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ANALYSIS OF EXHAUST GAS COMPOSITION OF INTERNAL COMBUSTION ENGINES USING LIQUEFIED PETROLEUM GAS

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Abstract. The problems of implementation of liquefied petroleum gas (LPG) supply systems are related with the fact that they are alternative systems used in engines constructed and optimized for work with other kinds of fuel. So assemblers of the systems have to evaluate power losses and at the same time ecological requirements. The experiment is devoted to the analysis of gas composition of engines working at different modes in order to specify the particularity of LPG system tuning and to obtain data for the evaluation of environmental pollution by numerical car dynamics models. It is estimated that the algorithms of current LPG systems balance between ecological requirements and optimization of external characteristics of engines, and the gas systems are characterized by a great inertia. Also, it is determined that more precise tuning algorithms must be constructed, and more tuning points and tuning, when an engine works in standard modes, must be foreseen.

Keywords: liquefied petroleum gas (LPG), exhaust gas, environmental pollution, external characteristic of internal combustion engine.

1. Introduction

Ecological environment and pollution is one of many problems solved in transport means production, which create the rice of ecological requirements. Now we have standard Euro IV [1]. The previous detailed investigations [2] demonstrate that regulation of fuel supply system is not simple according to exhaust emission parameters like CO, HC (hydrocarbons) and O_2, and the air-fuel ratio is not homologous to these parameters. The outer characteristics, power and torque, of internal combustion engines, are associated with ecological requirements by decreasing their border values, because we can't adjust the fuel supply system work by optimal characteristics when ecological requirements are following. Ecological requirements create especial difficulties when solving the problem of alternative fuels using in internal combustion engines. The analysis of environment pollution is very complicated, because many factors have an influence on exhaust emission contents.

Even the latest systems of fuel supply work by ecological requirements to adequate modes. Many investigations are made with gasoline supply systems [2, 3]. Modern catalyzing and gas recirculation EGR systems are used [4]. But when an engine works in maximal power and transitive modes, the ecological requirements are aside. Despite the fact that quite comprehensive investigations are performed and very versatile control systems are used [5], we must recognize, that internal combustion engines, which accord to ecological requirements, have worse outgoing characteristics. The LPG supply system evolution is of a low level in comparison with a gasoline one. All of LPG supply systems have typical power losses and specific thermo process [6].

There are some problems adjusting fuel supply system and engine control system to work properly when alternative fuels are used. The compensation of power losses without engine construction changes is one problem, and the second one is to correlate all systems with ecological requirements. But in LPG supply systems we must choose between power losses, ecological requirements and fuel consumption.

The applied side of LPG systems is associated with the fact they are alternative systems and are used in constructed and optimized engines to work with other kinds of fuel. So the assemblers of such systems have to evaluate power losses and ecological requirements. Obviously, the fuel rate increase is related with power losses. Ignoring the huge amount of adjustable parameters, the system is coordinated using two or three points in all band of modes finally, as the process for the engine to work with the LPG itself is not studied till the end.

This work is nominated for experiments with an internal combustion engine working in different modes, searching to specify the particularity of LPG system coordination. The obtained data are used for evaluation of environmental pollution, using the dynamics models of cars driving under different conditions, and performed to work with a classical fuel – gasoline or diesel.

2. Methodology

The main goal of the work is analysis of power losses and study of the ecological characteristics of motors working on LPG. Experiments are planned and test equipment is completed in order to perform the measurements of outer characteristics of an engine, and the composition of exhaust gases.

There are several methods to measure outer engine characteristics. The most usually used ones are two of them. The first method is the measurement of engine power and torque when an engine is mounted in a dynamometer stand. Producers of cars usually use this method. When characteristics are measured by another method, there is no need to demount the engine from a car. The driving wheels of a car are placed on schafts which make load when wheels rotate, in other words, spindles stopping wheels with power which is known. We chose the second method because to demount an engine is not necessary. The main problem in this case is a very expensive measurement equipment. We chose the stand "LPS 2000" of the firm "MAHA" for our experiments. This stand belongs to Vilnius Gediminas Technical University and is certified for research. The results can be given both in graphics and arithmetic values and saved in the computer memory.

