Three Dimensional Modelling of Combustion Process in SI Engine with Exhaust Gas Recirculation

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Introduction

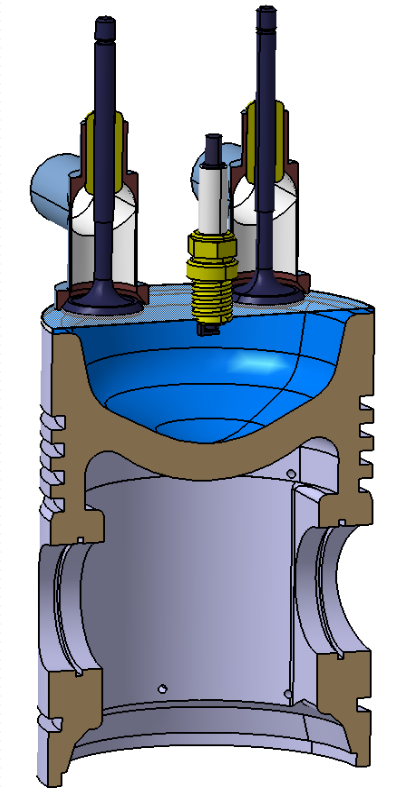
The paper presents results of the impact of EGR on the knock limit of the test engine. The impact of EGR on the NO concentration in the exhaust to the conditions of fixed ignition advance angle and the optimized conditions is presented.

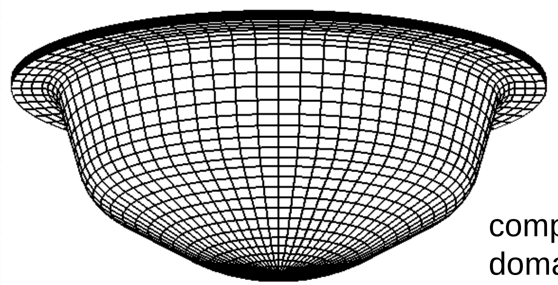
Steps of modelling:
- validation of a model based on the indication results,
- modelling of thermal cycle of engine with EGR,
- optimization of the thermal cycle of the test engine,
- determination of the knock limit.

The modeling was done in the AVL FIRE

AVL FIRE®

Test engine





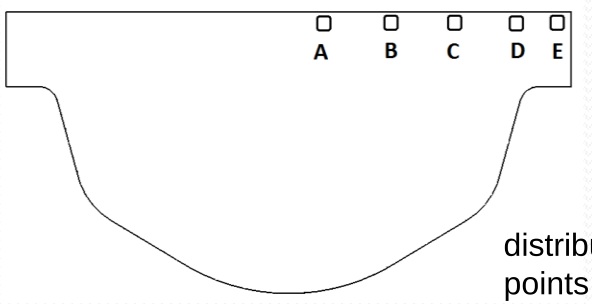


Fig. The computational mesh of combustion chamber and selected control volumes

Test engine and model assumptions

Engine parameters		
Engine rotational speed	-	1000 rpm
Cylinder bore	-	120 mm
Stroke	-	160 mm
Connecting-rod length	-	275 mm
Squish	-	2 mm
Initial conditions		
Initial pressure for 180 deg BTDC	-	0.9 MPa
Initial temperature for 180 deg BTDC	-	310 K
Lambda	-	1.0, 1.1, 1.2
EGR	-	0-12.5%
Fuel	-	C_7H_{13}
FIRE sub-models		
Turbulence model	-	k-zeta-f
Combustion model	-	Coherent Flame Model ECFM
NO formation model	-	Extended Zeldovich Model
Knock model	-	AnB

Test engine and model assumptions

Combustion proces was modelled using ECFM with 2-step chemistry mechanism for the fuel conversion. Hydrocarbon $\mathbf{C_7H_{13}}$ was taken as a fuel.

$$4C_7H_{13} + 41O_2 \rightarrow 28CO_2 + 26H_20 \qquad (1)$$

$$2C_7H_{13} + 7O_2 \rightarrow 14CO + 13H_2 \qquad (2)$$

The reaction (2) of formation of CO and H_2 is taken into account for stoichiometric and fuel-rich mixtures, while for lean mixtures this reaction is omitted.

