INFLUENCE OF OXYGEN CONCENTRATION ON COMBUSTION CHARACTERISTICS OF HYDROCARBON-AIR MIXTURES UNDER HIGH TEMPERATURE AND PRESSURE

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Abstract

The emission of NO_x, SO_x, HC and CO_2 from internal combustion engines is still a major issue in the development of modern engines. Especially for new concepts, like EGR (Exhaust gas recirculation), developed, detailed information about the pollutant formation is required. However, the experiments of actual standard engines are generally very complicated processes including the residual gas from the last cycle and the flow in an engine cylinder. Thus, experimental data measured using actual engines become unreliable. To obtain the essential data on combustion of hydrocarbon-CO_2-N_2-O_2 mixtures, the experiments have been performed under conditions of high temperature and pressure, which are achieved by a spark ignited opposed rapid compression machine. The main conclusions are as follows: (1) The maximum burning pressure decreases with decreasing oxygen concentration at same EGR ratio. (2) The total burning time decreases with decreasing the concentration of O_2 in methane-CO_2-N_2-O_2 and propane-CO_2-N_2-O_2 mixtures. (3) The reduction ratio of flame speed is relatively larger on the fuel rich side than that on the lean side. Numerical modeling was focused on the influence of EGR ratio on exhaust emission. Methane fuel was used in the modeling

Keywords: *combustion characteristics, rapid compression machine, modelling, methane*

1. Introduction

Combustion characteristics of hydrocarbon-air mixtures at high temperature and pressure are important for predicting the performance of internal combustion engines and high-speed jet engines. Some data are available on the combustion characteristics of hydrocarbon-air and natural gas mixtures in internal combustion engines.[1), 2), 3)] Furthermore, many researchers have carried out computer simulations to determine the combustion characteristics of internal combustion engines.[4), 5), 6)] The emission of NO_x, SO_x, HC and CO_2 from internal combustion engines is still a major issue in the development of modern engines. Especially for new concepts, like EGR (Exhaust Gas Recirculation), developed, detailed information about the pollutant formation is required. However, the experiments of actual standard engines are generally very complicated processes including the residual gas from the last cycle and the flow in an engine cylinder. Thus, experimental data measured using actual engines become unreliable.

To obtain the essential data on combustion of hydrocarbon-CO_2-N_2-O_2 mixtures, the experiments have been performed under conditions of high temperature and pressure, which are achieved by a spark ignited opposed rapid compression machine. The ranges of initial temperature and pressure established in the machine are 293 to 1000 K and 0.1 to 1.5 MPa, respectively.

Under these conditions it has been possible to obtain the fundamental combustion characteristics of hydrocarbon-CO_2-N_2-O_2 mixtures such as the maximum pressure, total burning time and flame speed for the fuels studied.

2. Experimental Apparatus and Procedure

Figure 1 shows the opposed rapid compression machine employed in this study. The bore of opposed rapid compression machine is 100 mm. The machine is rapidly driven using compressed air (0.5 MPa) drawn from a reservoir equipped with electric valves and the average polytropic index is about 1.34.[7),] The compression ratio is changed by changing the initial position of piston and by either changing the stroke or the diameter of the combustion chamber in the opposed machine. A spark plug, a pressure transducer (Piezo-type), ionisation probes and water jacket to regulate the temperature are equipped with combustion chamber. The flame speed S_f is measured by the ionisation probes located at two different positions from the centre of the combustion chamber where the pressure rise is less than 5% of its final value and the pressure is nearly constant. Methane and propane gas of 99% purity are used as fuels and a mixture of 79 % nitrogen and 21 % oxygen by volume is used as a substitute for air.

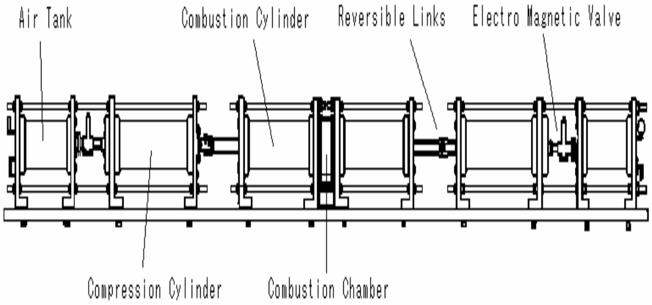
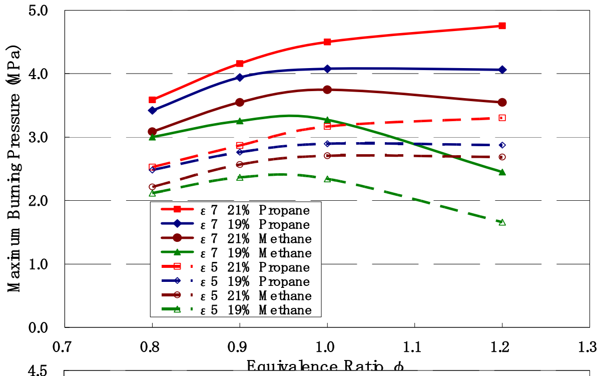