To perform ecological measurements, i e for analysis of exhaust gases, the engine diagnostic stand "DASPAS 65" which belongs to Transport Engineering Department of Kaunas University of Technology was chosen for this experimental part. Mobile gas analyzer "DEGAS" is one of the parts of this stand. "DEGAS" can measure the following parameters: CO_2 (%), CO (%), O_2 (%) and HC (ppm) quantity in the exhaust gas, also the coefficient λ, which characterizes the ratio of air and fuel. The analyzer can give real data both in an arithmetic and graphic expression. The stand program equipment was modified in order to save the experimental results in the computer memory. At present a gas analyzer has opportunity to rewrite all the measured parameters in the memory by 1-second interval during the whole experiment.

Gas equipment of three generations was analyzed. The worst one is the gas equipment of the first generation. The main parameter characterizing it is a baffle. The baffle is mechanically controlled and limits discharge of gas effusion. The gas equipment of the second and third generations differs from the first one insomuch as it has controlled active limiting discharge of gas effusion baffle. The efficient control of a baffle can be managed in two ways: using the void which is created in the engine fuel mixture feeding system (the second-generation system) or using a microprocessor (the third-generation system). Electronic tuning obtains much more parameters, increasing signals of an oxygen sensor. Further we will use marking of the systems given in Table 1.

Table 1. Marking of systems

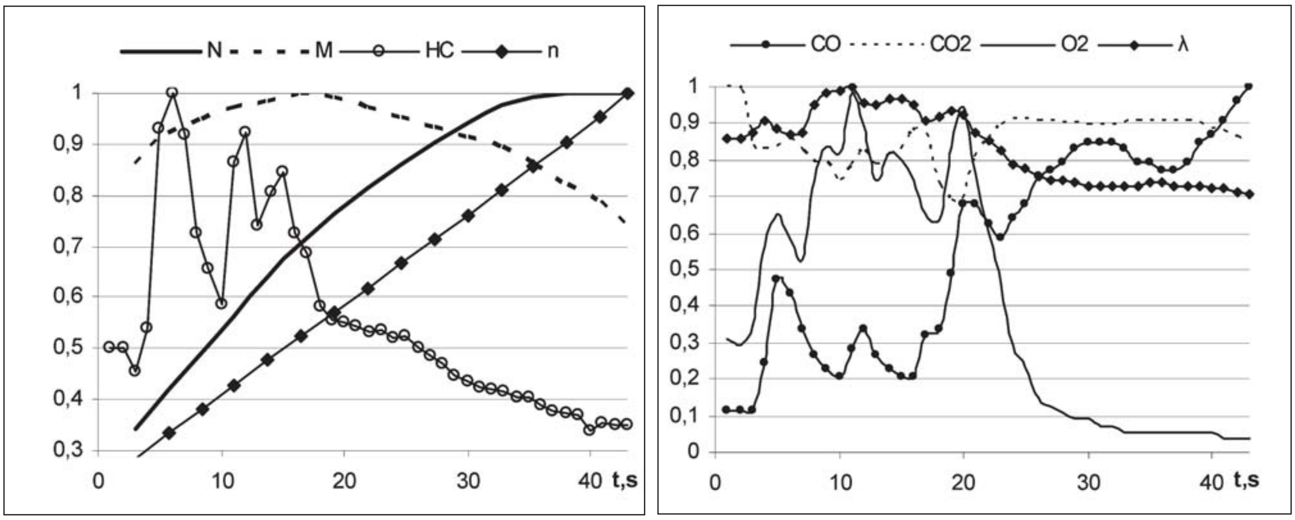
G	Engine works with gasoline
S1	Engine works with the 1st generation LPG equipment tuned up to max power
S2	Engine works with the 1st generation LPG equipment tuned up ecologically
S3	Engine works with the 2nd generation LPG equipment
S4	Engine works with the 3rd generation LPG equipment

We chose for experiments a popular car in Lithuania VW Passat, issued in 1991 year with 1,8 liter RP engine modification. The manufacturer's parameters of this car are: 66 kW near the 5400 rpm and 142 Nm near the 2600 rpm. In order to perform the experiment the first-generation gas equipment, after the second- and the third-generation gas equipment were mounted progressively during two-day period. All the gas equipment are certified in Lithuania and mounted at the Joint Stock Company "Propanas". This Company works on modification of cars with gasoline into cars using LPG. "Propanas" has all needed authorization for its activity. The gas equipment is made by the firm "BRC" (Italy).

