ANALYSIS OF COMBUSTION PROCESSES IN CI ENGINE FUELLED EITHER WITH DIESEL FUEL OR RAPE OIL METHYL ESTER AND ADDITIONALLY WITH ETHANOL

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Abstract

At the conference KONES'2005 combustion characteristics of CI engine fuelled with rape oil methyl ester (RME) and ethanol injected into inlet port have been presented. In this paper combustion processes in the engine fuelled with two base fuels: diesel oil (DF) or rapeseed oil methyl ester and additionally with ethanol have been analyzed and combustion parameters have been compared. Ethanol fraction has a serious influence on combustion. Addition of ethanol delays combustion in the initial stage but despite of that, combustion is completed earlier if the ethanol fraction is higher. This phenomenon takes place for both base fuels: RME and DF. However, for high speed (2200 rpm) and torque = 20 Nm (p_e = 0,256 MPa) ignition delay of DF was so long, that ignition took place 15 CA deg ATDC. Nevertheless of that, combustion was completed only about 5 CA deg later than for neat DF. Combustion processes for both fuels are similar, but there are some differences in ignition delay. At low load and high speed for fuelling with DF combustion extends for exhaust stoke. On account on diesel – knock the engine can not be loaded by higher torque at high speed. Besides ethanol fraction, there is a strong influence of load and speed on combustion parameters. Generally increase of speed decreases maximum pressure and increase of load increases it, as well for RME as for DF. The highest pressure has been measured for DF and ethanol injection.

Keywords: *rape oil methyl ester, diesel fuel, ethanol, heat release rate, fraction of fuel burnt, autoignition, ignition lag, combustion time*

1. Introduction

For last several years at Politechnika Radomska a project on fuelling CI engine with rape oil methyl ester (RME) and additionally with ethanol injection into inlet port has been carried out. At the conference KONES'2004 emission characteristics of the engine were presented and compared to characteristics of the engine fuelled with diesel fuel (DF) as a base fuel [1]. At the next KONES' 2005, combustion characteristics, i.e. pressure in the cylinder, heat release rate and fraction of fuel burnt in function of the CA were presented [2]. Also ignition delay and combustion time in function of ethanol energy to total fuel energy, Ω_E, were computed. These experiments show that the higher the fraction of ethanol, the longer the development of combustion in the earlier phase of combustion, but the shorter the total combustion period. In this paper comparison of combustion characteristics of the engine fuelled with two base fuels: RME or DF and additionally with ethanol have been presented, analysed and compared.

2. Engine test stand and course of investigation

Experiments were performed with the same single – cylinder engine at the same test – stand and the same measuring equipment as presented in [1] and [2]. Measurements of the pressure vs.

CA were carried out for three speeds: 1200, 1800 and 2200 rpm, for injection angle[*)] of base fuel = 30 deg BTDC, injection angle of ethanol = 60 deg ATDC and the same fuels, of which physico – chemical properties were given in [1, Table 2]. Input data for calculation of heat release rate were indicator diagrams of the pressure in the cylinder vs crank angle. Cylinder pressure was measured with AVL transducer 8QP 505 inserted into the cylinder head. Start of injection of base fuel (RME or diesel fuel) was determined as the beginning of injector needle lift, which was measured with inductive sensor QL 21D of Polish production. The high speed measurements were synchronized with crank angle measured with Introl sensor. All measured data were transmitted to the high – speed measurement system developed in the Department of Internal Combustion Engines and Automobiles of Politechnika Radomska [3]. Calculations of heat release rate and fraction of fuel burnt were carried out with the use of computer programme worked out also in Politechnika Radomska [4]. The programme is based on computer routines described in Heywood's book [5]: specific heat and enthalpy of the gases: CO_2, H_2O, O_2, N_2 as well as ethanol and diesel fuel were polynomial functions of temperature computed in each computation step (for RME there are no data of coefficients of the polynomial, so they were assumed to be the same as for diesel).

3. Results and discussion

3.1. Influence of ethanol fraction and load on combustion

Influence of ethanol fraction on combustion depends on the load, so the influence of both these parameters will be treated together in this subchapter. Ethanol fraction has a great influence on delay of burning at initial period of combustion especially at low load (20 Nm, p_e = 0,256 bar). For example it may be seen in the case of high speed, Figs 1-3 for RME and Figs. 4-6 for DF. This phenomenon is caused by the cooling effect of ethanol evaporation, despite of the kind of the base fuel, RME or DF. This effect - in the case of low load – is strong and results in delayed combustion, lower temperature level and lower pressure of the cycle and in the case of high load, (40 Nm, p_e = 0,572 MPa) is rather small and is compensated by high temperature and pressure, as a result of more fuel burnt.

[*)] This angle was set up by AVL Di Gas model 465, measuring the pressure of fuel before the injector. Real beginning of injection however was delayed in relation to the point of to the increase of the pressure and was assumed as the beginning of injector needle lift.

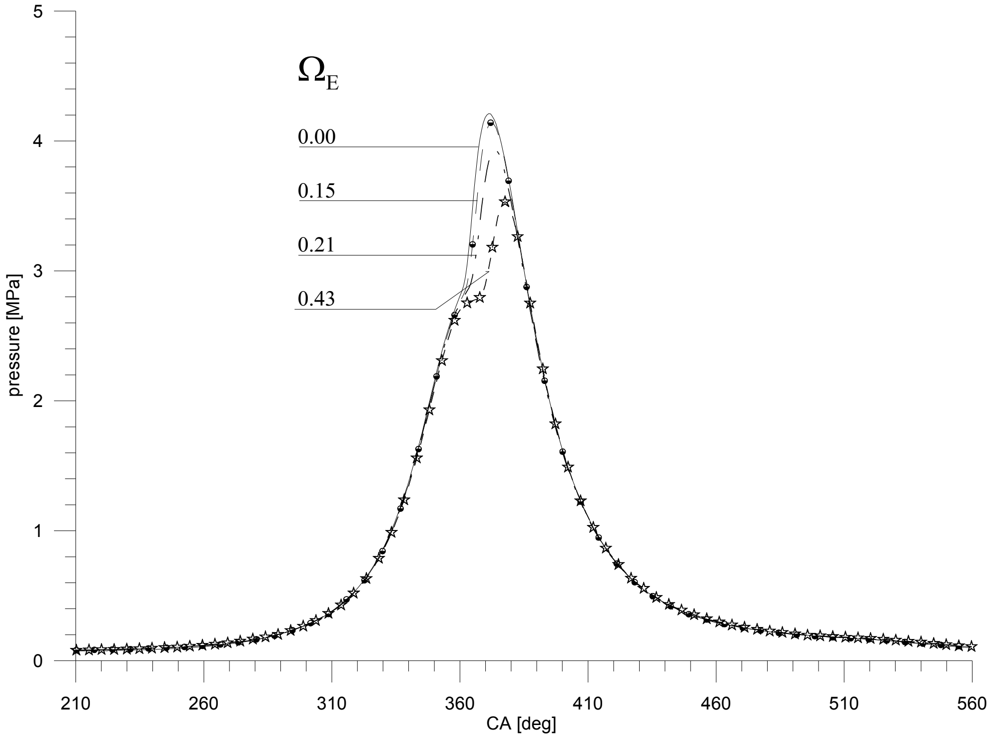

Fig. 1. Cylinder pressure in function of CA at low load (T=20 Nm, p_e = 0,256 MPa), speed 2200 rpm, injection angle of RME = 30 CA deg BTDC for different ethanol fractions Ω_E