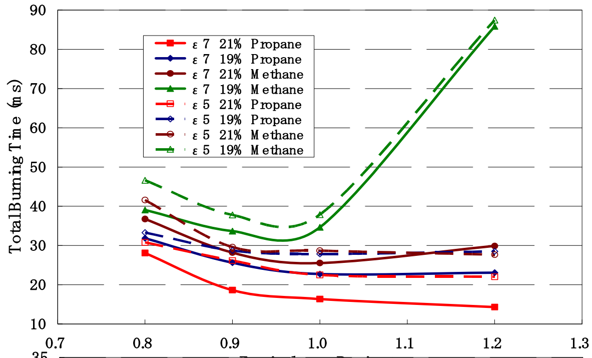
Fig.1. Schematic of the Opposed Rapid Compression Machine

3. Experimental Results And Discussion

Figure 2 shows the maximum burning pressure of methane-CO_2-N_2-O_2 and propane-CO_2-N_2-O_2 mixtures against equivalence ratio as a function of oxygen concentration. The CO_2 addition concentration is constant (5 vol %), and this value means the EGR ratio of 28% for actual engines. Two values of compression ratio were used (ε = 5 and 7) and four combustible mixture compositions were studied:

21%Propane: C_3H_8-N_2-CO_2-O_2 (vol.): C_3H_8: 4.03%, N_2: 72.02%, CO_2: 3.79%, O_2: 20.15%
21%Methane: CH_4-N_2-CO_2-O_2 (vol.): CH_4: 9.50%, N_2: 67.92%, CO_2: 3.57%, O_2: 19.0%
19%Propane: C_3H_8-N_2-CO_2- O_2 (vol.): C_3H_8: 4.03%, N_2: 73.85%, CO_2: 3.89%, O_2: 18.23%
19%Methane: CH_4-N_2-CO_2- O_2 (vol.): CH_4: 9.50%, N_2: 69.63%, CO_2: 3.67%, O_2: 17.19%





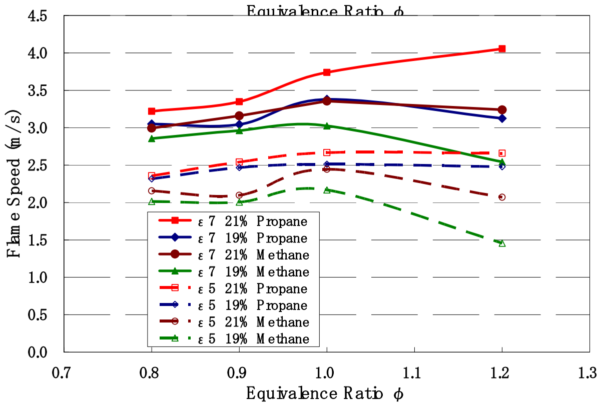


Fig.4. Flame Speed

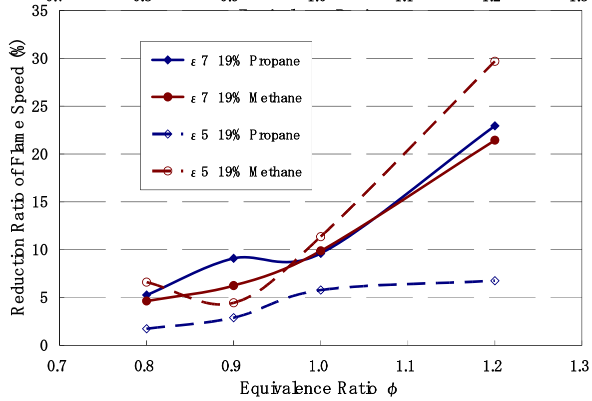


Fig.5. Reduction of Flame Speed

From this figure, it is found that the maximum burning pressure decreases with decreasing the concentration of O_2 in methane-CO_2-N_2-O_2 and propane-CO_2-N_2-O_2 mixture.

Figure 3 shows the total burning time of methane-CO_2-N_2-O_2 and propane-CO_2-N_2-O_2 mixtures against the equivalence ratio. From this figure it can be seen that the total burning time decreases with decreasing the concentration of O_2 in methane-CO_2-N_2-O_2 and propane-CO_2-N_2-O_2 mixtures.