The car was tested in a standard complement without gas equipment before the beginning of experiments. It was estimated that it matched the manufacturer's technical requirements. The engine was evaluated using data from the bases of technical engine characteristics in the diagnostic stands "DASPAS 65" and "Autodata CD-2 2004". The obtained data were used for comparison and evaluation of the work of the engine with LPG.

In this work environmental pollution was analyzed in greater detail. For this purpose acceleration, drive switchover and braking modes were separated. The stands were related and linked by a personal computer because the experimental data of power and torque moment were presented by the stand "LPS 2000", and exhaust gas composition was analyzed by the gas analyzer "DEGAS".

As the catalyst is in the car, a special stand connection to the catalyst was made for the measurement of exhaust gas composition. In this way we tried to measure real engine pollutants avoiding additional errors. The engine power N (kW), torque M (Nm), engine speed n (rpm), CO (%), HC (ppm), CO_2 (%), O_2 (%), time of experiment t (s) were fixed during all the experiments. The data fixed in the acceleration mode of the car driving with gasoline is given in Fig 1.



a b

Fig 1. Data fixed in acceleration mode

Testing was performed according to the following methodology:

1. Acceleration mode
1.1 The car is started up;
1.2 Working oil temperature increases;
1.3 The clutch is turned off, and the fourth gear is turned on;
1.4 The clutch is turned on little by little and together with the fourth gear is accelerated till maximum, the data begin to be fixed;
1.5 The clutch is sharply turned off when the maximal engine revolution is reached, and together the accelerator is released;
1.6 When the wheels stop rotating, the data stop to be fixed, the gear and the engine are turned off.
2. Braking mode
2.1–2.2 are analogous to 1.1–1.2;
2.3 The constant load of stand to the wheels is determined;
2.4 The clutch is turned off and the fourth gear is turned on;
2.5 The clutch is turned on little by little and together with the fourth gear is accelerated till maximum;
2.6 The clutch is sharply turned off when the maximal engine revolution is reached, and together the accelerator pedal is released, the data begin to be fixed;
2.7 When the wheels stop rotating, the data stop to be fixed, the gear and the engine are turned off.
3. Mode of different loads
3.1–3.2 are analogous to 1.1–1.2;
3.3 The clutch is turned off and the gear is turned on (first, second or three);
3.4 The clutch is turned on, and a set speed of wheels is reached;
3.5 The load of a stand is determined;
3.6 The mode is maintained till the data settle;
3.7 The data are fixed;
3.8 The experiment is completed.

3. Pollution at the acceleration mode

The first experiments with LPG have already confirmed that all the parameters of an internal combustion engine change. The obtained power changes are analogous to the results published in the publication “Transport Means 2003” [7].

Environmental pollution analyses are rather complicated, as the data given by other authors [8] is related with λ coefficient which describes the air-fuel ratio. It appeared that fuel supply control systems do not maintain a constant coefficient λ, when power changes. The values of the coefficient are obtained comparing an ideal ratio with the present ratio during the measurement. The coefficient λ is equal to 1, when the air-fuel ratio is ideal and equal to 14,7 (using gasoline in the car). The closest to an ideal case is a gasoline fuel supply system, working according to a classical principle – λ increases in a small-power band, when the rotations of an engine are small and approache $\lambda = 1$ (Fig 2a, curve G) working in an average-power band. LPG supply systems do not keep stable λ, their variations are considerable, when the power changes (Fig 2a, curves S1-S4). The standard tuning procedure is especially inaccurate, it is system S1. S3 tuning system is obviously imperfect, that’s why λ is increased a lot in a small-power band and decreased in a big-power band. Electric tuning system S4 is more stable and the closest to a gasoline system. But its inertia is bigger due to the particularity of fuel amount tuning system.

In our work modeling possibilities of engine work with LPG are the most interesting because when the program equipment was modified, environmental pollution was evaluated as a ratio between exhaust gas dependence on the engine power. The obtained experimental data are given in Figs 2, 3.

The measurements of CO_2 show that the quantity of this compound in the exhaust gas of gasoline systems slightly depends on the load and varies in the result spread margins (Fig 2b, G). Practically all LPG supply systems, separate smaller amounts of CO_2 in exhaust gas. When a system is regularized ecologically, the amount of CO_2 in LPG systems approaches the amount of CO_2 in gasoline systems working at the same power. This confirms the problems, when we speak about the environmental pollution reduction, when not a whole complex system is studied, but separate amounts of components are regulated.