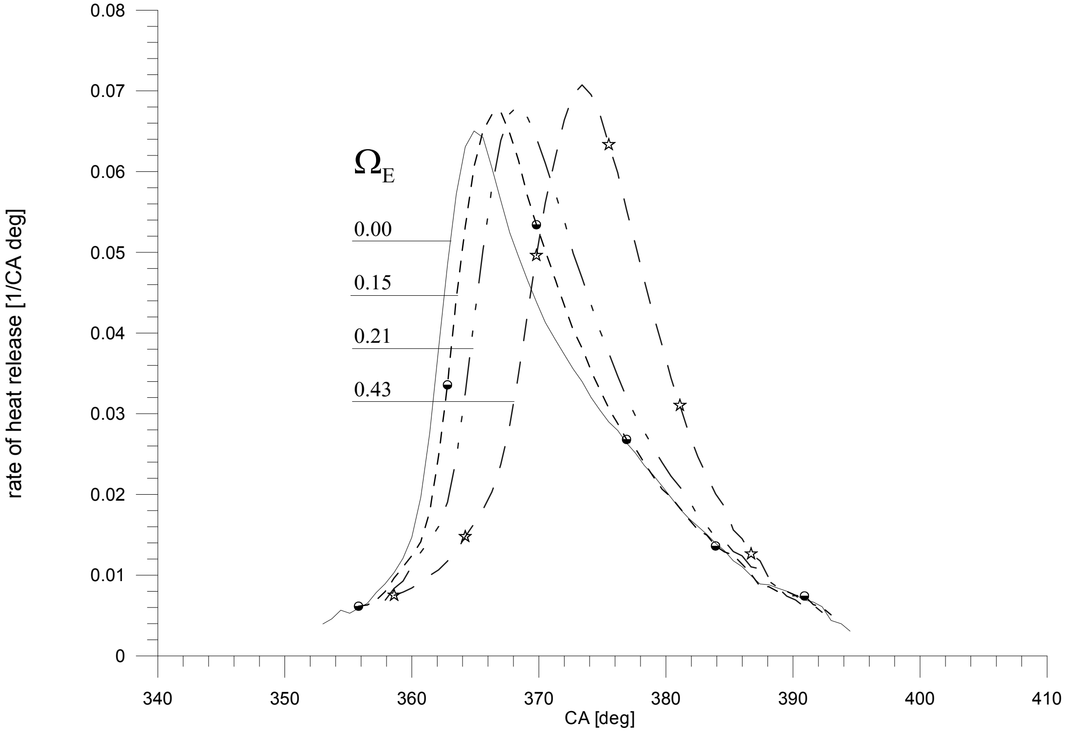

Fig. 2. Relative rate of heat release in function of CA at low load (T=20 Nm, p_e = 0,256 MPa), speed 2200 rpm, injection angle of RME = 30 CA deg BTDC for different ethanol fractions Ω_E

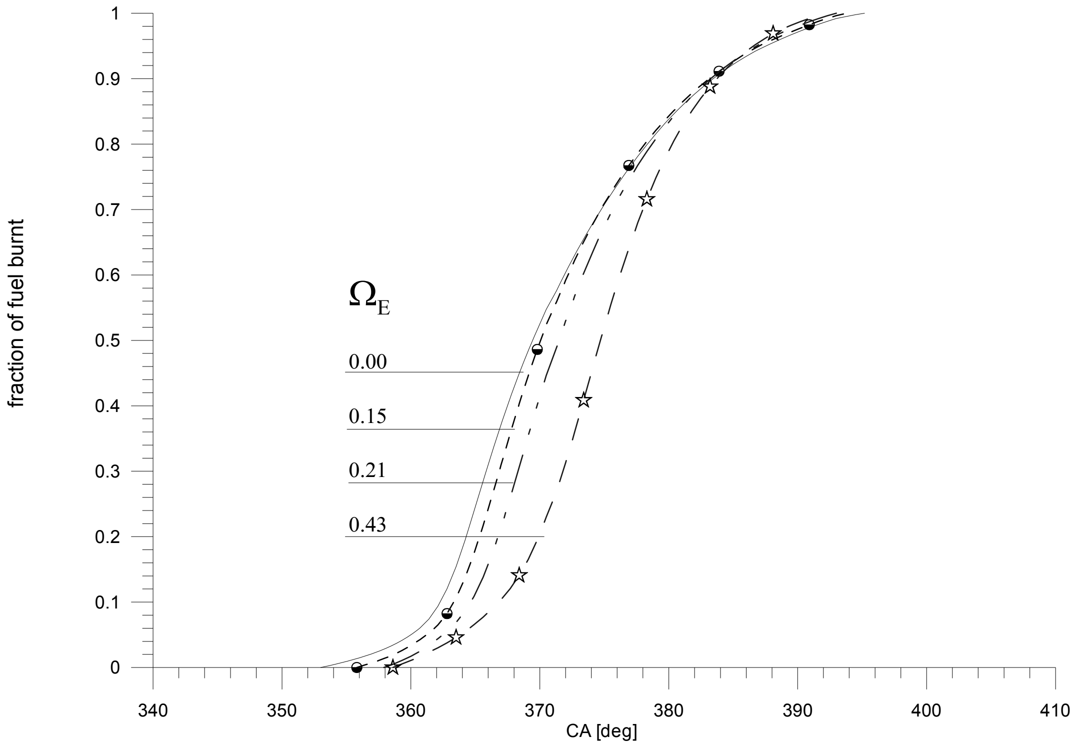

Fig. 3. Fraction of fuel burnt in function of CA at low load (T=20 Nm, p_e = 0,256 MPa), speed 2200 rpm, injection angle of RME = 30 CA deg BTDC for different ethanol fractions Ω_E

