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STUDY OF THE INFLUENCES OF BLENDING DIFFERENT PROPORTIONS OF PROPANE INTO METHANE ON COMBUSTION CHARACTERISTICS AT THE KNOCK THRESHOLD BY USING RCM

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Abstract

A spark-ignited Rapid Compression Machine (RCM) has been used to investigate the influences of the different proportions of methane-propane mixtures on the combustion characteristics at knock threshold operating condition. First, the threshold operating points of the mixtures have been obtained and the results indicated that the piston driving pressure reduces from 142 bars to 90 bars as the propane content in the mixture increases. As a spark plug was fitted in this RCM, the optimum spark timing was also investigated. It was established that spark timing should be set synchronize with the piston at TDC, due to the free movement of the piston. In most RCMs, piston can move toward TDC following the equilibria of forces due to the absence of con-rod. Finally, knock intensity of the different mixtures has been studied. Pre-heating system in RCM with and without trace heating system; effects of flow-rate and lambda variations on peak pressure, ignition delay time and ARR; threshold operating conditions of pure methane, 90% methane and 10% propane, 80% methane and 20% propane, 70% methane and 30% propane; effect of driving pressure on the knocking intensity for mixture of methane and propane for heavy and light knockings are presented in the article.

Keywords: *Rapid Compression Machine, knock threshold operating condition, peak driving pressure, knock intensity*

1. Introduction

The major initiatives are to reduce dependence of natural gas energy resources; Natural gas has been used during recent years, while, it is not always economical to be used due to the price of the energy. Thus, it is necessary to investigate the possibility of other unknown gaseous fuels. There are so many reasons for gaseous fuels to be replaced of liquid fossil fuels. They significantly produce much less pollutant emissions such as particulate matter (PM), Unburned hydrocarbon (HC) and Carbone monoxide (CO) [2, 7, 9, 10].

Rapid Compression Machine (RCM) is known as an experimental device to simulate a single compression stroke of ICEs. It can be used to study the auto-ignition of different mixtures under highly repeatable; well-characterized, and controlled conditions [1, 3].

Most RCMs are used to investigate auto-ignition of the liquid mixtures with different strategies, while the mixtures are always compressed; however, this RCM used a spark plug to ignite the gaseous mixtures. Here, in this study the in-cylinder temperature stabilization has been obtained by adjusting the heating elements set points and using heating cables.

The effects of different lambdas on the ignition delay time and peak pressure has been investigated to figure out the improvement of the RCM repeatability for various mixtures on methane-propane.

Furthermore, the influences of blending various proportions of propane into the methane on the mixtures resistance against knocking have been studied. The mixtures tested are pure methane, methane 90% propane 10%, methane 80% propane 20%, and methane 70% propane 30%. Moreover, the knock intensity of the pure methane has been obtained for light and heavy knockings.

2. Test setup and experimental setup

Figure 1 shows the RCM used in this study, which can emulate a compression and expansion stroke in a real engine. Fig. 2 shows the mixing bottle where the methane and propane with different volumetric proportions are mixed. A window was equipped at the right part of the combustion chamber to observe entire combustion occurring in the chamber. Detailed descriptions of the RCM can be found in most related publications [4-6, 8, 11].

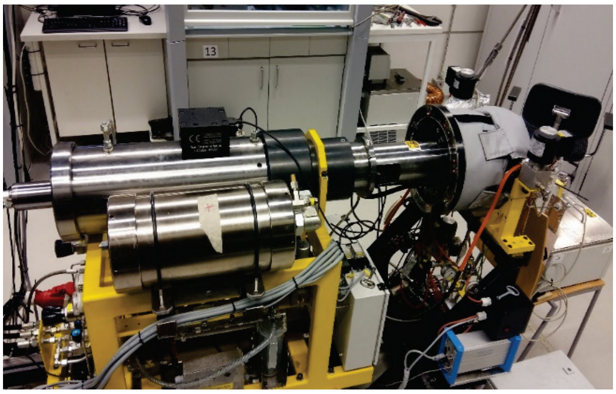

Fig. 1. RCM used in this study

Fig. 1. Mixing reactor of methane and propane fuels

Tab. 1. Specifications of the RCM

Bore	B = 84 mm
Stroke	S = 120-250 mm
Compression ratio Driving pressure	CR = 5-30 Up to 80 bar
Piston bowl	d_{bowl} = 42 mm bowl Depth = 4 mm
Cylinder pressure	p_{max} up to 250 bar
Cylinder head	Flexible, Pre-chamber, 1.5 cm3
Pressure detection	Piezoelectric transducer 0-300 bar
Heating system	Distributed heating system throughout the cylinder and cylinder head at 80ºC-120ºC
Ignition system	Spark plug, Pre-chamber
Fuel	Methane/Propane mixture

The following experimental process was adopted. Combustible mixtures of methane and propane with various compositions were prepared by the partial pressure of each component. Compressed air supplied from a bottle pushes the piston that is connected with a cam moved in a straight line, leading to compress the mixture. At an intended timing, the mixture was ignited by the spark plug placed on the cylinder head. Once the combustion was complete, the chamber was vented and then flushed with air and after that, the chamber before starting the test is vacuumed to cool down the system to the initial temperature of the experiment. Electrical heating elements and heating cables were placed circumferences of the cylinder to heat up the temperature of the chamber. The temperature of the chamber was controlled and monitored by a thermocouple. It is expected the temperature measurement not exceed more than ±2K. In-cylinder pressure was measured by a Kistler piezoelectric transducer. A laser displacement sensor was used to detect the piston position. Tab. 1 summarizes the specifications of the RCM used in during the tests.

3. Fuels and properties of mixtures:

Table 2 summarizes the specifications of the methane and propane proportions in the mixtures. First, pure methane was tested in the RCM and then the propane with 10%, 20% and 30% were blended in the 90%, 80% and 70% methane, respectively. The mixtures compositions are detailed as:

$$A.CH_4 + B.C_3H_8 + X.(O_2 + 3.76N_2).$$

Tab. 2. Specifications of the methane and propane mixtures tested in the RCM

Specifications	Base Methane (100%) Propane proportion mixture (%Vol.)			
Methane proportion (%Vol.) A	100	90	80	70
Propane proportion (%Vol.) B	0	10	20	30
$AFR_{Stoichiometric}$	9.52	10.95	12.33	13.7
Final fuel pressure (bar)	0.18	0.16	0.14	0.12
Final air-fuel pressure (bar)	2.28	2.24	2.2	2.18
X (number of moles of air per mole of fuel in mixtures)	2	2.3	2.6	2.9
LHV mixtures (MJ/m^3)	35.88	41.61	47.34	53.07
Fuel Temperature at mixing reactor	323 K			
Fuel temperature at chamber	354 K			

Where X denotes the number of moles of oxygen per mole of fuel in the mixtures individually and air is assumed consisting of $O_2 + 3.76N_2$.according to the testes done in the laboratory, the lambda was set to 1.2. the initial temperature was set 81°C. Tab. 2 indicates the portions of fuels and air individually.

4. Results and discussion

In-cylinder temperature of the RCM was investigated to figure out the stable temperature condition in the chamber during the tests as higher initial temperature can lead to higher knock intensity with respect to the same mixture. Heating elements were mounted through piston liner and piston bowl. Exterior surface of the cylinder was also supported by a heating trace cable, which it can be heated up to 80ºC (orange cable in Fig. 1). The wall heating elements and piston bowl elements were heated up to 110ºC, 75ºC, respectively. While the elements reached to the set points after one hour, the temperature of the chamber was not stabilized even after 3 hours as shown in Fig. 3. According to the temperature gradient rise, it can be clearly seen that the heating set points are too high for being stabilized. Therefore, the set points were re-defined and reduced to 93ºC and 80ºC, however, the RCM cylinder was pre-heated by trace cable during the mid-nights to achieve 60ºC shown in Fig. 4, since the interior heating elements are switched on, system can stabilize itself at 80ºC less than 2 hours (Fig. 5).