The unburned gas phase consists of 5 main unburned species:
fuel, O_2, N, CO_2 and H_2O.

The burnt gas is composed of 11 species:
O, O_2, N, N_2, H, H_2, CO, CO_2, H_2O, OH and NO.

Test engine and model assumptions

The EGR was determined as a percentage of the total inlet mass flow rate as follows:

$$\%EGR = \frac{\dot{m}_{EGR}}{\dot{m}_a + \dot{m}_f + \dot{m}_{EGR}}$$

where:

$\dot{m}_{EGR}$ - mass rate of EGR,

$\dot{m}_a$ - mass rate of air,

$\dot{m}_f$ - mass rate of fuel respectively in kg/s.

Model validation

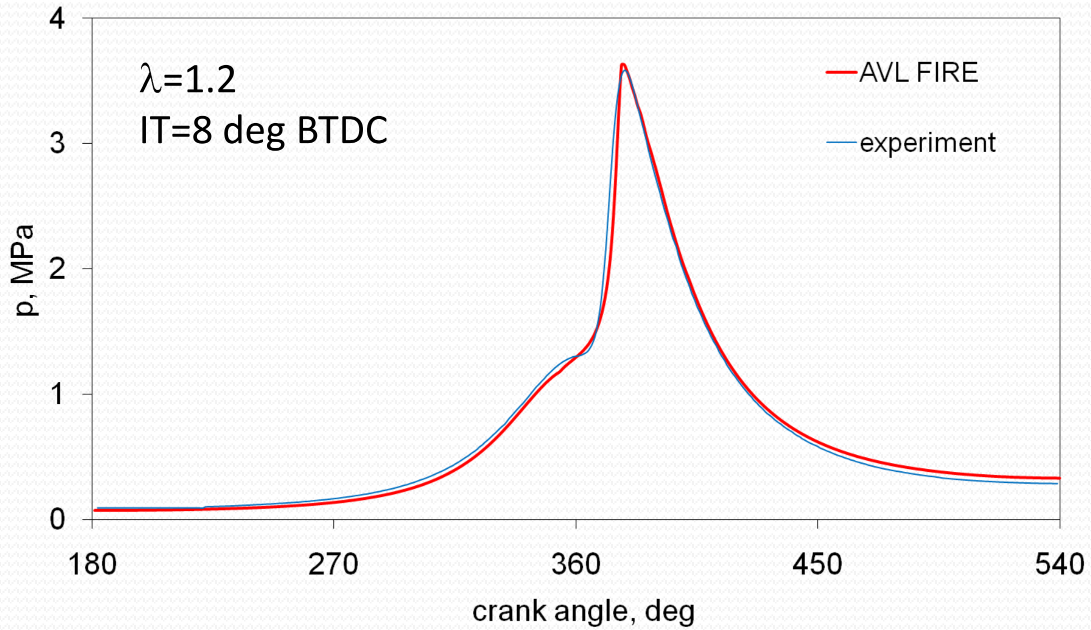
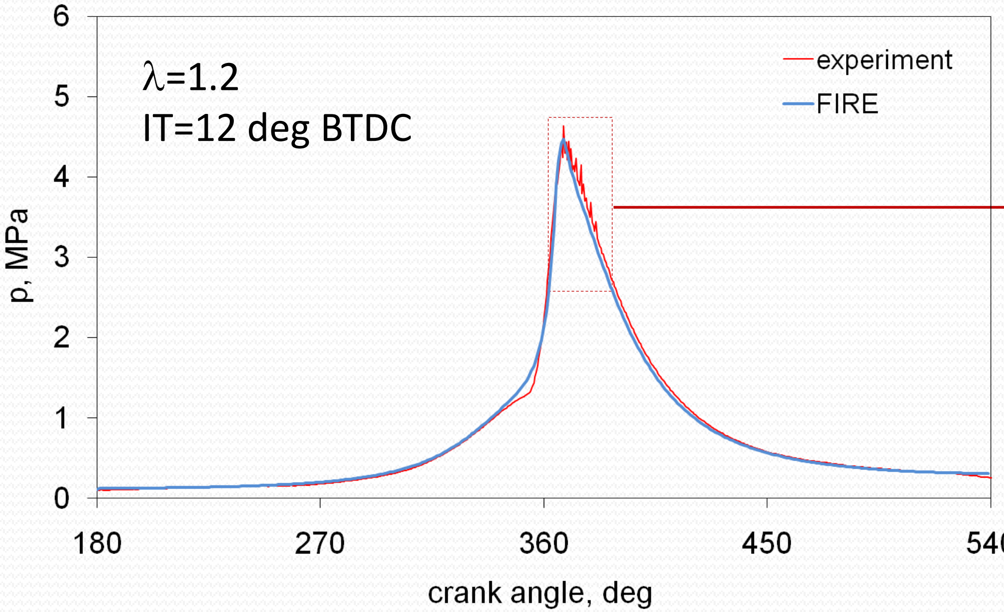


