Lean Operating Limit of Spark Ignition Engine Fuelled with Different Homogeneous Mixtures

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Abstract
In order to check the possibility of efficient fuelling of SI engine with lean homogeneous mixtures the different modes of engine fuelling were tested. For experimental purposes gasoline-air mixtures and propane-butane-air mixtures were applied. The results of the work give engine performances vs. mixture strength and show some phenomena, such as burning rate or cycle to cycle variation for used fuels and modes of fuelling. As far as gasoline - air mixtures are concerned the non-conventional fuelling modes were proposed and tested.

1. Introduction
According to worldwide trend, many research centres focus on fuelling SI engine with homogeneous and heterogeneous lean mixtures [1]. Update GDI engines are fuelled with homogeneous mixtures only in the area of high load and speed. For part load stratified charge is used. Due to that, combustion systems are complicated and the inherent conflict of mixture formation and stratification occurs [2]. So, efforts which lead to improvement of combustion of lean homogeneous mixtures, especially during part load engine operation, are very important. Fuelling with lean gaseous mixtures offers a possibility of decreasing of NOx emission (as well as HC emission) and improvement of engine overall efficiency. General objective of this work is to investigate the combustion processes of lean mixtures for different modes of fuelling such as thermal activation of the fuel and/or charge turbulization. Also gas propane - butane as a fuel for lean engine operation was investigated.

2. Concepts of fuelling
Engine, originally fuelled with carburettor, was adapted to the four modes of fuelling (Fig. 1):
1. Fuelling with the fully evaporated gasoline which is provided to the inlet port with a thin pipe ahead of the inlet valve. In this case the mixture is chemically activated and turbulized by gasoline vapour jet. The gasoline was evaporated in the vaporizer heated by exhaust gases.

![Fig.1 Four modes of fuelling the engine](image-url)
2. Fuelling with fully evaporated gasoline provided in the same way as in the point No 1 but additionally turbulized by air jet. The air jet (about 10% of total air flow) is provided to the cylinder by additional thin pipe ahead the inlet valve. In this case charge is turbulized both by the vapour jet and by the air jet.

3. The gasoline is provided by conventional carburettor and additional air jet (as in the point No 2) is applied for turbulization of the charge.

4. The propane – butane – air mixture is created in the mixer, which is installed under Venturi nozzle.

For each type of fuelling modes main air flow was provided by carburettor Venturi nozzle. As a base for comparison the carburettor fuelling was used.

3. Experiments
3.1. Test stand
Experiments were carried out at the test stand shown in Fig.2. As an experimental engine the engine of Fiat CINQUECENTO 704 was used, of which only one cylinder worked, while the inlet port of the second cylinder was choked. The engine (1) was connected to the eddy-current dynamometer Vibrometer 3WB15 (2).

Air was supplied to the engine through the flowmeter (6A), surge-tank (4), pipe (3) and a carburettor (3). Liquid fuel was supplied to the carburettor (3) from the tank (9); fuel flow rate was measured with the use of the volumeter (11). In the case of fuelling with fuel vapour, the fuel was injected into the vaporiser (19) heated by exhaust gases and evaporated. The fuel vapour was supplied to the engine through the pipe (22) of which the outlet was placed above inlet valve. The vapour is under small constant pressure, so that it could enter the cylinder mainly during suction stroke (Fig.1). Directed air stream was created by injection of air through thin pipe with the use of small compressor (23).

As far as carburettor fuelling is concerned, changing of air-fuel ratio was carried out with the use of different fuel nozzles with different flow area. For propane – butane fuelling mode the regulation of mixture strength was done by changing of gas volume in the mixer. Emissions were measured as follows: NOx with Beckman analyser Model 951, (16), hydrocarbons with Beckman Model 402 CO, CO2 and O2.

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COV_{imel} = \frac{\sigma_{imel}}{imel} \cdot 100\%
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where \(\sigma\) is the standard deviation of imep in each individual cycle.
3. Description of Experiments
Experiments were carried out for constant speed of the engine, 3000 rpm. In order to compare results, especially pressure diagrams and burning rate diagrams the same ignition timing value (48 degree before TDC) was applied for all fuelling modes. All parameters were measured and/or computed with the use of measuring and data acquisition system based on the card of Kithley Co.
Measured quantities were as follows: Pressure in engine cylinder, torque, fuel consumption, air flow, exhaust gas components, including NO_x, CO, HC, and coefficient of air excess λ. Coefficient of air excess λ was measured directly with analyser and also computed from measured air flow and fuel flow rates (for the control purposes).