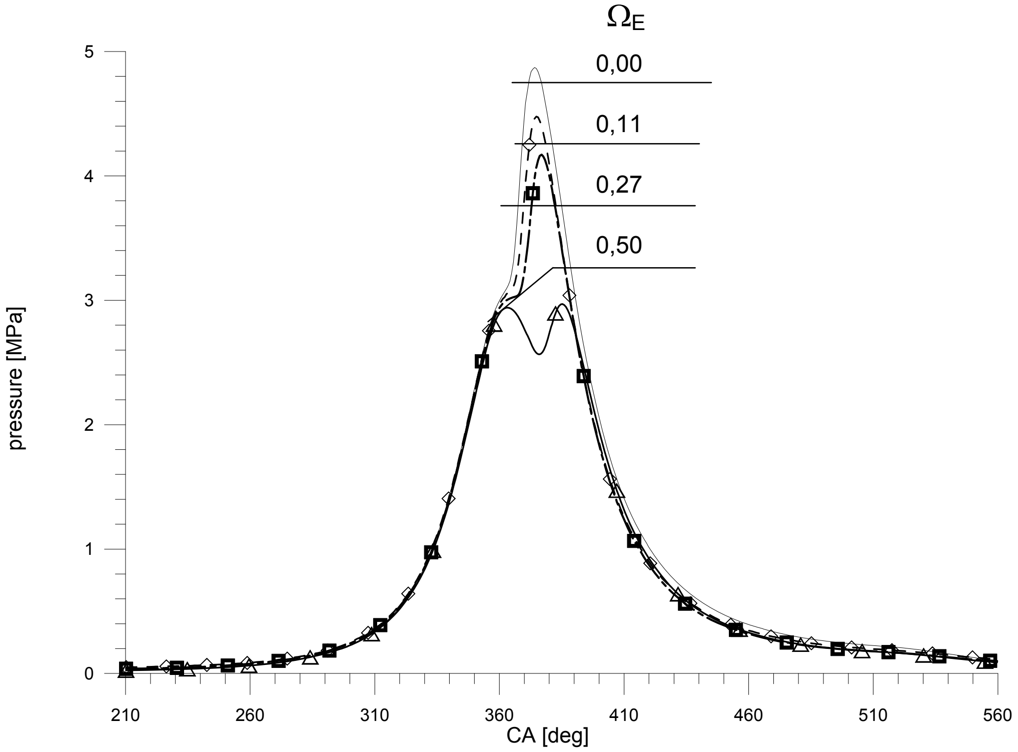

Fig. 4. Cylinder pressure in fraction of CA at low load (T=20 Nm, p_e = 0,256 MPa), speed 2200 rpm, injection angle of DF = 30 CA deg BTDC for different ethanol fractions Ω_E

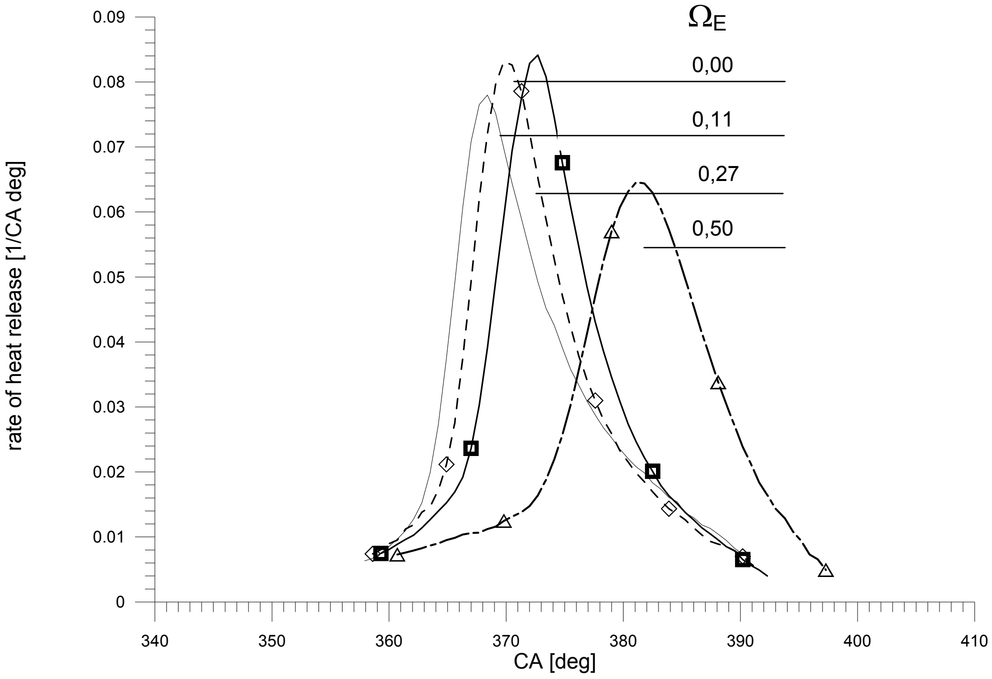

Fig. 5. Relative heat release rate in function of CA at low load (T=20 Nm, p_e = 0,256 MPa), speed 2200 rpm, injection angle of DF = 30 CA deg BTDC for different ethanol fractions Ω_E

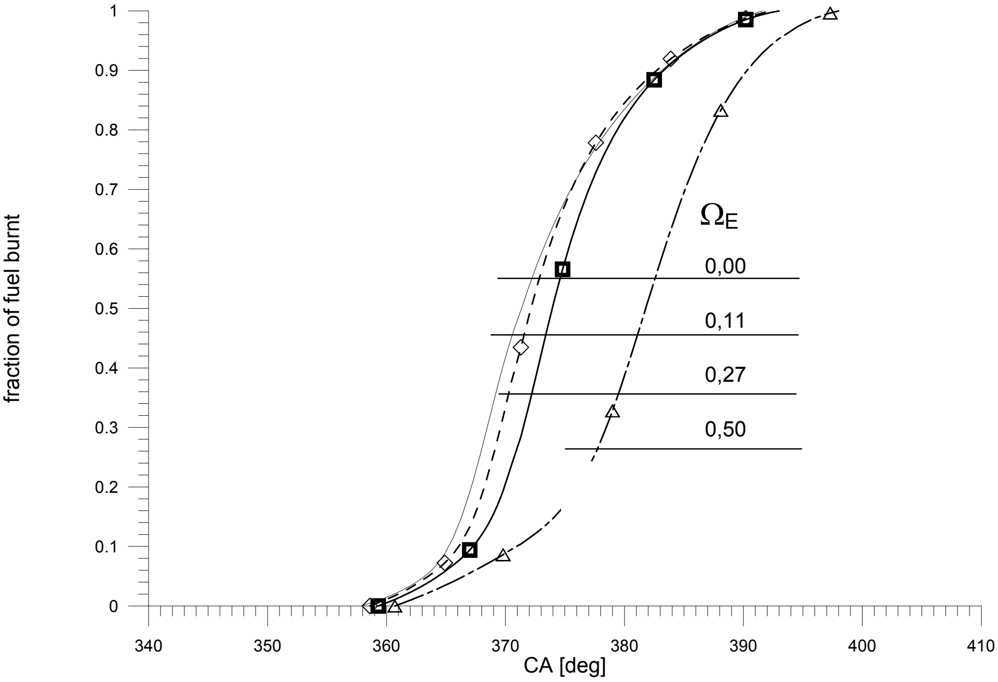

Fig. 6. Fraction of fuel burnt in function of CA at low load (T=20 Nm, p_e = 0,256 MPa), speed 2200 rpm, injection angle of DF = 30 CA deg BTDC for different ethanol fractions Ω_E

Delayed autoignition is especially visible for high ethanol fraction Figs. 4-6. In this case autoignition takes place 15 CA deg ATDC, Fig. 4. In the same conditions however, for RME fuel this phenomenon doesn't exist because RME is more prone to ignition than DF.

In the case of high ethanol fraction (nevertheless of load), when more fuel is in gaseous state combustion characterizes with premixed/rapid phase. Mixing controlled combustion phase appears for neat base fuel and low ethanol fractions, at high load (40 Nm, p_e = 0,572 MPa) what is marked in diagrams of heat release rate by second maximum or a cusp, Figs. 7-10. In the first case combustion is controlled with chemical kinetics, while for the second case with diffusion (of fuel vapour from droplets of RME/DF to air and vice versa).

This phenomenon doesn't take place for higher ethanol fraction, when combustion is controlled by chemical kinetics [5].

Despite of delayed combustion at the initial period, combustion of the total fuel is completed earlier for higher fraction of ethanol irrespective of the load and speed. (This may not be true for diesel fuel and very high fraction of ethanol, e.g. for $\Omega_E \approx 0,5$, Fig. 6).

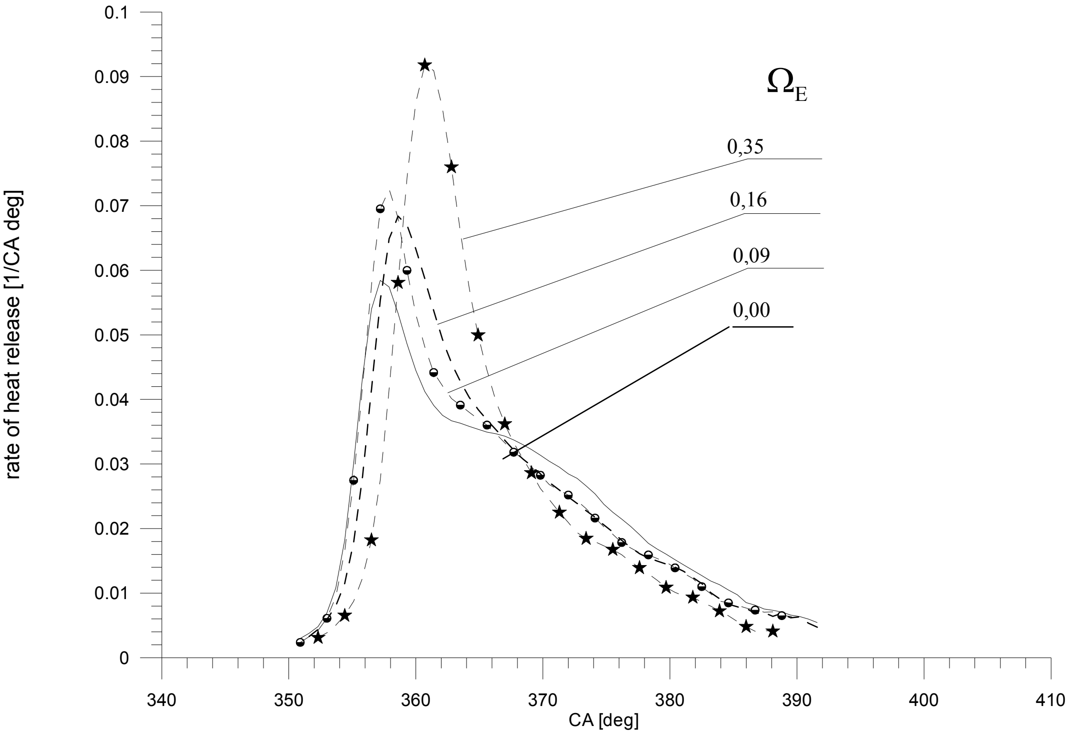

Fig. 7. Relative rate of heat release at high load (T=40 Nm, p_e = 0,512 MPa), speed 1200 rpm, injection angle of RME = 30 CA deg BTDC for different ethanol fractions Ω_E

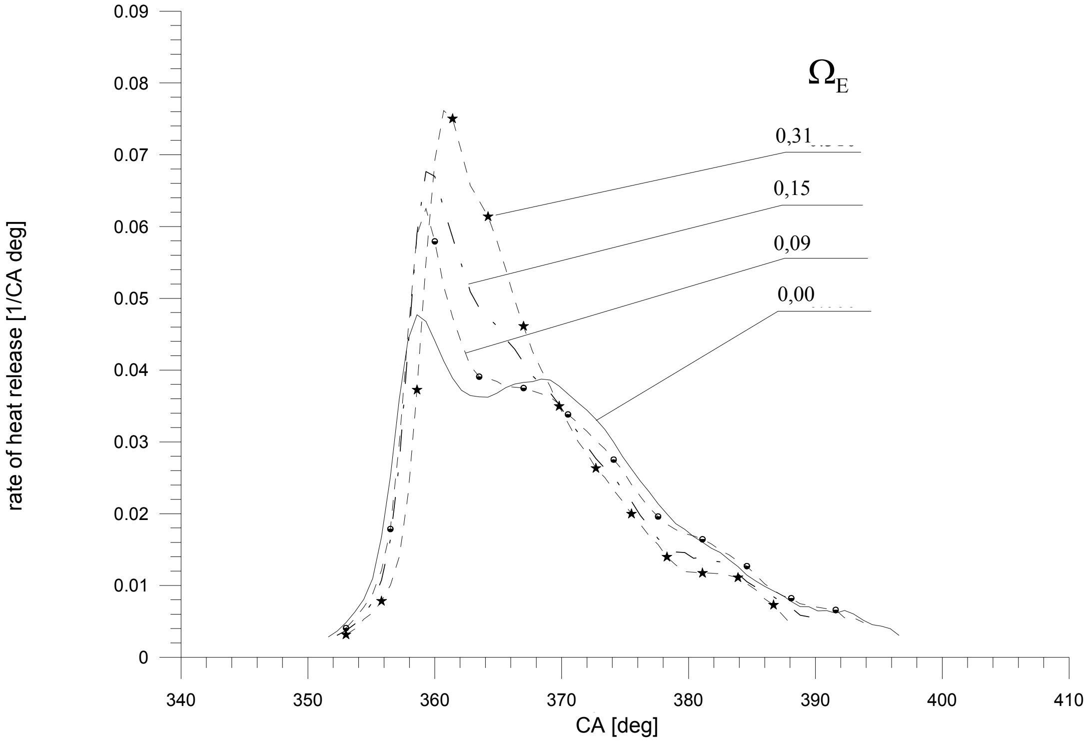

Fig. 8. Relative rate of heat release at high load (T=40 Nm, p_e = 0,512 MPa), speed 1800 rpm, injection angle of RME = 30 CA deg BTDC for different ethanol fraction Ω_E