Fig. Courses of pressure obtained by indicating of real test engine and by modeling using FIRE software

Model validation



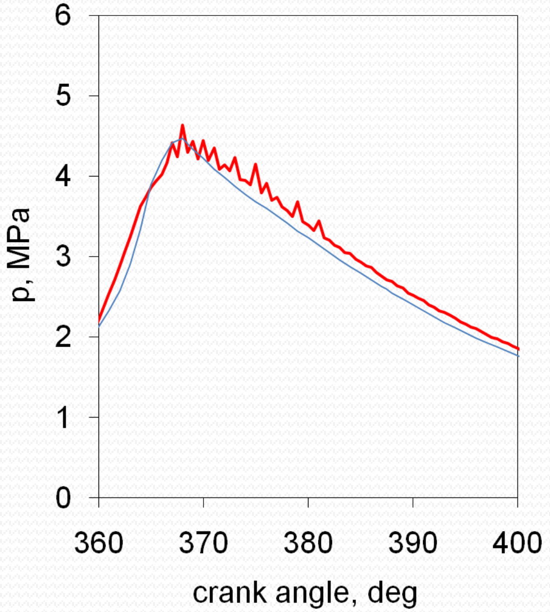


Fig. Comparison of pressures courses with knock combustion

Results of optimiztion of thermal cycle of the test engine

Effect of EGR on the indicated efficiency and the mean indicated pressure for various EGR shares, at a constant angle of ignition, equal to 10 deg BTDC.