The experiments have proved that separate algorithms are necessary for the regulation of CO and HC amounts. The control algorithms used by manufacturers are intended for greater regulation of CO amounts. A gasoline fuel supply system is the most perfect from this point of view. As we see from the character of the curves, all the systems are characterized by inertia, i e jump when the accelerator valve is sharply turned on, and the process does not settle for a longer time. So inertness of a system would be one of evaluation criteria. LPG, except S4, shows the main regulation problem, i e the systems are tuned and tested when an engine works without load, meanwhile the work modes and the load noticeably differ (Fig 3a). Ecological regulation helps to reduce the exhaust CO amount, when an engine works in an average-power mode (Fig 3a, S1, S2). The acceleration mode of a system with vacuum regulation is insufficient due to a big inertia from the point of view of environmental pollution.

Studying LPG systems according to the HC criterion, we have to acknowledge that pollution is lower comparing with a gasoline system when an engine works in a big-power mode, but the amount of HC increases in small-

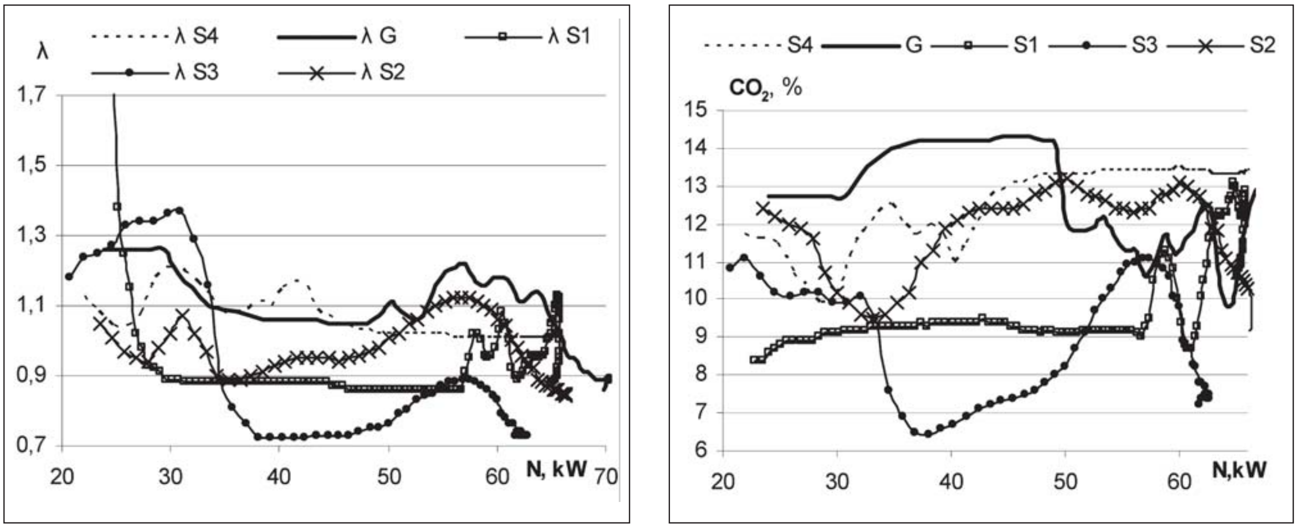


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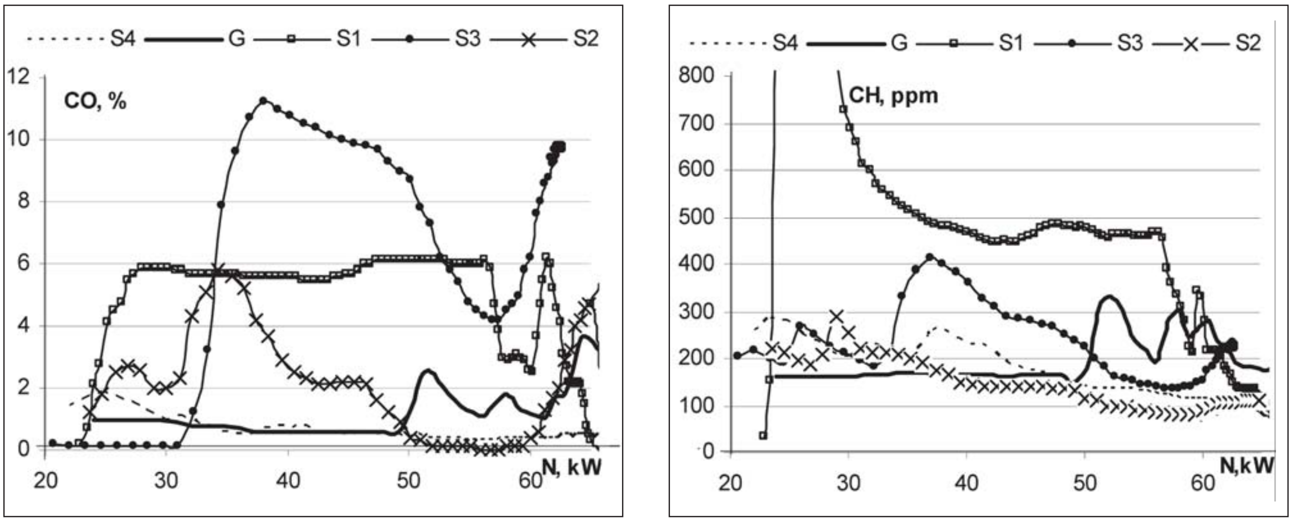
Fig 2. Coefficient λ (a) and CO_2 (b) for driving with different-generation systems and gasoline



a b

Fig 3. CO (a) and HC (b) for driving with different-generation systems and gasoline power modes, what is associated with the inertia of systems, especially S3 (Fig 3b). Pay attention to the dependence of HC in system S1, this dependence at small power band couldn't be fully reflected even when its max value reaches 3485 ppm.

The investigation results show that manufacturers use different tuning algorithms. The most perfect fuel systems are a compromise – ecological requirements are met up to a certain power value, and pollution is regulated, but when a certain mode is reached, a system tries to maintain the mechanical characteristics, i e to maintain power and torque (Fig 3a; b, G). LPG systems having ecological tuning maintain ecological requirements in the whole mode range, but their outer characteristics are worse by 2–3 %.