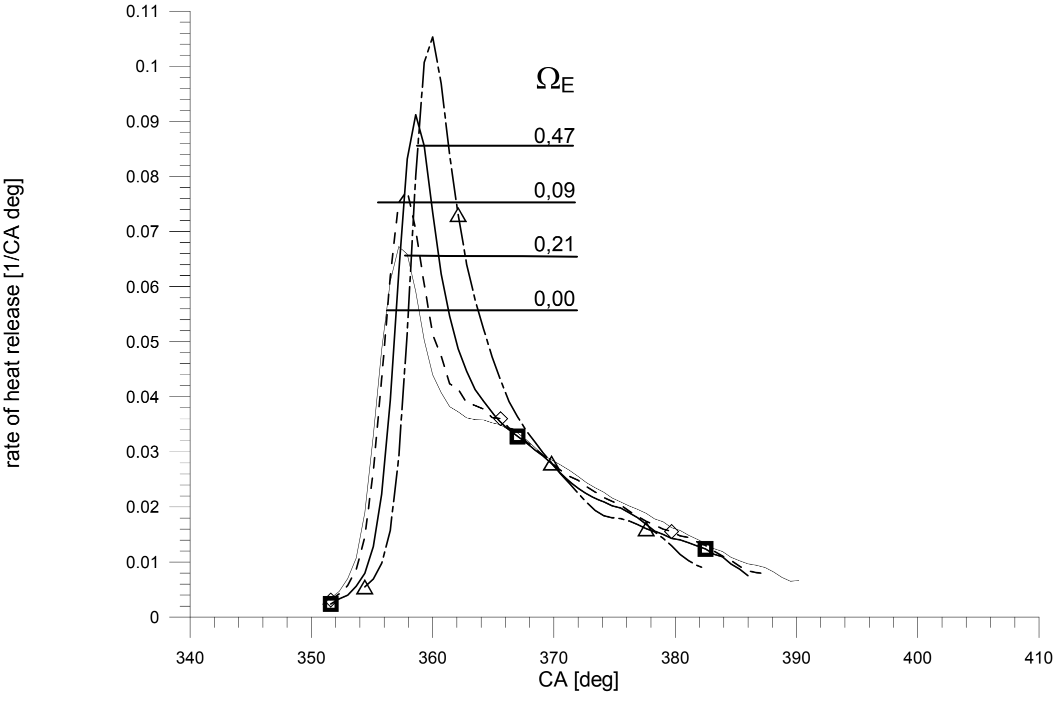

Fig. 9. Relative rate of heat release at high load (T=40 Nm, p_e = 0,512 MPa), speed 1200 rpm, injection angle of DF = 30 CA deg BTDC for different ethanol fractions Ω_E.

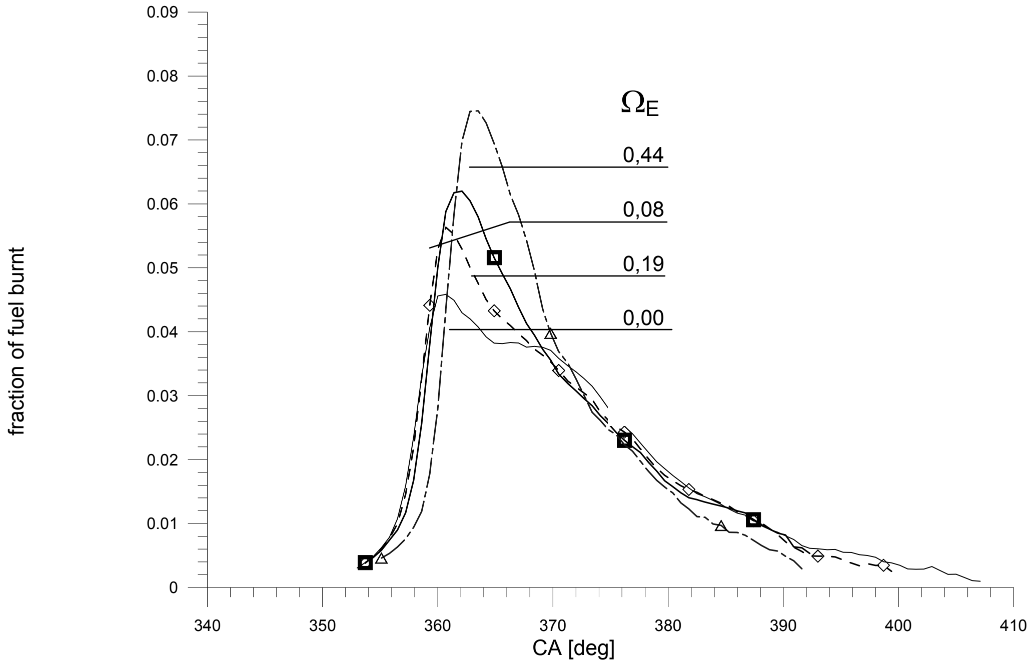

Fig. 10. Relative rate of heat release at high load (T=40 Nm, p_e = 0,512 MPa), speed 1800 rpm, injection angle of RME = 30 CA deg BTDC for different ethanol fractions Ω_E

3.2. Influence of engine speed on combustion

At high speed combustion processes are delayed and shifted towards expansion stoke for both base fuels: RME and DF. As far as the influence of engine speed on maximum pressure is concerned, the results are ambiguous. For RME fuel the higher the speed, the lower the pressure as well as at low and high load. For diesel fuel maximum pressure takes place for middle speed, 1800 rpm and is the highest including RME. (This speed is the speed of maximum torque of the engine fuelled with diesel fuel). The influence of the speed on maximum pressure results from the fact that time in which fuel droplets can evaporate, autoignite and be burnt at high engine speed is shorter than at low speed, combustion process is delayed resulting in lower maximum pressure.

3.3. Ignition delay and combustion time

Ignition delay τ_{id} combustion time τ_c and total combustion time $\tau_{id} + \tau_c$ (in CA degs) for both base fuel at three speeds, two loads and several values of ethanol fraction Ω_E are shown in Table 1 and in Figs 11-13.

From these diagrams it may be concluded, what follows:

- Total time of combustion decreases with increase of ethanol fraction, with exception at high speed (n=2200 rpm) for diesel fuel at low load (Fig. 13a), when the influence of cooling effect of ethanol evaporation on ignition delay (Table 1) is high.
- Time of combustion generally decreases with increase of ethanol fraction also with exception at high speed for diesel fuel at low load (Fig. 13a), when increases for high ethanol fraction ($\Omega_E \approx 0,5$, Table 1).
- Ignition delay, which is mostly burdened with errors (especially the end of ignition delay), is rather independent from speed, load and kind of base fuel, but is the longest for the highest ethanol fraction, ($\Omega_E \approx 0,5$, Table 1).
- Combustion time of DF at low load decreases quickly with increase of Ω_E at low speed (Fig. 11a), then decreases slowly at middle speed (Fig. 12a) and then increases at high speed (Fig.

13a). The same tendency may be seen for total combustion time for DF. For RME this is not true: both times decrease with increase of Ω_E.