4. Results and Discussion
The comparison of results obtained for all proposed fuelling modes and carburettor looks as follows (Fig. 3 - 9).

Fig. 5: Burning rate vs C.A.

Fig. 6: Brake torque vs coefficient of air excess

Fig. 7: Volumetric efficiency vs. coefficient of air excess for five fuelling modes
4.1. Fuelling with evaporated fuel (mode No 1)
For this mode of fuelling the rate of pressure rise increase and the burning rate are the highest. It is especially interested because the volumetric efficiency was decreased by about 8% (for $\lambda = 1.24$) in comparison with carburettor fuelled engine (Fig. 7). It is very encouraging results, because it shows that there is a potential possibility of efficient fuelling of spark ignition engine with lean homogeneous mixture. As far as brake torque is concerned, it is lower up to $\lambda = 1.4$. The drop of its value reached max. 10 %. (Fig. 6). This drop of brake torque is caused by higher (about 25 °C) temperature of the mixture (in comparison with carburettor fuelling), which results in the decrease of volumetric efficiency. The amount of mixture in the engine cylinder is lower in each cycle. The second reason of the brake torque fall is non-optimized spark advance (48 deg. BTDC). It is interesting that the brake torque for $\lambda > 1.4$ becomes higher for this mode in comparison with conventional fuelling mode, although HC emission is higher.
The high mixture temperature is also the reason of higher NO$_x$ emission (Fig. 8).
Higher HC emission is partially caused by large valve overlap period in the research engine (33 degree). The outlet of fuel vapour is very close to the exhaust valve. So, fuel vapour is partly lost, more than for conventional engine (Fig. 9). It is the second reason of lower torque.

4.2 Fuelling with evaporated fuel and air fumigation by directed jet (mode No2)
Fumigation with additional air brought similar results as far as brake torque is concerned (there is slight improvement in comparison with fuelling mode No 1 Fig. 6). There was also observed the significant increase of brake torque in comparison with carburettor fuelling for $\lambda \geq 1.4$.
Hydrocarbons emission is higher in comparison with carburettor fuelled engine but lower than vapour fuelled engine (Fig. 9). Also the COV$_{\text{imp}}$ was higher for $\lambda \geq 1.25$ (Fig. 10). Emission of NO$_x$ was higher in the whole range of coefficient of air excess $\lambda$ (Fig. 8).

4.3 Fuelling with liquid gasoline and fumigation with directed air jet (mode No3)
Interesting results were obtained for slight modification of conventional fuelling by carburettor. While brake torque was almost on the same level, HC emission for $\lambda = 1.4$ was lowered almost twice, (Fig. 9), then in the case of carburettor fuelling. Emission of NO$_x$ was at the same level, but for $\lambda = 1.4$ it was about 40% lower, (Fig. 8). The COV$_{\text{imp}}$ was almost constant in the range of $\lambda = 0.95 \div 1.45$ (Fig. 10).

4.4. Fuelling with gas propane – butane (mode No 4)
Gas propane - butane seems to be very good fuel for fuelling the engine with lean mixtures. The burning rate is much more higher than for gasoline which is delivered to the engine in different modes. Also emission, especially CH one is better than for gasoline fuelling.

Conclusions
1. Fuelling with homogeneous mixtures is very encouraging, mainly due to that the torque may be changed not as so far by
amount of the mixture, but by its quality, i.e. F/A. As the result of that the work of charge exchange will be lower in the partly absence of throttling.

2. Fuelling with homogeneous mixture results in reasonable decrease of NOx up to 80%.

3. Thanks to the faster burning of thermally prepared air-gasoline mixture there is potential possibility (after application of sequence injection of the vapour and adjusting of spark angle) of efficient combustion of air-gasoline mixtures in a wide range of A/F.

4. In comparison with gasoline, fuelling with propane-butane extends operation range of the engine towards leaner mixtures thanks to relatively high combustion rate. Similar results were obtained in [5]. Of course, spark advance should be adjusted to obtain optimum engine performance. The spark advance for presented results was the same for all fuelling modes because of comparison purposes and was optimum only for fuelling with liquid gasoline mode.

5. The decrease of brake torque for relatively rich mixture caused by lower volumetric efficiency (gas or vapour confines the air volume, which can be supplied to the engine cylinder) changes as the mixture is leaner. For $\lambda = 1.35 - 1.4$ the brake torque is higher because of faster gas and vapour combustion.

To improve the effect of fuelling the engine with lean propane-butane mixture the injection of the gas is proposed [6].

Literature:


