POSSIBILITY TO REDUCE KNOCK COMBUSTION BY EGR IN THE SI TEST ENGINE

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Abstract

The paper presents the results of modelling thermal cycle of internal combustion engine including exhaust gas recirculation. The test engine can not achieve the optimum parameters of work due to occurrence of the knock combustion. The influence of EGR on the limits of the knock occurrence in the engine was studied. It turned out that few percent of exhaust gases in the fresh charge effectively shifts the knock limit to higher ignition advance angles. The values of the limit ignition timing for the test engine was determined in order to avoid combustion knock. Larger share of EGR caused too much slowing the spread of the flame inside the combustion chamber of the test engine. EGR at constant angle of ignition was very effective in limiting the content of NO in the exhaust, but on the other hand it has an adverse effect on the engine parameters. The engine operate with exhaust gas recirculation in order to obtain the possible best parameters the ignition timing should be optimized. However, that with increasing values of the thermodynamic parameters of thermal cycle of engine increased NO content in the exhaust. The paper presents results of modelling thermal cycle of IC engine, including exhaust gas recirculation and knock combustion. The object of researches was the S320ER spark ignition internal combustion engine supplied with petrol. The engine was operated at a constant speed of 1000 rpm. Modelling of the thermal cycle of the test SI engine in the FIRE software was carried out.

Keywords: *combustion, knock, exhaust gas recirculation, modelling, thermal cycle*

1. Introduction

Researches based on numerical simulations using advanced mathematical models have recently been developing very intensively. Advanced numerical models coupled with increasing computational power allow not only flow processes but also combustion to be modelled in 3D. Although the mathematical models of processes occurring in engine cylinder are very sophisticated, they are still incomplete ones. The requirement to obtain proper numerical modelling results is to apply experimental research results to mathematical models.

Engines are designed to maximize economy and power while minimizing exhaust emissions. This is dictated by growing concern about decreasing energy resources and environmental protection. Therefore, is still carried out intensive research and development in internal combustion engines. Still are carried out researches to improving the combustion process, introduces a new fuel such as hydrogen, and is made to optimize engine parameters. The engine should operate with the possible greatest efficiency with the least toxic compound emissions. Maximizing the performance of the engine (BMEP) usually causes the occurrence of the so-called knock combustion. This type of combustion is very dangerous for the engine. It can cause damage to the engine combustion chamber components. This phenomenon can destroy piston, exhaust valves or rings. Due to this disadvantageous effect it is important to avoid knock phenomenon but on the other hand due to efficiency reasons, it is desirable to work as close to knock combustion as possible.