Table 1: Characteristics times of combustion

Engine working parameters		Diesel Fuel				RME			
		Ω_E	CA deg			Ω_E	CA deg		
n [rpm]	T [Nm]		τ_{id}	τ_c	$\tau_{id} + \tau_c$		τ_{id}	τ_c	$\tau_{id} + \tau_c$
1200	20	0,00	11,96	35,86	47,82	0,00	12,4	41,0	53,4
		0,18	11,26	36,56	47,82	0,15	10,7	40,0	50,7
		0,42	11,97	35,15	47,12	0,26	9,7	38,0	47,7
		0,52	13,37	31,63	45,01	0,54	11,7	34,0	45,7
1200	40	0,00	9,44	40,08	49,52	0,00	10,0	42,0	52,0
		0,09	9,86	37,27	47,13	0,09	9,3	40,0	49,3
		0,21	11,27	35,15	46,42	0,16	11,0	41,0	52,0
		0,47	12,67	30,94	43,61	0,35	11,0	37,0	48,0
1800	20	0,00	9,87	39,37	49,24	0,00	9,9	36,0	45,9
		0,14	10,58	37,27	47,85	0,14	10,2	34,0	44,2
		0,31	10,58	37,27	47,85	0,25	11,2	33,0	44,2
		0,47	11,98	34,45	46,43	0,48	11,2	33,0	44,2
18000	40	0,00	9,17	56,25	65,42	0,00	8,9	45,0	53,9
		0,08	9,27	47,81	57,68	0,09	9,9	42,0	51,9
		0,19	11,28	39,38	50,66	0,15	8,9	38,0	47,8
		0,44	12,68	37,27	49,95	0,31	9,9	36,0	45,9
2200	20	0,00	11,99	36,56	48,55	0,00	7,8	42,0	49,8
		0,11	13,4	34,45	47,85	0,15	10,8	38,0	48,8
		0,26	14,1	34,45	48,55	0,21	12,8	35,0	47,8
		0,49	28,4	38,67	52,07	0,43	12,4	34,0	46,4
2200	40	Diesel – knock occurred. Measurements were not carried out				0,00	9,8	45,0	54,8
						0,10	11,8	38,0	49,8
						0,13	13,8	34,0	47,8
						0,29	12,4	34,0	46,8
2200	10	0,00	11,28	37,97	49,25	Measurements were not carried out			
		0,11	12,69	36,56	49,25				
		0,26	13,39	40,08	53,47				
		0,49	13,10	49,22	62,32				

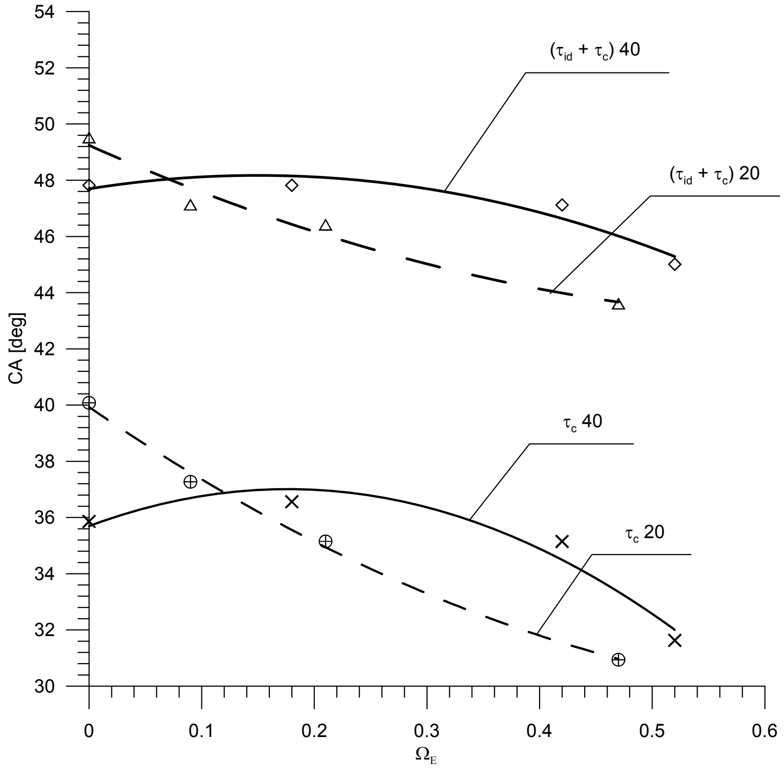

Fig. 11a. Combustion time τ_c [CA deg] and total combustion time τ_{id} + τ_c [CA deg] in function of ethanol energy fraction Ω_E at 1200 rpm and two loads for base fuel DF

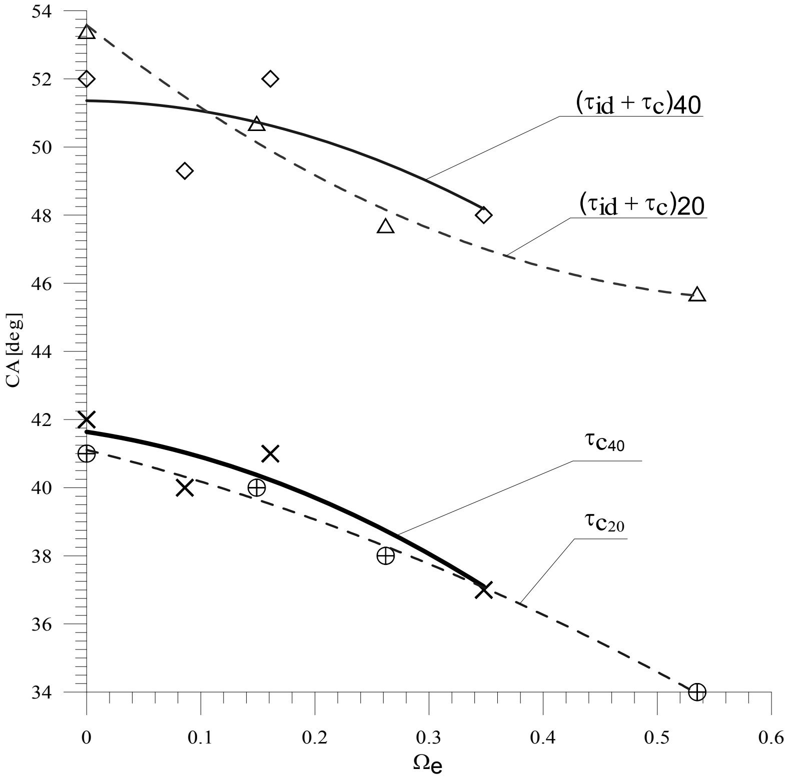

Fig. 11b. Combustion time τ_c [CA deg] and total combustion time τ_{id} + τ_c [CA deg] in function of ethanol energy fraction Ω_E at 1200 rpm and two loads for base fuel RME.