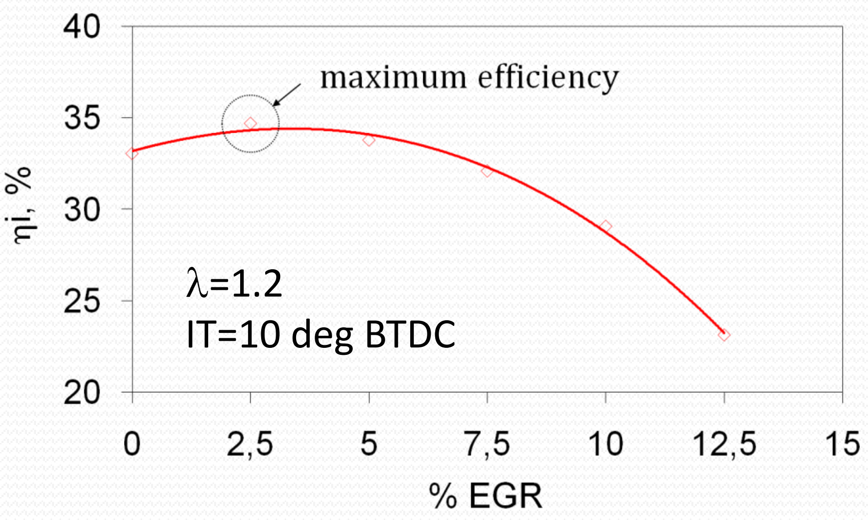


Fig. Indicated thermal efficiency

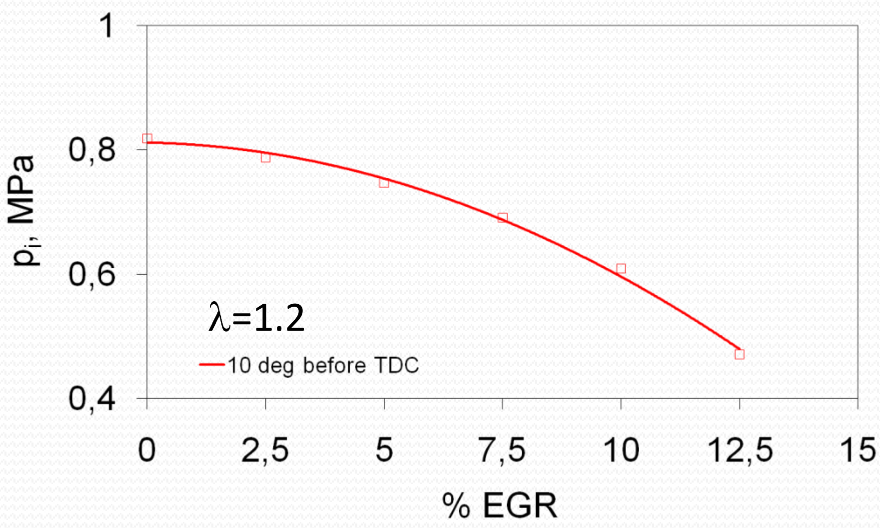


Fig. Indicated mean pressure

Results of optimiztion of thermal cycle of the test engine

Comparison of the indicated thermal efficiency curves obtained for a different EGR ratio and for:

- fixed angle of ignition advance equal to 10 deg before TDC,
- ignition timing for maximum efficiency
- conditions limited by knock onset.

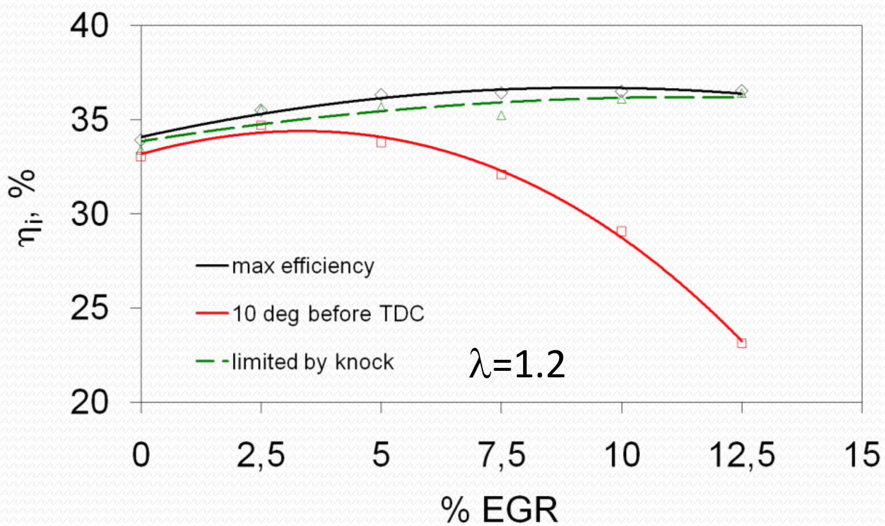


Fig. Indicated thermal efficiency

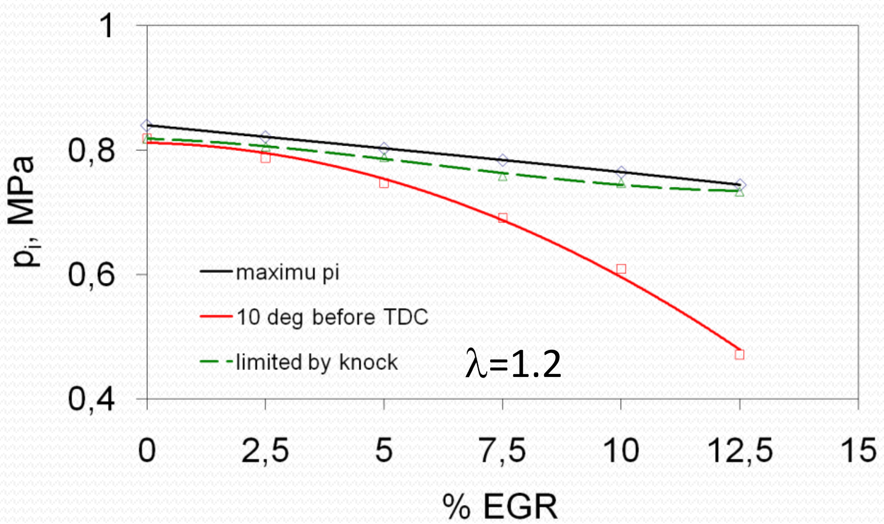


Fig. Indicated mean pressure

Results of optimiztion of thermal cycle of the test engine

The curve called „knock onset" refers to the critical angle of ignition at which begins knock combustion in the test engine. The second curve defines the ignition angles for which the maximum efficiency could be achieved but because of the danger of knock phenomenon can not be achieved.