The flame speed of methane-CO_2-N_2-O_2 and propane-CO_2-N_2-O_2 mixtures against the equivalence ratio as a function of O_2 concentration are shown in Figure 4. The measurement of flame speed by ionisation probes method is carried out at a position 15 mm and 20 mm from the centre of combustion chamber, where the pressure rise is less than 5% of its final value (Maximum burning pressure). From this figure it is found that with increasing the O_2 concentration the flame speed increases and its maximum value for methane-CO_2-N_2-O_2 is at 1.0 of equivalence ratio. Furthermore, the maximum flame speed for propane-CO_2-N_2-O_2 mixtures is observed at 1.2 of equivalence ratio. It is due to the effect of thermal dissociation.

Figure 5 shows the reduction of flame speed of methane-CO_2-N_2-O_2 and propane-CO_2-N_2-O_2 mixtures against equivalence ratio as a function of compression ratio. The reduction of flame speed R_f is given by:

$$R_f = \frac{S - S_{O_2}}{S} \times 100$$

where:

S: Flame speed at density 21vol% of oxygen

S_{O_2}: Flame speed at density 19vol% of oxygen

As seen from this figure, under constant oxygen concentration (19vol%), the reduction ratio of flame speed is relatively larger on the fuel rich side than that on the lean side.

4. Numerical Modeling

Numerical investigations were carried out at the Institute of Heat Engineering at Warsaw University of Technology. The CFD code KIVA-3V rel.2 was used for calculations. Numerical modelling covered two different compression ratio of rapid compression machine (5 and 7) with three different equivalence ratio of methane-air mixture (0.8, 1.0 and 1.2) and three EGR levels (0%, 10% and 20% of EGR). Three-dimensional computational mesh was prepared with average cells size of about 0.5 mm^3. For each case the initial conditions (before compression) were kept the same – mixture pressure 0.1 MPa and temperature 300K. The EGR composition was taken for each case separately and based on calculation results for cases with 0% of EGR.

5. Results of Simulations and Discussion

The influence of Exhaust Gas Recirculation is very clear. For higher compression ratio and low equivalence ratio EGR increases HC and CO_2 emission but decreases significantly NO_X emission; CO increases for 10% of EGR (in comparison with no EGR) and decreases slightly for 20% of EGR but still remains higher than for case without EGR. For stoichiometric equivalence ratio only unburned hydrocarbons fraction increases for higher EGR ratios but the emission of CO_2, CO and NO_X decreases. For high equivalence ratio EGR the emission of HC and CO decreases but the CO_2 emission increases; NO_X fraction is at the same level for 20% and 0% of EGR but is much higher for 10% of EGR.