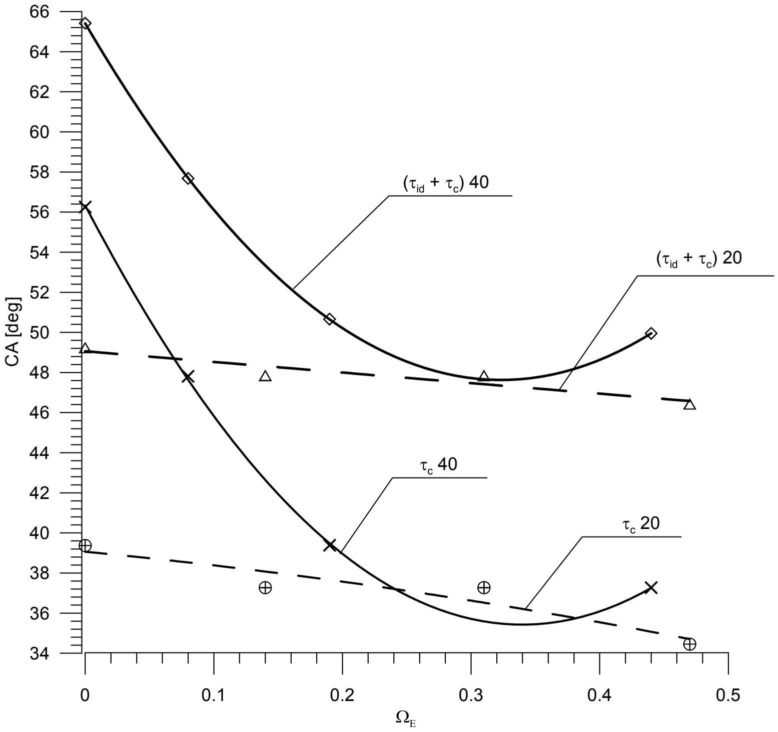

Fig. 12a. Combustion time τ_c [CA deg] and total combustion time τ_{id} + τ_c [CA deg] in function of ethanol energy fraction Ω_E at 1800 rpm and two loads for base fuel DF

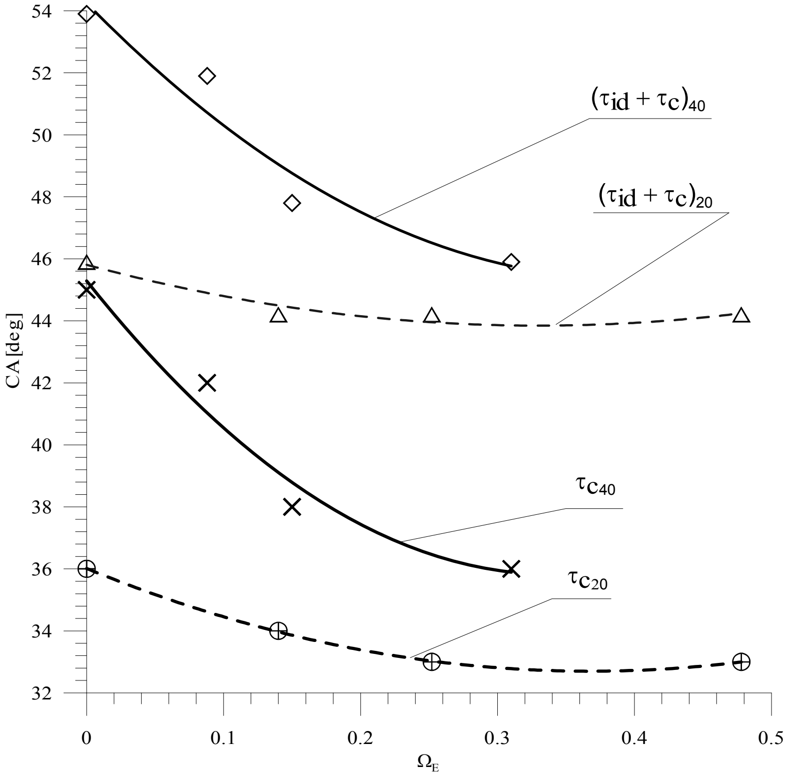

Fig. 12b. Combustion time τ_c [CA deg] and total combustion time τ_{id} + τ_c [CA deg] in function of ethanol energy fraction Ω_E at 1800 rpm and two loads for base fuel RME

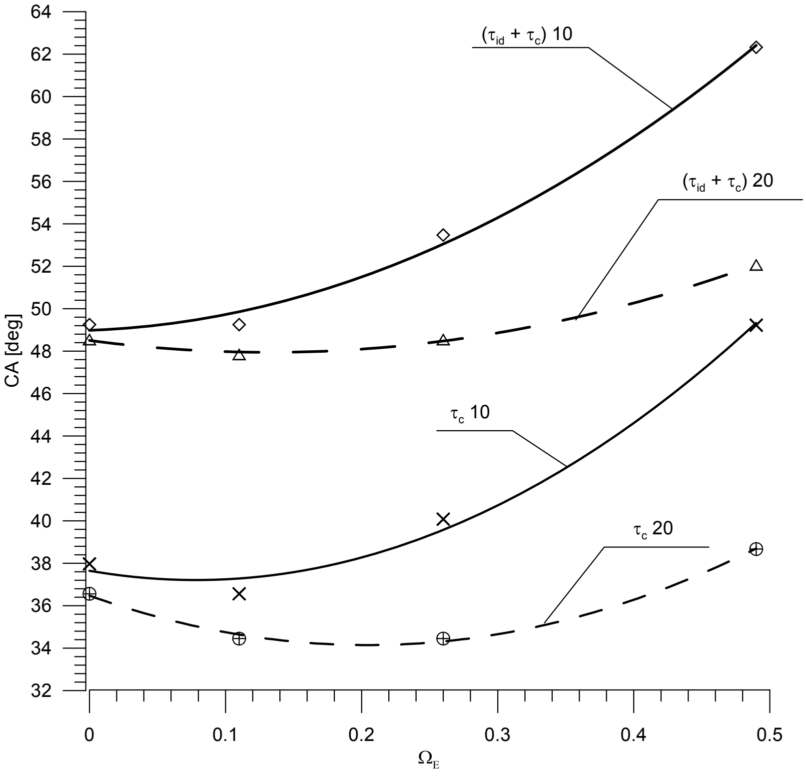

Fig. 13a. Combustion time τ_c [CA deg] and total combustion time $\tau_{id} + \tau_c$ [CA deg] in function of ethanol energy fraction Ω_E at 2200 rpm and two loads for base fuel DF

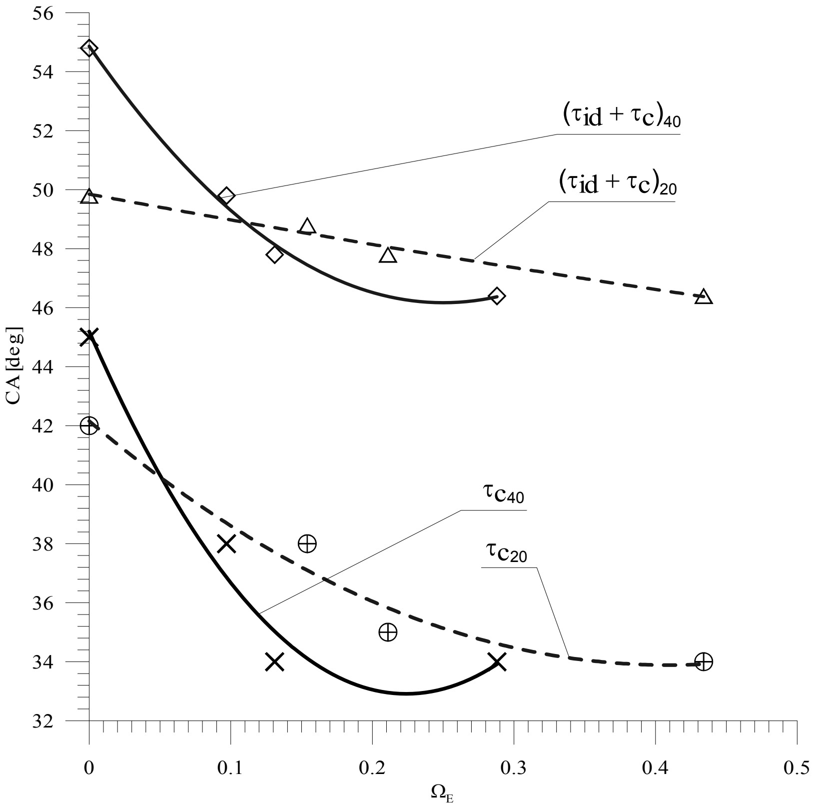

Fig. 13b. Combustion time τ_c [CA deg] and total combustion time $\tau_{id} + \tau_c$ [CA deg] in function of ethanol energy fraction Ω_E at 2200 rpm and two loads for base fuel RME