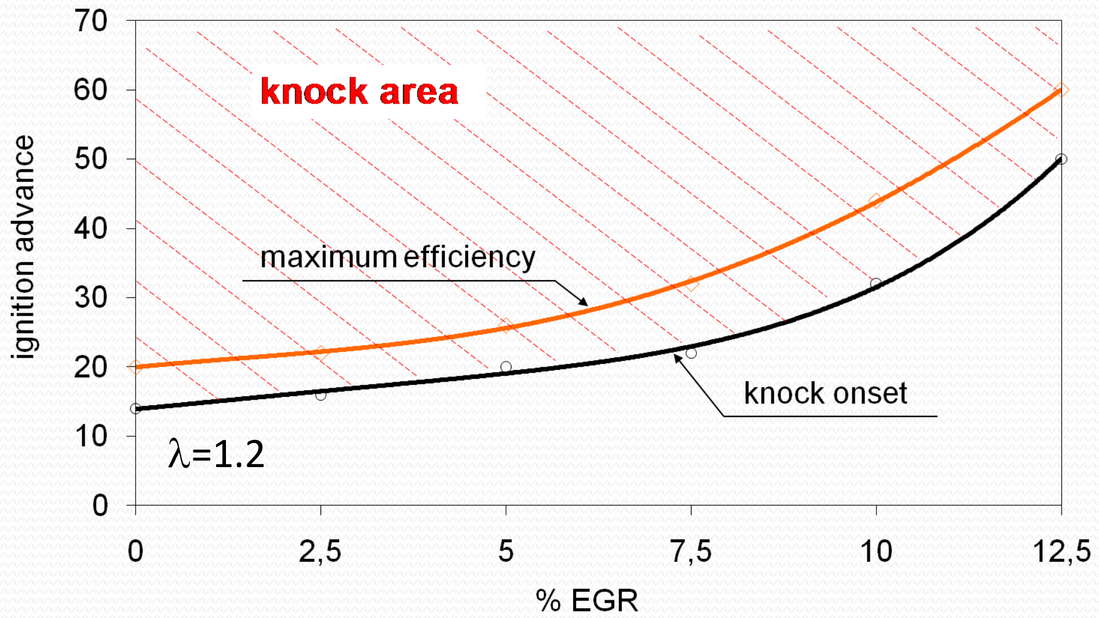


Fig. Knock area for the test engine

Results of optimiztion of thermal cycle of the test engine

With the increasing of EGR participation is necessary to increase the ignition advance angle for optimal operating conditions. Increasing the angle of ignition resulted in the initiation of knock combustion. The test engine does not tolerate more than 12.5 % of EGR.