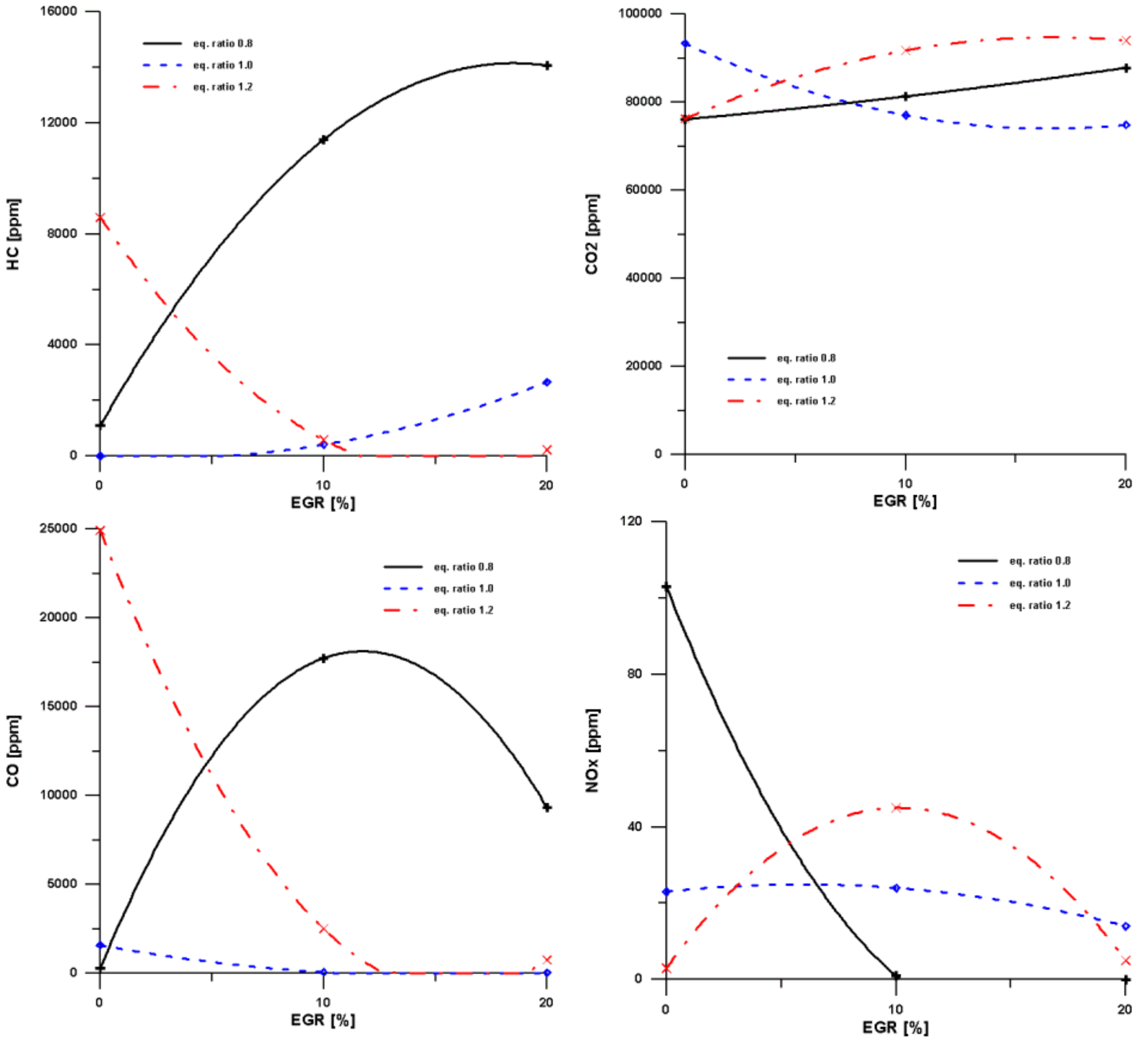


Fig. 6. Calculated exhaust emission for different EGR ratio; compression ratio equal to 7

For lower compression ratio and low equivalence ratio HC and NO_X emission decreases but emission of CO and CO_2 increases. For stoichiometric mixtures: HC emission increases and CO_2 emission decreases for higher EGR ratio; CO fraction decreases for 10% of EGR but then grows a bit for 20% of EGR; NO_X emission remains almost at the same level. For high equivalence ratio significant drop of HC and CO emission can be observed but CO_2 and NO_X emission grows.