4. Environmental pollution at different loads

At this time the equipment was tuned up in such a way that an operator could get data about the position of the engine valve. The stand was matched in order to maintain a constant value of loads on the wheels, and environmental pollution was measured under such conditions. As we observed the inertia of systems in the acceleration mode, we performed a set of trials when the engine worked in a steady mode but a different power acted upon it. Gasoline and S2 systems were compared. The characteristics of environmental pollution were approximated by the first- and second-degree rate equations:

$$HC = a_{0H} + a_{1H}N, \qquad (1)$$

$$CO = a_{0c} + a_{1c}N + a_{2c}N^2, \qquad (2)$$

where N – engine power, kW.

The parameters of the equations are given in Table 2. The obtained characteristics are not absolute, as they are determined at a maximal power.

We experimented additionally on changes in environmental pollution, when the load and the position of the throttle changes. We were faced with the problem of comparison of results, because there are two variables when evaluating the engine power – engine speed and power. As the outer characteristics of an internal combustion engine are not linear, the power of the same value can be obtained by a different speed in a particular band of characteristics. We determined additionally the importance of speed for the engine's work without load. The obtained results are given in Table 3.

It is confirmed that the engine's speed does not have an essential influence on the exhaust gas composition when the load is not big. The correlation analyses validates that the amount of CO increases and that of HC decreases when the rotations increase. The most stable values are when the mechanical characteristics in the system are corrected, but this is obtained to the account of ecology.

Table 2. Values of equations

	a_{0c}	a_{1c}	a_{2c}	a_{0H}	a_{1H}
G	7,2199	–0,3404	0,0430	200,26	–0,3927
S1	–10,208	0,0775	–0,009	1840,9	–27,163
S3	–18,948	1,0512	–0,010	322,39	–1,9608
S2	15,6900	–0,0629	0,0069	290,75	–3,0704
S4	4,1241	–0,1359	0,0120	382,31	–4,5482