Knock combustion is an anomalous combustion process occurring in internal combustion engines. This phenomenon is characterized by the occurrence of pressure oscillations. The most accepted theory that explains engine knock is the auto-ignition theory [4]. The auto-ignition theory states that when the fuel–air mixture in the end gas region ahead of the flame front is compressed to sufficiently high pressure and temperature, the fuel oxidation process can occur in parts or in the entire end gas region. This releases the chemical energy in the end gas region at extremely high rates resulting in high local pressures. The non-uniform pressure distribution inside the combustion chamber causes pressure waves or shock waves to propagate across the chamber causing noise which is known as knock [4]. In engine evolution, the Exhaust Gas Recycle (EGR) technique was firstly adopted in compression ignition engines to limit the NO_x formation rate by limiting the combustion temperature owing to the dilution of the fresh charge with a certain amount of exhaust gases recycled at the engine intake. Today, EGR is commonly used also in spark-ignition engines since this technique is able to both limit the NO_x formation rate and improve engine thermodynamics at some operating points. EGR, in fact, decreases pumping losses at partial load, while improves the detonation resistance at full load operation [2, 8, 4]. In some engines, a fraction of the engine exhaust gases is recycled to the intake to dilute fresh mixture for control of NO_x emission [6]. In order to reduce the in-cylinder temperature, a charge dilution must be done. One of the effective methods used to dilute the fresh charge is to recycle some part of the exhaust gases back into the cylinder. Using EGR will lead to a decrease in the in-cylinder temperature and a decrease in knock combustion propensity. This method makes possible to improve ignition timing to achieve higher values of thermal efficiency compared to engines operates on mixtures without fraction of EGR. In addition, exhaust gas recirculation will reduce the in-cylinder NO_x production [2]. The study of combustion process in the spark ignition engine with exhaust gas recirculation has been conducted by many scientists. Similarly, in the literature can be found many papers on exploring the knock process in the internal combustion engines. These are, first of all, the results of experimental studies. And so Cha and all [5] used the EGR system to reduce NO_x emission, to improve fuel economy and suppress knock by using the characteristics of charge dilution. They concluded that the EGR rate at a given engine operating condition increases and in addition the combustion instability increases. The combustion instability increases cyclic variations resulting in the deterioration of engine performance and emissions. Therefore, the optimum EGR rate should be carefully determined to obtain the better engine parameters and emissions. An experimental study has been performed to investigate the effects of EGR on combustion stability, engine performance, NO_x and the other exhaust emissions. EGR reduced the formation of NO_x emission rate from 25.4% up to 89.6% with EGR on standard engine. As EGR being applied, not only flame propagation speed but also the peak burned gas temperature and pressure were decreased [5]. Therefore, ignition timing advance is required to minimize the power loss and to achieve the stable combustion. Parameter COV_{imep} was proportional to EGR rate and was decreased as spark timing was advanced. When EGR was applied, brake power was reduced in inversely proportion to EGR rate, and is increased as the spark timing is more advanced [5]. In literature are also many works regarding to the study of combustion knock in the internal combustion engine. The biggest part of the work relates to experimental research. The authors determined the area of engine operation, where knock can appear. Szwaja and all [12] have conducted IC engine studies examining combustion knock characteristics with hydrogen and gasoline fuels in a spark ignited, single cylinder cooperative fuel research engine. Through the comparisons with gasoline, it was found that knock detection techniques used for gasoline engines, can be applied to a hydrogen engine with some modifications. This work gives insight for further development in real time knock detection. This would help in improving same parameters of hydrogen engines while allowing the engine to be operated closer to combustion knock limits to increase engine performance and reducing possibility of engine damage due to knock. Olliver and all [16] proposed a new method to detect the knock. This method is based on the analysis of heat transfer in engine. Kirsch and all [14] have been developed a mathematical model to simulate the occurrence of knock in the gasoline engine. A generalized chemical reaction scheme which embodies the essential kinetic features of the degenerate branched chain reactions responsible for auto-ignition was then refined to give an accurate simulation of these observations. This model has been used to study the origin of severity in the CFR engine. In confirming that high end-gas temperatures are of major importance in de-rating sensitive fuels under "severe" engine conditions. This study gives a confidence in approach to engine simulation, and especially in the chemical aspect of the model [14]. Chun, Heywood and Keck [13] have been studied a model to predict the onset of knock phenomenon in a SI engine. They were used experimental data from a large number of individual cycles, over a range of operating conditions, where knock occurred. The unburned gas temperature used in the kinetic model was calculated from the measured cylinder pressure assuming that knock originates in that part of the end-gas region which is compressed adiabatically. The model indicated that auto-ignition under knocking conditions is a two stage process. They affirmed that knock occurs first in the adiabatic core of the end-gas and the sensitivity of the model to the reaction rate constants, the agreement between theory and experiment was encouraging [13]. Sazhin at al. [15] have been used the Shell model to modelling auto ignition in gasoline and diesel engines. The possibility of use of the modified Shell model to more reactive fuels have been investigated with the example of n-heptane.

The authors show the results of the analysis of the impact of EGR on the knock limit of the test engine. Paper presents the impact of EGR on the NO concentration in the exhaust to the conditions fixed ignition advance angle.