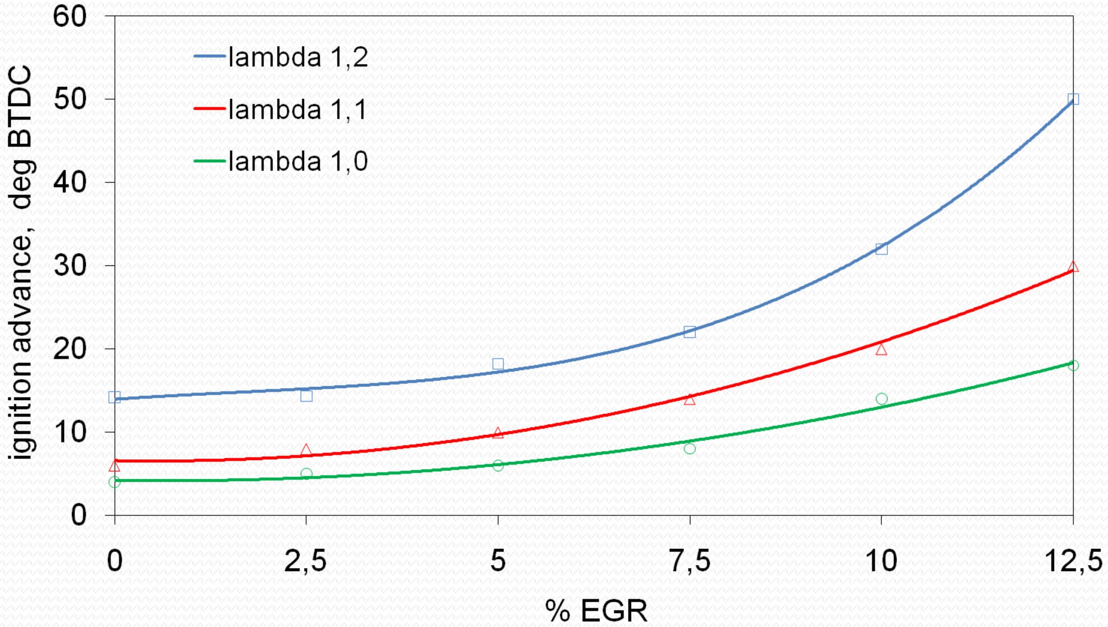
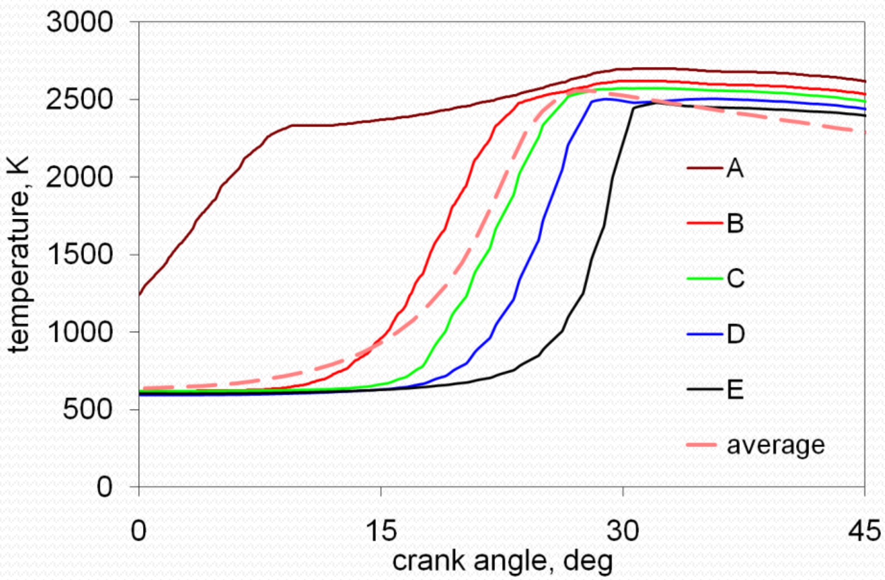
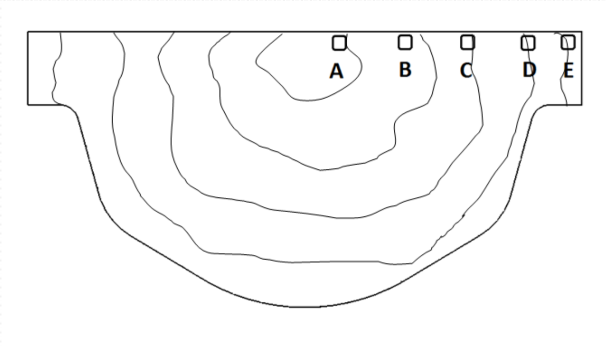


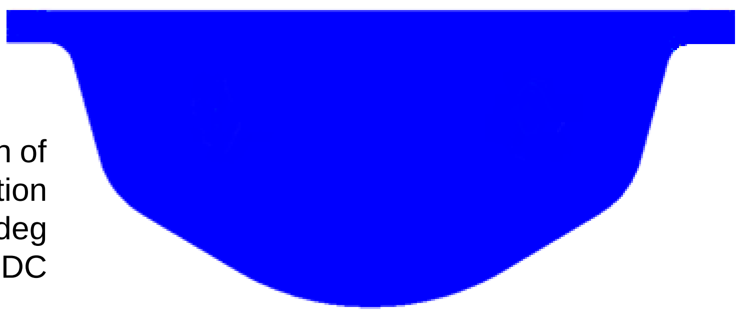
Fig. Maximum acceptable ignition angles for different coefficients of excess air, and various percentages of EGR