Table 3. Values of CO, HC and errors

	rpm	850	2000	3000	4000	5000
G	HC	448,8	425,8	262	202,4	171,8
	σ_{HC}	32,9	35,5	13,2	6,5	2,6
	CO	0,43	0,61	0,64	0,62	0,61
	σ_{CO}	0,06	0,02	0,01	0,01	0,01
S4	HC	458,8	419,8	254,2	175,2	158,6
	σ_{HC}	14,4	34,6	13,8	5,4	2,7
	CO	0,44	0,41	0,45	0,42	0,41
	σ_{CO}	0,11	0,01	0,03	0,01	0,01
S3	HC	382	85	60,8	204	286,8
	σ_{HC}	21,6	18,5	5	6,8	20,2
	CO	0,6	0,2	0,19	0,8	3,97
	σ_{CO}	0,08	0,01	0,01	0,05	0,12
S2	HC	558,8	513	362	400,2	429,4
	σ_{HC}	9,3	28,4	30,4	7,8	23,4
	CO	0,59	0,64	1,18	3,71	4,78
	σ_{CO}	0,14	0,16	0,15	0,21	0,29

5. The braking mode

Transitional modes cause the biggest part of problems arising when investigating environmental pollution, especially in evaluating inertia of fuel systems. For this purpose we study separately the braking mode, i e pollution from an internal combustion engine when the throttle is sharply closed. The obtained data are presented in the form of curves in Figs 4, 5. At a given mode increase of pollution is noticed in all the systems.

The more ecological systems, the more complex processes go on at the braking mode. In a gasoline system