2. Test engine and model assumptions

The paper presents results of modelling thermal cycle of IC engine, including exhaust gas recirculation and knock combustion. The object of researches was a spark ignition S320ER internal combustion engine supplied with gasoline. The engine was operated at a constant speed of 1000 rpm. Modelling of the thermal cycle of the test SI engine in the FIRE software was carried out. The work investigates the impact of EGR on engine operating parameters, NO content in the exhaust gases and reduces engine knocking phenomena.

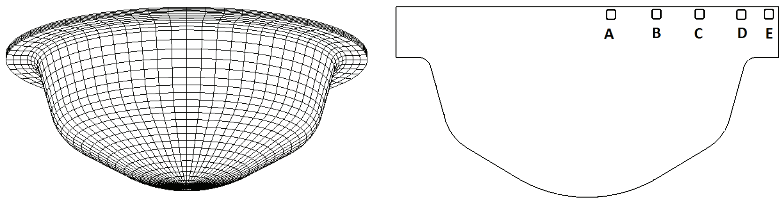

Fig. 1. The computational mesh for combustion chamber and selected control volumes

Two-layered wall boundary layer was considered. Model tests were carried out in FIRE software. In Tab. 1 are presented main engine parameters, initial conditions and FIRE sub-models.

Computations were conducted for the angle range from -180 deg before top dead centre (BTDC) to 180 deg after top dead centre (ATDC). The computational mesh of the modelled combustion chamber (Fig. 1) of the S320ER test engine consisted of nearly 30000 computation cells. The EGR was calculated as a percentage of the total inlet mass flow rate as follows:

$$\%EGR = \frac{\dot{m}_{EGR}}{\dot{m}_a + \dot{m}_f + \dot{m}_{EGR}}, \tag{1}$$

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.

Result of validation of the model is presented in Fig. 2. There are presented the courses of combustion pressures obtained as a result of indicating the real test engine and modelling with FIRE software, respectively, for the same initial conditions and settings and spark ignition advance timing.

Tab. 1. Modelling parameters

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

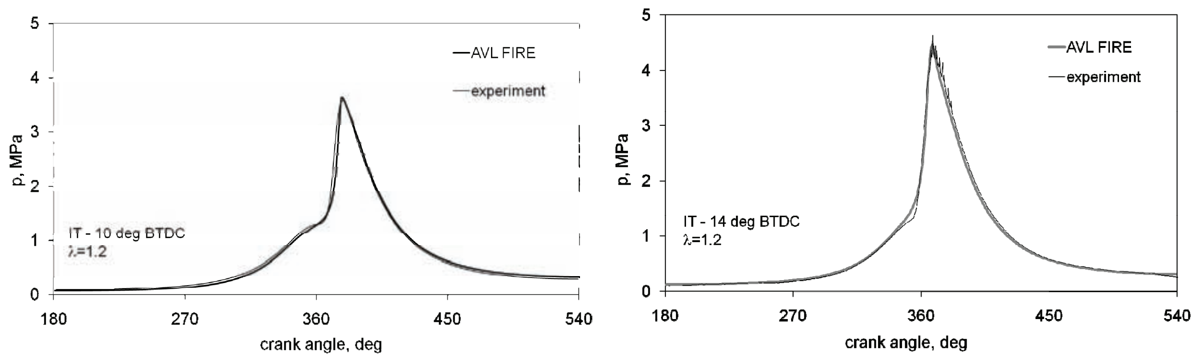

Fig. 2. Courses of pressure obtained by indicating of real test engine and by modelling using FIRE software, without and with knock combustion

In Fig. 2 are also presented pressure courses received from indication of the real engine and received as a result of modelling, in case knock combustion occurrence. On the course of modelled pressure are invisible the characteristic pulsations of pressure. Information on the presence of knock combustion was taken from an analysis of the spatial distribution of a parameter called Knock Reaction Rate.