Pressure sensor equipped outside of the RCM controls the partial pressure of each component. So that, it was necessary to investigate the accuracy of filling the mixture in the chamber in pursuance of increase the reliability of the RCM performance. Peak pressure and ignition delay time for various proportions of the methane and propane mixtures were investigated. Fuel and air were fed as premixed and separate into the cylinder, with low and high flow rate.

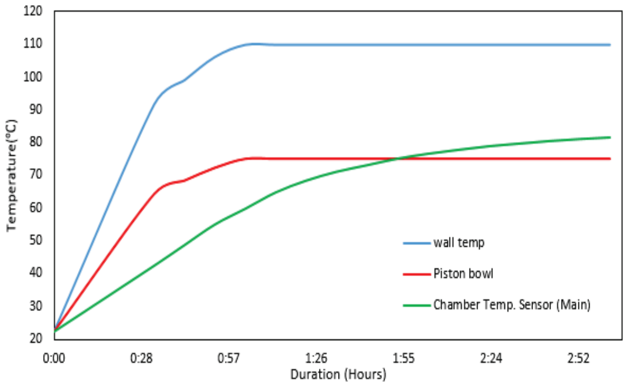

Fig. 3. Pre-heating system in RCM, setting points of 110℃ and 75℃, without Trace heating system

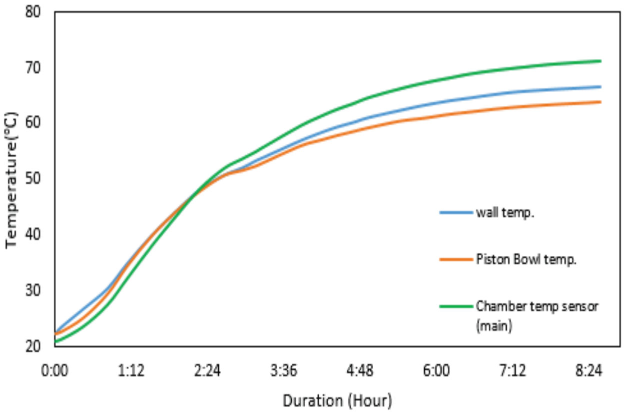

Fig. 4. Pre-heating system of RCM, Only with trace heating system

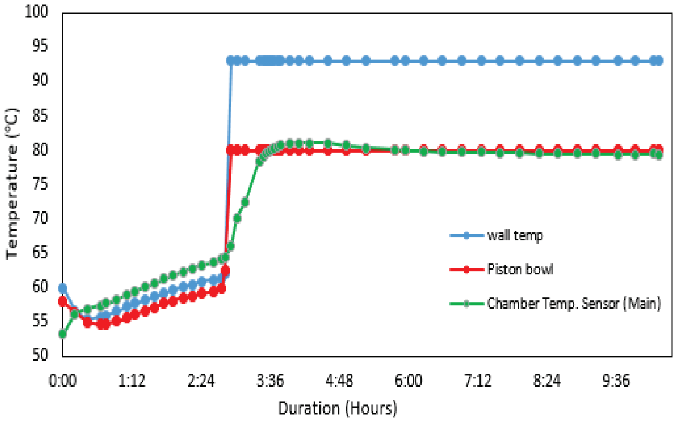

Fig. 2. Heating elements setting points of 93℃ and 80℃, with initial trace heating

Figure 6 shows the effects of low and high flow rate on the peak pressure of the mixture, since first fuel and air were pre-mixed in the mixing reactor and then they were fed separately in to the cylinder. According to the results released by RCM, low flow rate mixtures with premixed and non-pre-mixed strategies have higher inaccuracy. It found that it is not possible that the mixture is ignited since the lambda is too either lean or rich. On the other hand, repeatability of the peak pressure and ignition delay time significantly drops for normal flow rate, since the lambda exceeds either more than 1.5 or 0.67. Fig. 7 indicates the effects of the flow rate and lambda on the ignition delay time. It is obvious that the lambda between 0.9 and 1.26 has the lowest inaccuracy and consequently misfiring and in-complete combustion occur several times for both very lean and rich mixtures.

Tab. 3 Standard error and percentages errors of peak pressure and compression ratio for different methane-propane mixture

Fuel	Mean Pmax	Mean CR	Std Dev. Pmax	Std Dev. CR	Pmax Error %	CR Error %
Pure methane	142.2	24.6	0.86	0.32	0.6	1.3
90%Methane20%propane	113.9	19.7	0.58	0.38	0.5	1.9
80%Methane20%propane	104. 5	18. 5	0.5	0.20	0.5	1.1
70%Methane30%propane	98.9	17	1.03	0.25	1	1.5

Figure 8 displays the effects of blending higher propane proportions into the methane on the threshold operating condition. Peak pressure reduces since the propane content increases in the mixtures. Besides, the compression ratio of the mixtures reduces as driving pressure decreases. It displays that pure methane has the highest tolerance against knocking, so that peak pressure reaches 142 bar at threshold point. Since the mixture consists of 90% methane and 10% propane peak pressure and driving pressure drop to 114 bar and 21 bar, respectively. Peak pressure and driving pressure reduce to 104 bar and 20 bar since the propane in the mixture increase to 20%. Although the resistance of the mixture reduces as propane content increased in the ‘mixture, the influences of the higher propane contents in the mixture gets lower and lower. So that, peak pressure and driving pressure stood at around 100 bar and 19 bar, correspondingly at threshold operating conditions.

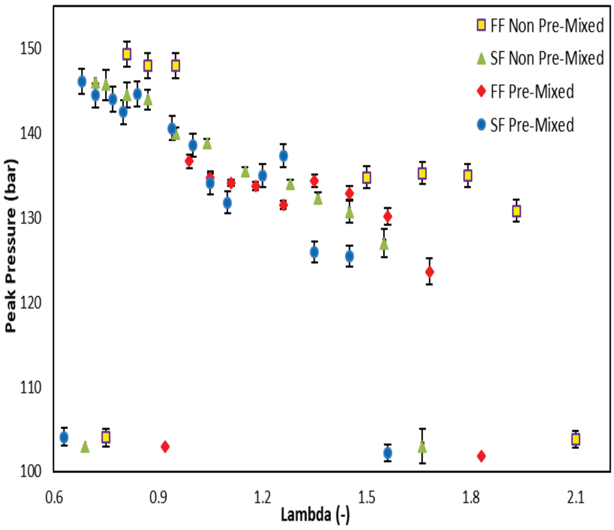

Fig. 6. Effects of flow-rate and lambda variations on peak pressure and ARR

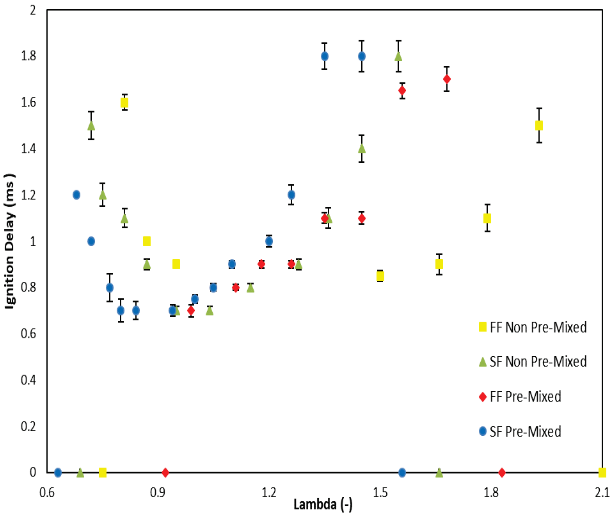

Fig. 3. Effects of flow-rate and lambda variations on ignition delay time and ARR

The repeatability of the threshold operating point for each mixture also has been studied; the peak pressure and compression ratio errors have been summarized in Tab. 3. According to the results, both peak pressure and compression ratio have very small variation in producing and repeating the results for the same test Tab. 3 reveals that pressure sensor can be more reliable in comparison with piston sensor, due to lower errors that it produces and in addition due to movement of the piston after each shot which it needs adjustment to the reference point.