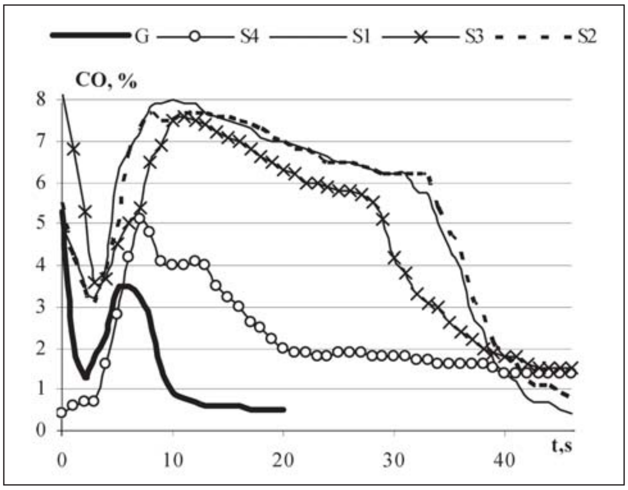


Fig 4. CO concentration for driving with different LPG systems and gasoline

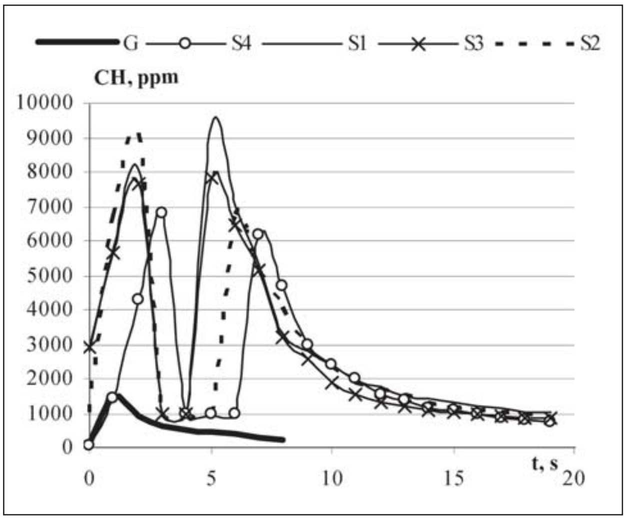


Fig 5. HC concentration for driving with different LPG systems and gasoline

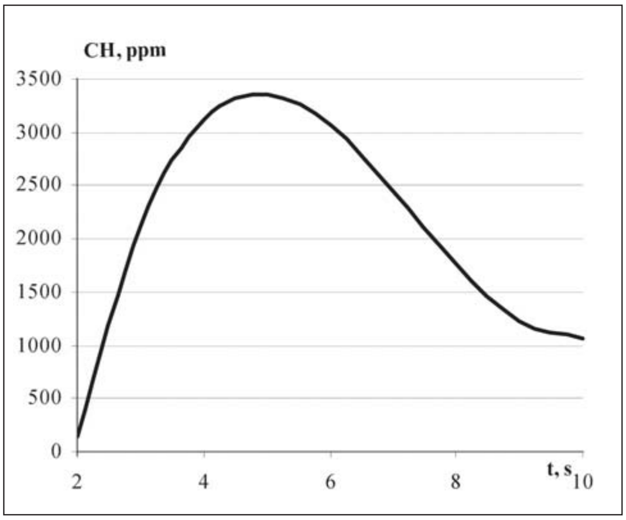


Fig 6. Integral HC conformation of S1 system

Table 4. Values of ΣCO and ΣHC

	Σ CO	Σ HC
G	21,1	5120
S1	133,2	33998
S2	125,8	33720
S3	131,3	26640
S4	59,7	30420

Table 5. Maximal values of CO and HC

	CO, %	HC, ppm
G	3,5	1478
S1	8	9395
S2	7,7	9092
S3	7,6	7839
S4	5,1	6776

they settle only during 10 seconds, in a gas system this process takes place noticeably longer – for 20–40 seconds. The bigger part of fuel-feeding systems stop fuel feed when the rotations are sharply reduced from maximal up to slightly bigger than idle motion rotations, at the same time the fuel supply is renewed. In this way the braking mode is shortened. Failing this system the braking mode is considerably longer. Decrease of pollution in these systems is associated with a stop of gas feeding, but a system has also to assure the engine's work at an idle motion. The measures do not stop the engine from causing additional increase of pollution, especially in the gas supply systems. From this point of view gasoline systems are more perfect. We evaluated the amount of pollutants till the end of the mode, i e till a stable idle motion mode. The results obtained measuring stabilization modes in relative units are given in Table 4.

6. The drive switchover mode

The drive switchover mode is not modeled on the stand. A calculation scheme is constructed with an assumption that normally the switchover process continues up to 1 second. As we see, the speed of an engine falls insignificantly during such time period. Gasoline feeding systems also break the fuel supply during this time period. A part of the acceleration process was modeled according to the methodology given in the paper „Transport" [9], where the opening angles of the throttle are different. The LPG system of the 1st generation is an exception; it is adjusted according to an optimal power. This system is famous for the peak of a sharp exhaust of pollutants, and this part is analyzed separately, i e when the process goes on during the drive switchover. The dependence is shown in Fig 6.

We decided to evaluate the quantity of pollutants by an integral function when all the data were analyzed. The obtained quantity of pollutants in such a way was used for further record. As we have assumed the mode lasts 1 second, when switching drives normally, we evaluated the maximal quantity of pollutants released during 1 second, when the maximal power mode passes to the braking mode. Maximal quantities of CO and HC are shown in Table 5, when an engine works with gasoline and different LPG systems.

7. Conclusions

Having the results of modeling, the following was concluded:

1. The performed experiments allow to forecast environmental pollution which is due to cars driving with LPG, when their engines work in different modes. It is possible to foresee more precisely the quantities of regulated exhaust products in standard situations of car traffic (on streets, roads, crossroads). This is done by connecting the data with computer programs of car dynamics.

2. The algorithms of current LPG systems balance between ecological requirements and optimization of external characteristics of an engine.

3. All LPG supply systems are characterized by a great inertia. Gas systems have an especially great inertia. The more parameters evaluate a control system, the more problems with inertia. A steady time of some gas systems reaches 10 seconds.

4. The investigation shows that more precise tuning algorithms must be created, more points of tuning must be foreseen, conditions, where mechanical characteristics have to be ensured at the expense of ecology, must be defined more strictly.

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VIDAUS DEGIMO VARIKLIO, VAROMO SUSKYSTINTOSIOMIS DUJOMIS, IŠMETAMŲJŲ DUJŲ SUDĖTIES TYRIMAS

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Santrauka

Naudojant suskystintųjų dujų sistemas automobiliuose, pritaikytuose veikti benzinu, susiduriama su įvairiomis, aplinkos taršos problemomis. Todėl sistemų montuotojai turi įvertinti ne tik galios nuostolius, bet ir kaip tos sistemos atitinka ekologinius reikalavimus. Eksperimentuojant siekta ištirti variklio, veikiančio įvairiais režimais, išmetamųjų dujų sudėtį, nustatyti tokios sistemos derinimo ypatumus ir gauti ekologinės taršos vertinimo duomenis analizuojant automobilio skaitmeninius dinaminius modelius. Nustatyta, kad būtina sudaryti tikslesnius suskystintųjų dujų sistemų reguliavimo algoritmus, numatyti daugiau derinimo taškų ir derinti variklį apkrovus, jam veikiant tipiniais režimais.

Prasminiai žodžiai: išorinė vidaus degimo variklio charakteristika, suskystintosios dujos, aplinkos tarša, išmetamosios dujos.

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