3. Results and analysis

The paper presents results of 3D modelling thermal cycle engine operating at a constant rotational speed. The work investigates the influence of EGR on engine operating parameters, on NO content in the exhaust gases and reduces engine knocking phenomena. The study was conducted for the excess air ratio equal to 1.0…1.2. The test engine was characterized by a high tendency to appear combustion knock. After the validation of the model were started modelling. Highly compatible modelling results with those obtained experimentally (Fig. 2) was obtained. Calculated engine efficiency is the gross efficiency, the modelling does not include charge exchange loop. In Figure 3 presents the results of optimizing the thermal cycle of engine. With the participation of EGR is necessary to increase the ignition advance angle for optimal operating conditions. For the tested engine, increase the ignition advance angle resulted in the knock process initiate. Possible maximum values of η_i and p_i for different EGR shares are shown in Fig. 3.

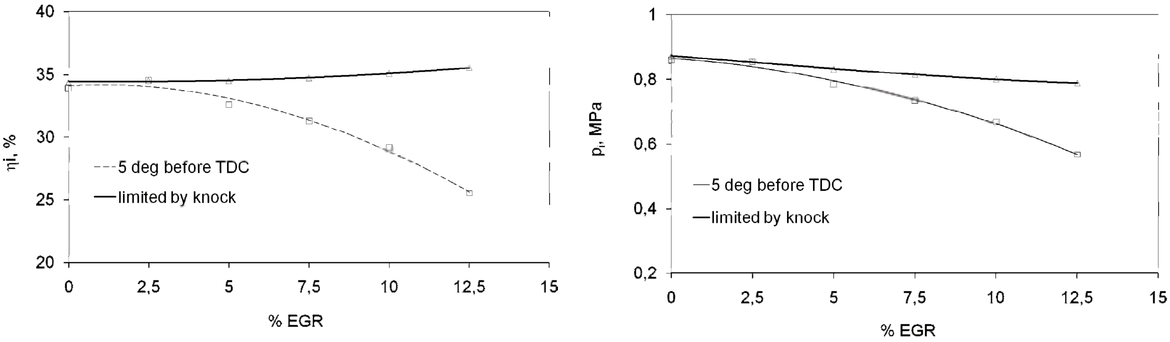

Fig. 3. Results of thermal cycle optimization, indicated efficiency and mean indicated pressure, λ=1.1

The test engine could not work under conditions where there is danger of knock phenomena occurs. For maximum EGR ratio, equal 12.5%, increased indicated thermal efficiency from 25% do 35.5%. This was due to change in the angle of ignition advance. For maximum efficiency, with 12.5% EGR, the ignition advance should be changed to 30 deg BTDC. The maximum ignition timing for these conditions could be below than 30 deg BTDC. Optimizing the ignition angle has also a positive effect on the value of the mean indicated pressure.

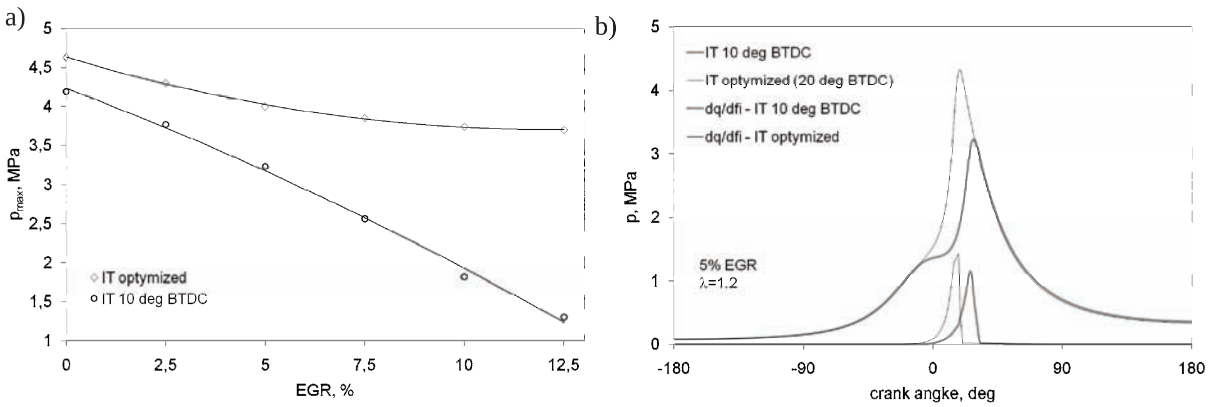

Fig. 4. EGR impact on the maximum value of pressure for optimal conditions and constant ignition angle and comparison of pressure traces

For the test engine, for λ = 1.2 and 12.5% share of EGR, resulted in the disappearance of the combustion process. After optimizing the cycle, the engine can work at a satisfactory parameter values.