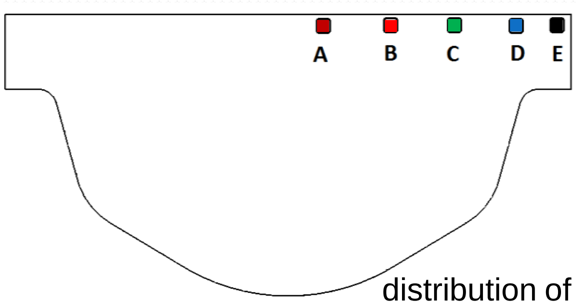
Detection of knock combustion





cross-section of the combustion chamber 30 deg after TDC

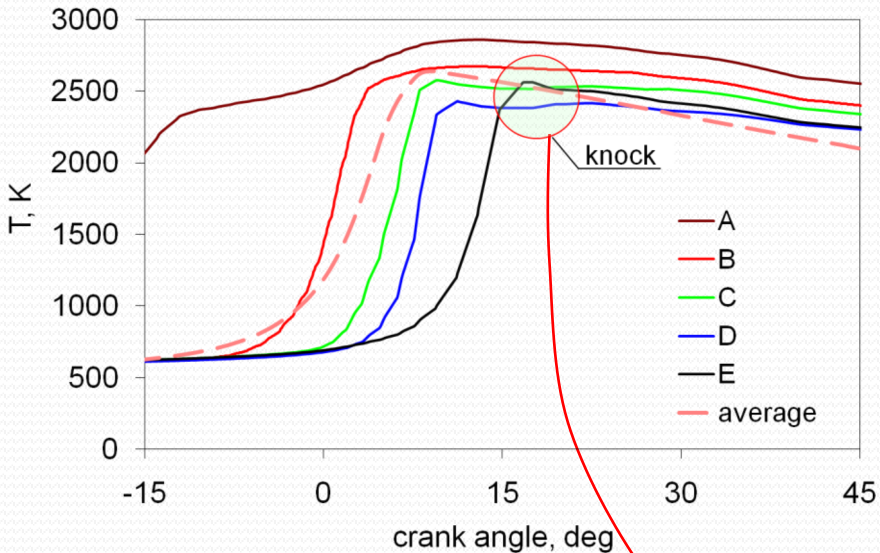




distribution of points

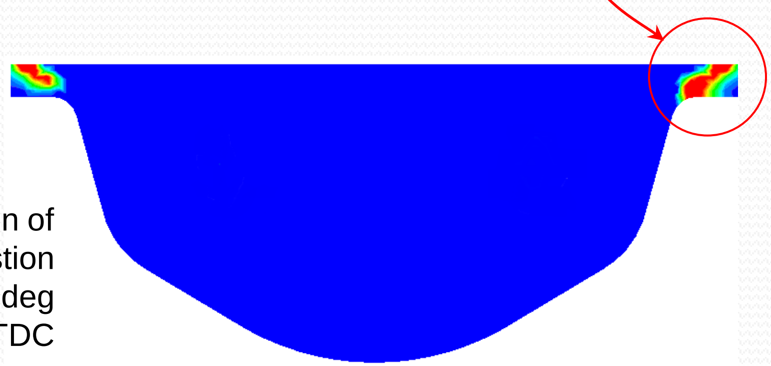
Fig. The case without knock

Detection of knock combustion

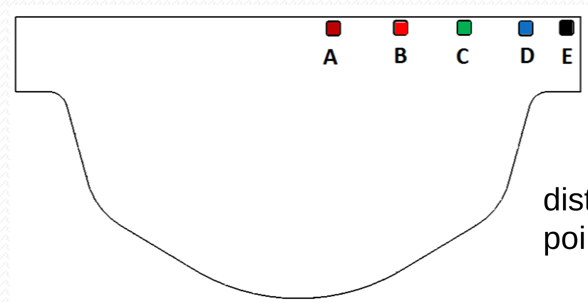


Courses of instantaneous temperature at selected control volumes of the combustion chamber.