3.4. Comparison of combustion parameters for two base fuels

Conclusions referring to comparison of the base fuels may be drown from Table 2a and 2b and also from formerly shown Figs 1-6. Generally, combustion phenomena in the engine fuelled with RME or DF are similar. Increase of ethanol fraction results in delayed combustion, and in the case of DF which is prone to diesel – knock, ignition may take place after TDC and/or the engine cannot be loaded by as high torque as for RME fuel. Nevertheless of the kind of fuel is considered, the higher the fraction of ethanol, the shorter the combustion period.

Table 2a: Characteristics parameters of combustion of RME fuel

n [rpm]	T [Nm]	Ω_E	Angle of beginning of injection CA deg BATDC	P_{max}, MPa	Angle of P_{max} CA deg ATDC
1200	20	0,00	20,4	6,107	7,7
		0,15	19,7	5,623	7
		0,26	19,7	5,631	7
		0,54	19,7	5,349	7,7
1200	40	0,00	19	6,146	9,1
		0,09	18,3	6,421	8,4
		0,16	19	6,547	8,4
		0,35	19	7,003	8,4
1800	20	0,00	16,9	5,033	8,4
		0,14	16,2	4,764	9,1
		0,25	16,2	4,761	9,1
		0,48	16,2	4,650	10,6
1800	40	0,00	16,9	5,464	10,6
		0,90	16,9	5,441	9,8
		0,15	16,9	5,849	9,8
		0,31	16,9	5,999	9,8
2200	20	0,00	14,8	4,210	11,3
		0,15	14,8	4,134	12,6
		0,21	14,8	3,927	13,4
		0,43	13,4	3,527	17,6
2200	40	0,00	14,1	4,449	13,4
		0,10	13,4	4,682	12,7
		0,13	14,8	4,783	12,7
		0,29	14,1	5,003	13,4

The influence of ethanol fraction on maximum pressure at low and high load is the same for both base fuels. Generally, for DF as a base fuel, the maximum pressure is higher than for RME. Maximum pressure slightly decreases with increase of engine speed and is higher at higher load. With increase of ethanol fraction, maximum pressure is shifter towards expansion stroke.

Table 2b: Characteristics parameters of combustion of Diesel Fuel (DF)

n [rpm]	T [Nm]	Ω_E	Angle of beginning of injection CA deg BTDC	P_{max} MPa	Angle of P_{max} CA deg ATDC
1200	20	0,00	20,4	5,573	7,0
		0,18	19,7	5,508	7,7
		0,42	19,7	5,628	7,7
		0,82	19,7	5,384	9,1
1200	40	0,00	19	6,135	9,1
		0,09	18,3	6,281	8,4
		0,21	19	6,305	8,4
		0,47	19	6,663	8,4
1800	20	0,00	16,9	5,720	9,1
		0,14	16,2	5,645	11,3
		0,31	16,2	5,735	10,6
		0,47	16,2	5,147	13,4
1800	40	0,00	16,9	6,132	12,0
		0,08	16,9	6,104	11,3
		0,19	16,9	6,348	11,3
		0,44	16,9	6,609	11,3
2200	10	0,00	14,8	4,865	14,8
		0,11	14,8	4,470	15,5
		0,26	14,8	4,163	17,6
		0,49	13,4	2,967	26,0
2200	20	0,00	14,1	3,579	16,9
		0,17	13,4	3,267	19,0
		0,39	14,8	2,934	4,2
		0,52	14,1	2,892	3,5

4. Conclusions

The following general conclusions from the investigation may be drown:

- Diesel fuel may by replaced by rape oil methyl ester as a base fuel for CI engine with additional injection of ethanol into inlet port

- In the case of dual – fuelling, for high ethanol fractions, limiting load is determined by diesel – knock, which occurs earlier for DF than for RME
- Principally fuelling with ethanol is advantageous for high engine power on account on non – knocking combustion.

Acknowledgement

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References

[1] Kowalewicz A., *Emission Characteristics of Compression Ignition Engine Fuelled with RME/DF and Ethanol,* Journal of KONES Internal Combustion Engines, vol. 11 No 1-2 p.

[2] Kowalewicz A., *Combustion Characteristics of Compression Ignition Engine Fuelled with RME and Ethanol,* Journal of KONES, European Science Society of Powertrain and Transport Publication, Warsaw 2005, Internal Combustion Engines, vol. 12, No 1-2, p. 163-174.

[3] Różycki A., *Microcomputer System for Measurement of High Speed Parameters for CI Engines,* 8th European Automotive Congress, Bratislavia 2001.

[4] Pawlak G., *Ocena wpływu zasilania silnika o zapłonie iskrowym strumieniem odparowanego paliwa na przebieg spalania ubogiej mieszanki paliwowo – powietrznej,* PhD Thesis, Politechnika Radomska, 1999.

[5] Heywood J.B., *Internal Combustion Engine Fundamentals,* McGraw – Hill Book Co., N.Y. 1988.

List of notations

n – engine speed, rpm
T – torque, Nm
φ – crank angle, deg

relative rate of heat release $= \dfrac{1}{m_E \cdot W_{uE} + m_{RME/ON} \cdot W_{uRME/ON}} \cdot \dfrac{dQ}{d\varphi}$, 1/deg CA

where:
m_i – mass of the *i* fuel (RME or DF) per cycle
W_{ui} – heating value of fuel *i*
dQ – heat evolved from both fuels in computation step $d\varphi$

x – fraction of fuel burnt $= \dfrac{1}{m_E + m_{RME/ON}} \cdot \dfrac{dM}{d\varphi}$

where:
m – as above
dM – mass of both fuel burnt in computation step $d\varphi$

τ_{id} – ignition delay, CA deg
τ_c – combustion period, CA deg
Ω_E – ratio of ethanol energy to total fuel energy (ethanol energy fraction)

$$\Omega_E = \frac{m_E \cdot W_{uE}}{m_E \cdot W_{uE} + m_{RME/ON} \cdot W_{uRME/ON}}$$

Abbreviations

ATDC – after top dead centre
BTDC – before top dead centre
CA – crank angle
CI – compression ignition
DF – diesel fuel
DI – direct injection
RME – rape oil methyl ester