In Fig. 5 are shown the temperature courses at the control volumes for the appearance of the knock combustion conditions without EGR and with EGR. There are also shown the temperature courses at selected control volumes, which give possibility to conclude about the appearance of the knock phenomenon. On the basis of temperature courses can be deduced about knock combustion in the modelled combustion chamber. In the control volume for 15 deg ATDC temperatures at point E is higher than the temperature at the point D. This difference in temperatures at volume E before reaching the flame front may indicate the occurrence of auto-ignition. On the presented cross-section of the combustion chamber can be seen the place of formation of the knock combustion. This phenomenon of knock appears in the squeezing volume of the combustion chamber of modelled test engine.

The combustion duration was calculated as the crank angle interval from the spark ignition to the end of combustion where the heat release reaches its maximum [2].

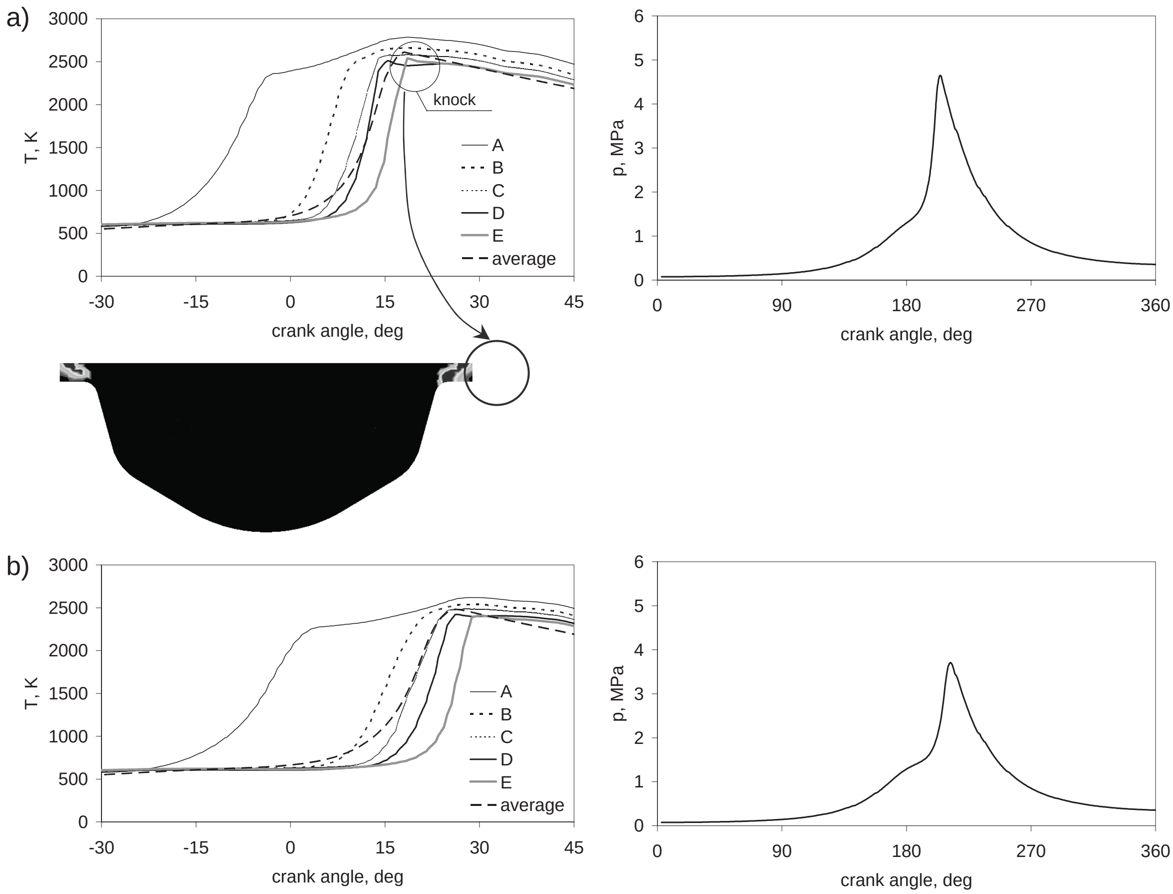

Fig. 5. Temperature in selected control volumes of the combustion chamber and the temperature averaged over the instantaneous volume of the combustion chamber and the corresponding average pressure in the combustion chamber, ignition timing 14 deg BTDC, λ=1.2, a) 0% EGR, b) 5% EGR

The increase of EGR share decreases the oxygen concentration which slowed down the combustion rate and increased combustion duration. With the increasing participation of EGR and the increase in excess air ratio increases the combustion phases in the test engine. These are the values for the optimized conditions.