Fig. The case with knock



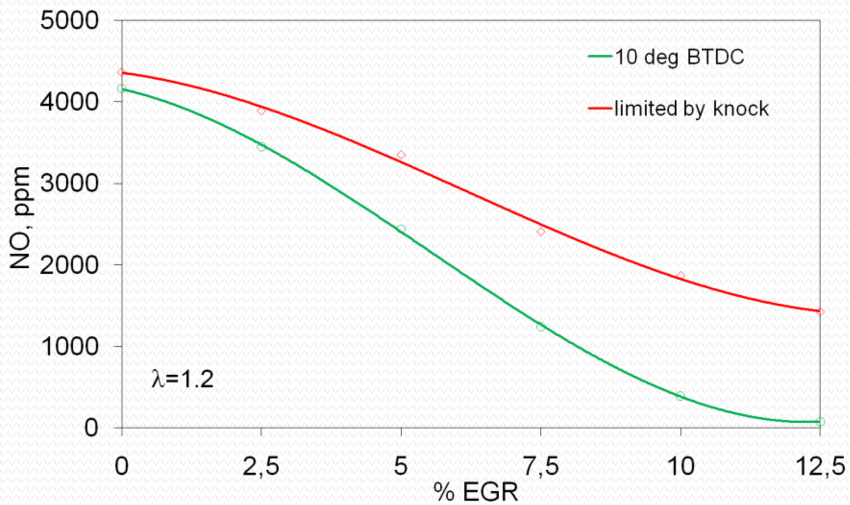
cross-section of the combustion chamber 20 deg after TDC

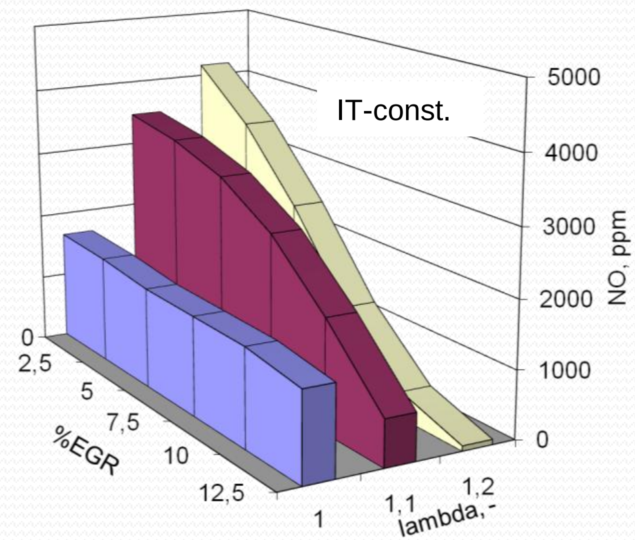


distribution of points

Impact of EGR on NO content in exhaust gases

- 12.5 % of exhaust gases caused the decrease of NO in the exhaust from more than 4000 ppm NO to several percent. It also resulted in decrease in the mean indicated pressure from 0.75 MPa to 0.47 MPa. And the indicated engine efficiency from 33 % to 23 %.
- After optimization of the thermal cycle, for the share of 12.5 % EGR, it has increased the value of mean indicated pressure to 0.73 MPa and indicated efficiency to over 35 %.
- At the same time, for a 12.5 % share of EGR increased NO content in the exhaust to 1425 ppm.





Conclusions

- Maximum values of thermodynamic parameters of the test engine are limited by the occurrence of knock phenomenon.
- The values of the limit advance angles for the test engine was determined in order to avoid combustion knock.
- The test engine does not tolerate more than 12.5% of EGR. Larger share of EGR caused too much slowing the spread of the flame inside the combustion chamber.
- Exhaust gas recirculation at constant angle of ignition is very effective in limiting the content of NO in the exhaust, but on the other hand it has an adverse effect on the engine performance.
- Exhaust gas recirculation is beneficial not only to reduce the toxicity of exhaust gases but also effectively shifts the formation of the knock limit.