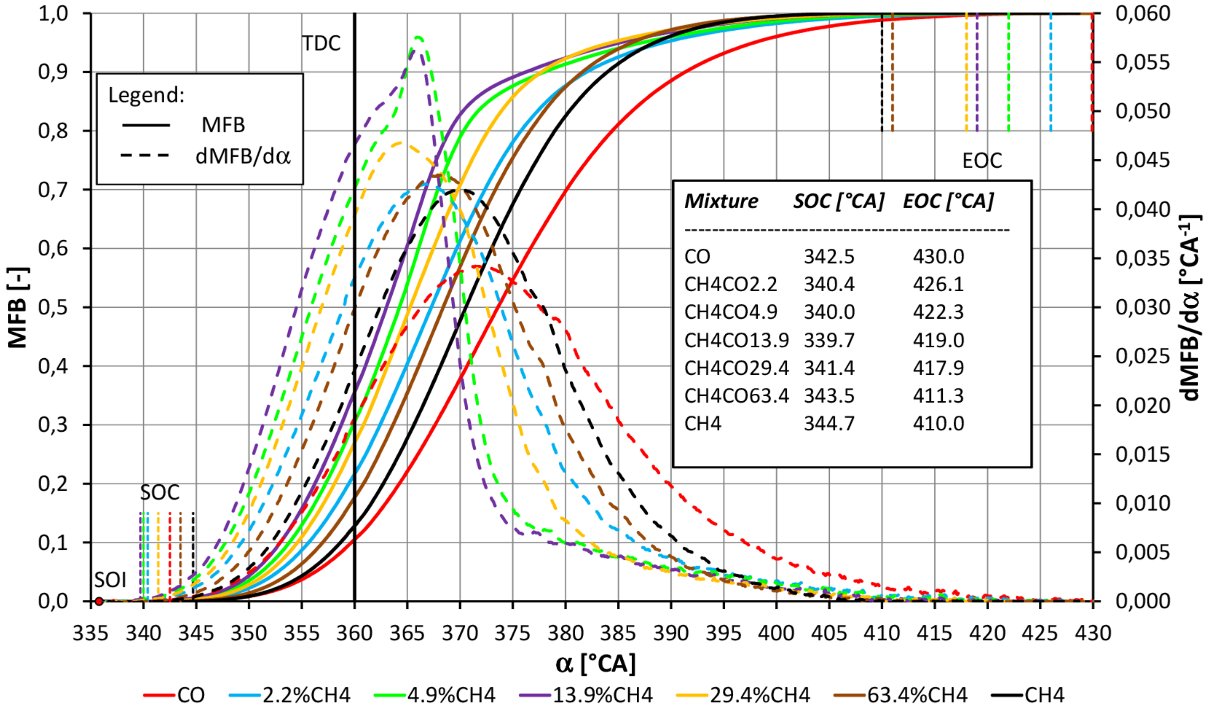


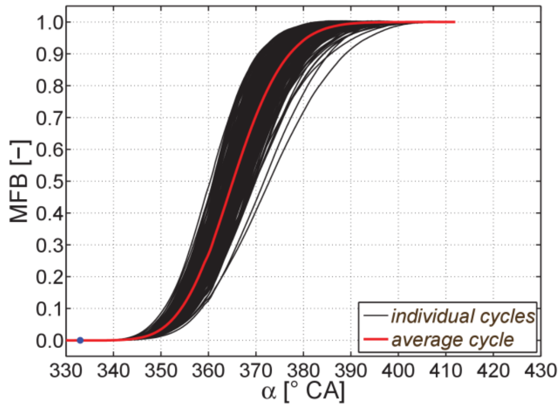
Fig 3: Course of burning of fuel as dependent on the crankshaft angle for various mixtures of CH_4 and CO (SOI – Start of Ignition, SOC – Start of Combustion, EOC – End of Combustion)

In Fig.4 the main combustion period (10-90 MFB) for pure methane lasts 22.2 °CA and for carbon monoxide it lasts 24 °CA. The shortest main combustion period (17 °CA) relates to operating on CH4CO with 5% vol. of CH_4. The ignition delay (from sparking to 5% of MFB) is the shortest when the internal combustion engine operates on 5% methane in mixture with CO and the value of delay is 15 °CA. For pure methane, this value is 22 °CA, and for pure carbon monoxide it is 18 °CA.

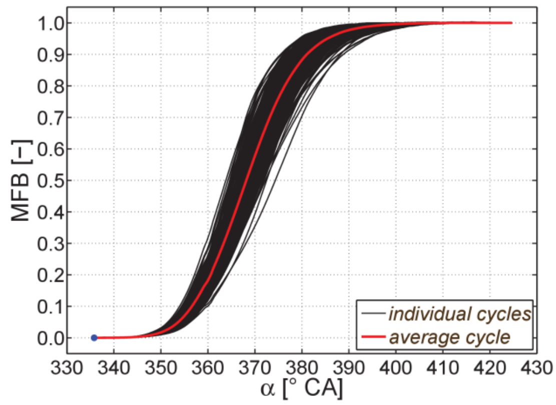
CONCLUSION

For burning methane mixed with carbon monoxide, the following findings regarding the power and economic parameters, as well as parameters related to combustion of the mixture of CH_4 and CO in the engine cylinder at 1 500 min^{-1} can be summed up:

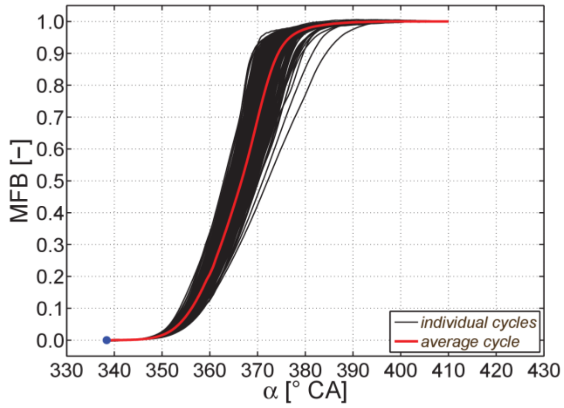
- by increasing the CH_4 content in the mixture with CO, the volumetric heating value of stoichiometric fuel-air mixture is reduced from 3 473 kJ/m^3 for CO to 3 172 kJ/m^3 for CH_4,
- the performance parameters (indicated mean effective pressure) with a growing share of CH_4 increase by about 5.5 %, from 0.87 MPa for CO to 0.92 MPa for CH_4,
- with increasing CH_4 there occurs a decrease in the hourly fuel consumption, the difference between pure CO and pure CH_4 is approximately 82 %,
- increasing percentage of CH_4 also leads to higher maximum pressure in the cylinder, from 4.7 MPa for carbon monoxide to 5.6 MPa for methane,
- increase in the pressure rise rate has been recorded after gradual addition of CH_4 to the mixture, from the original value 0.139 MPa/1°CA for CO to 0.191 MPa/1°CA for CH_4,



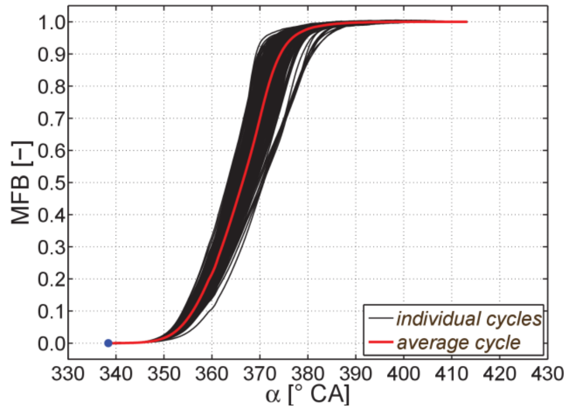
CH_4 (φ_{ign} = 27°CA BTDC)



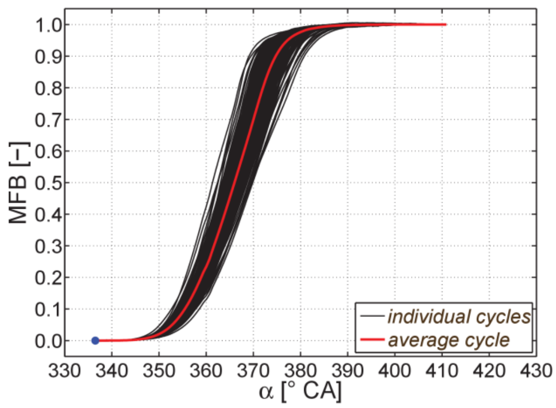
CO (φ_{ign} = 26°CA BTDC)



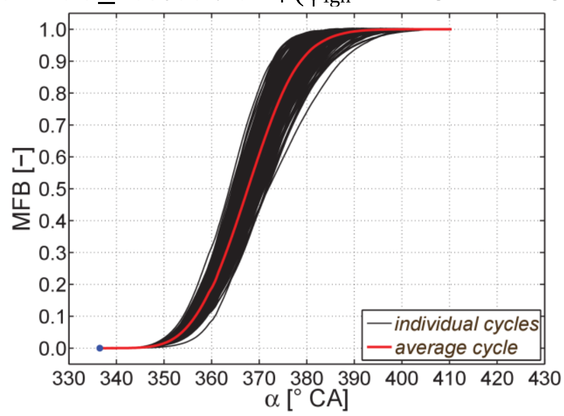
CH4CO_5%vol.CH_4 (φ_{ign} = 22°CA BTDC)



CH4CO_10%vol. CH_4 (φ_{ign} = 22°CA BTDC)



CH4CO_20%vol. CH_4 (φ_{ign} = 23°CA BTDC)



CH4CO_30%vol. CH_4 (φ_{ign} = 24°CA BTDC)

Fig 4: Mass fraction burnt (MFB) dependent on the crankshaft angle (α) (Conditions: optimum ignition angle, load $\alpha_{throttle}$ = 100 %, air excess ratio λ = 1, revolutions n = 1500 min^{-1})

- with a small amount of methane (around 5 to 15% vol.) in a mixture with carbon monoxide, the mixture is significantly faster burned, which is also demonstrated by maximum pressure in the cylinder (7.1 MPa) or pressure rise rate (0.326 MPa/1°CA). This proportion of CH_4 also leads to a more uniform running of the engine in terms of the coefficient of variation for the monitored internal engine parameters,
- conclusive results show that a greater proportion of CH_4 than CO in synthesis gases suits better to achieving higher power and less fuel consumption.

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