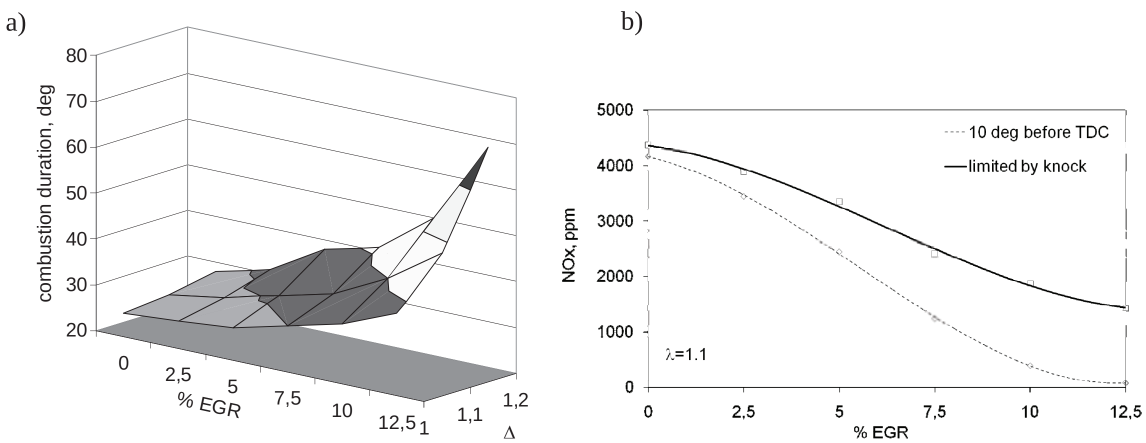

Fig. 6. Combustion duration (a) and NO concentration (b)

Exhaust gas recirculation at constant angle of ignition is very effective in limiting the content of NO in the exhaust (Fig. 6b). The value 12.5 % of the share of EGR caused the decrease of NO in the exhaust from more than 4000 ppm NO to several percent. However, it also resulted in decrease in the mean indicated pressure to 0.47 MPa (λ=1.2). At the same time for a 12.5 % share of EGR increased NO content in the exhaust to 1425 ppm.

4. Conclusions

Results of modelling and optimizing of thermal cycle of an internal combustion engine with exhaust gas recirculation are presented. Maximum possible values of thermodynamic parameters of the modelled test engine are limited by the knock combustion occurrence. The values of the limit ignition timing 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 of the test engine. EGR at constant angle of ignition was very effective in limiting the content of NO in the exhaust, but on the other hand it has an adverse effect on the engine parameters. After optimization thermal cycle in respect of the ignition timing, for 12.5% of EGR, achieved value of mean indicated pressure equal to 0.74MPa and efficiency equal to 35%. Such participation of EGR resulted in a decrease in NO concentration in exhaust gases to 1560 ppm. Exhaust gas recirculation is beneficial not only to reduce the toxicity of exhaust gases but also effectively shifts the formation of the knock limit.

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