5. Knock Intensity

In the RCM, knocking is strongly affected by changing driving pressure. The mixture is more prone since the driving pressure increases due to rising the temperature at the EOC process. Fig. 8 depicts the influence of increasing driving pressure, approaching to the threshold points. It shows that increasing the driving pressure leads to abnormal combustion, driving pressure in the RCM plays exactly the role that compression ratio has in the reciprocating engines (with crank-shaft and con-rod). Intensity of the knocking varies based on the driving pressure and EOC temperature, which it is caused by auto-ignition of the mixture before the main propagation flame reaches the unburned gas region. Fig. 9 shows the heavy and slight fluctuations in pressure caused by knocking, while higher amount of propane was blended into the methane.

Although these figures are plotted for a single experimental data point for each driving pressure, several tests were performed for each driving pressure and the qualitative repeatability and generality were confirmed, as described in Fig. 8.

6. Conclusion

The following conclusions obtained from this study, which are summarized as:

1. In-cylinder temperature should be stabilized to produce repeatable results. Temperature should be set for 93ºC with the installed heating equipment to reach stable 81ºC in temperature. It leads to repeatable and accurate results.
2. Ignition delay and peak pressure measured data for both very lean and very rich mixtures are not stable. Ignition delay time inaccuracy increases since either lambda exceeds leaner than 1.3 or richer than 0.7.
3. Effect of adding propane on methane in the mixture shows that it reduces the resistance of the mixture against knocking, however, higher proportions of propane blended into the methane has lower impact on the knocking phenomenon. It shows when the propane content reaches to 30%, the peak pressure dropped very slightly in comparison to the mixture with 10% propane content.
4. Knock intensity of the pure methane was obtained, since driving pressure increases from threshold operating point to light knocking and then to heavy knocking. It depicts that when the knock intensity exceeds 0.3 mbar, heavy knocking occurs and for lower than this fluctuation light knocking occurs.