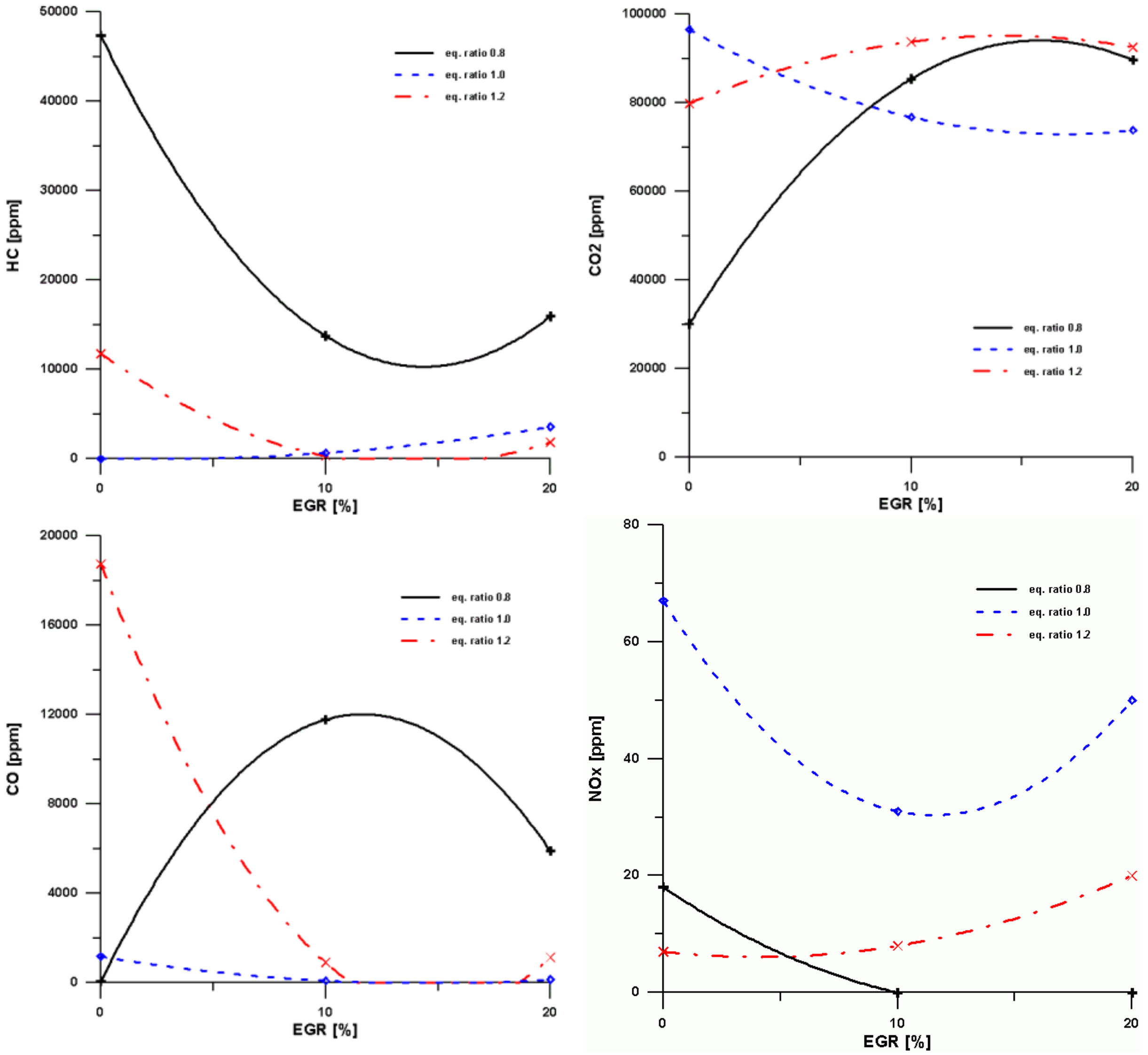


Fig. 7. Calculated exhaust emission for different EGR ratio; compression ratio equal to 5

An increase of HC together with CO can be explained in two ways. First of all, mixture contains less oxygen (relative to fuel) and heat release rate is lower (per unit of mixture mass) because there is an additional amount of CO_2, H_2O and N_2 in fresh mixture. Decrease of NO_X is mainly forced by lower combustion temperature – lower heat release rate per unit of mixture. The CO_2 emission is an effect of fuel combustion – if larger amount of the fuel has been burned (CH_4, HC and CO) the larger amount of CO_2 has been emitted. Complete results of calculation are presented in Table1, Figure 6 and Figure 7.

6. Conclusions

Experiments were carried out to determine the combustion characteristics of methane-CO_2-N_2-O_2 and propane-CO_2-N_2-O_2 mixtures at high temperature and pressure conditions by using an opposed rapid compression machine. The main results are as follows: 1) The maximum burning pressure decreases with decreasing oxygen concentration at same EGR ratio. 2) The total burning time decreases with decreasing the concentration of O_2 in methane-CO_2-N_2-O_2 and propane-CO_2-N_2-O_2 mixtures. 3) The reduction ratio of flame speed is relatively larger on the fuel rich side than that on the lean side.

Table1. Calculated exhaust gas composition

	Compression ratio 7				Compression ratio 5			
ϕ	HC [ppm]	CO_2 [ppm]	CO [ppm]	NO_X [ppm]	HC [ppm]	CO_2 [ppm]	CO [ppm]	NO_X [ppm]
0% EGR								
0,8	1099	76111	283	103	47347	30116	52	18
1,0	4	93357	1581	23	5	96532	1174	67
1,2	8594	76216	24929	3	11747	79825	18746	7
10% EGR								
0,8	11394	81312	17723	1	13743	85391	11767	<1
1,0	417	77043	66	24	666	76767	90	31
1,2	594	91760	2521	45	316	93776	909	8
20% EGR								
0,8	14068	87814	9324	<1	15939	89638	5891	<1
1,0	2669	74841	39	14	3571	73809	141	50
1,2	228	94021	760	5	1836	92560	1137	20

Numerical modelling showed some main hints for detailed experimental investigation of EGR influence on emission from spark-ignited engines fuelled with methane. Exhaust Gas Recirculation influences significantly on combustion process. Larger amount of inert gas (CO_2, H_2O and N_2) makes combustion slower and maximum temperature is lower. This decreases NO_X emission but can increase emission of HC and CO (if combustion is too slow). The CO_2 emission corresponds with fuel combustion ratio – it grows when larger amount of fuel has been burned.

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