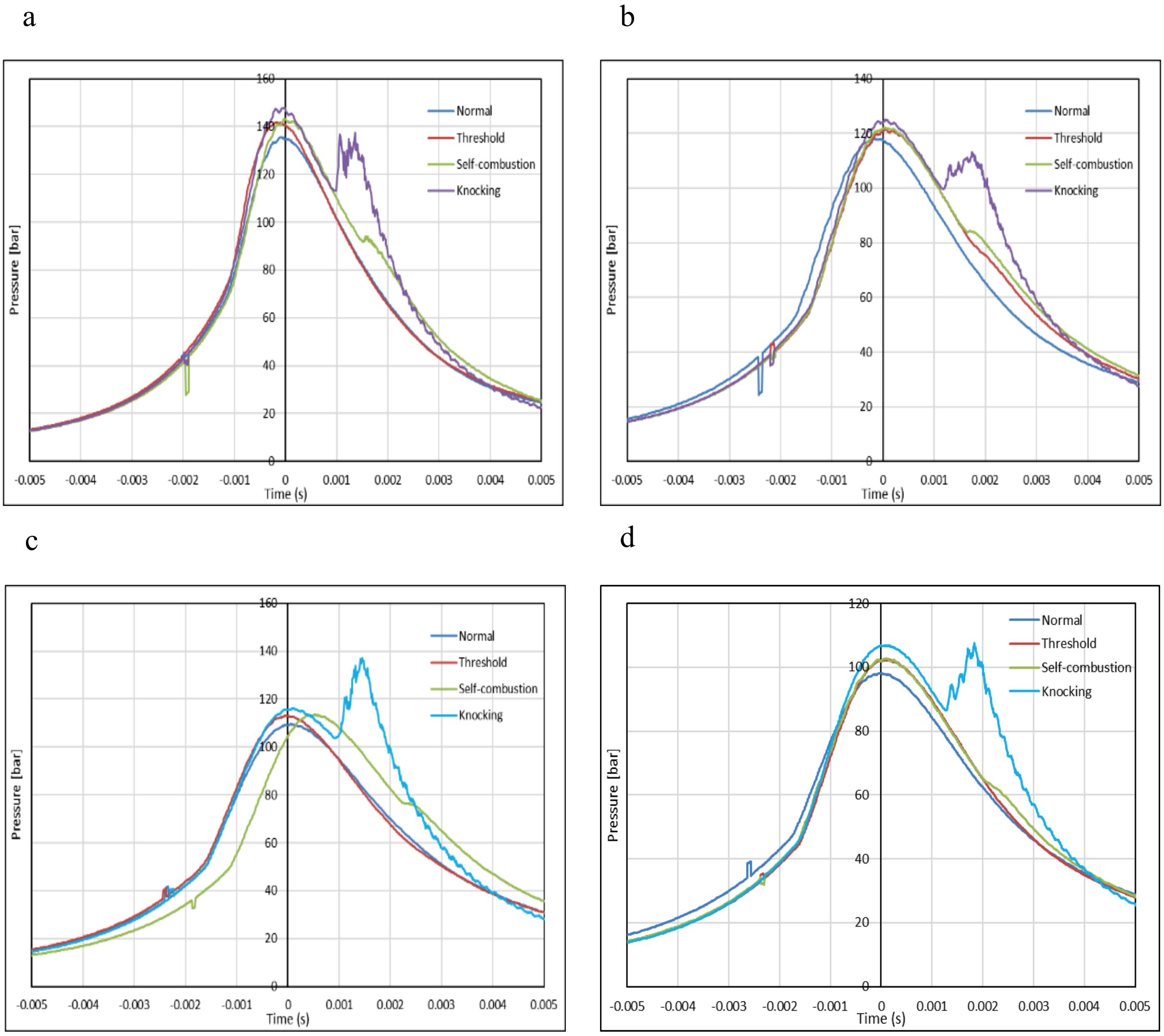

Fig. 4. Knocking threshold operating conditions of a)pure methane b) 90% methane 10% propane c) 80% methane 20% propane d) 70% methane 30% propane

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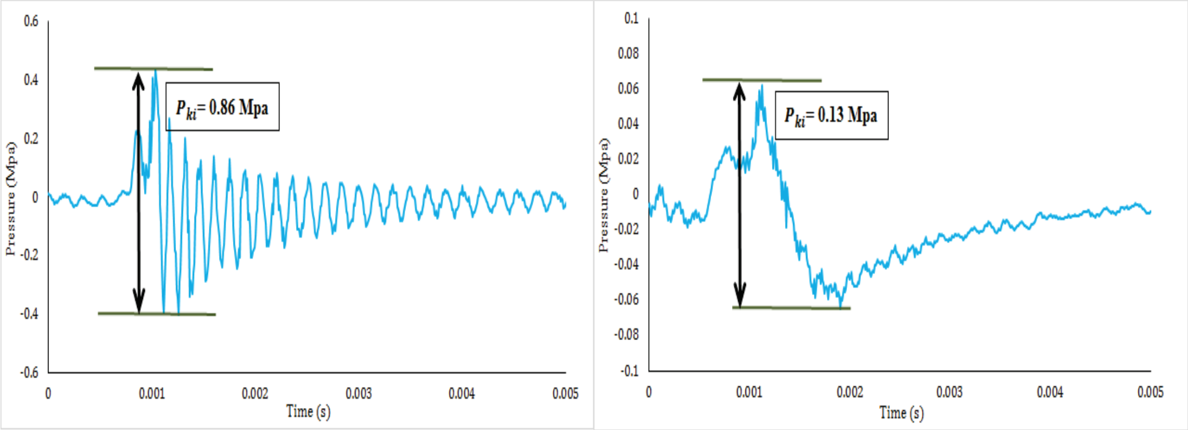

Fig. 5. Effect of driving pressure on the knocking intensity for mixture of methane and propane for heavy and light knockings

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