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Control of spark ignition IC engines operating on alternative fuel mixtures

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Abstract: Authors consider propane widely spread in Russian Federation for low cost and for reducing emissions of harmful substances in exhaust gases. To deal with its main limitations: reduction in engine power and torque when used in gas phase, it is proposed to add portions of gasoline to propane. As parameters of this mixture differs from gasoline or propane alone, paper presents control method that includes IC engine process model, algorithms to set control parameters (ignition and fuel systems) and approach to decrease knock occurrence probability. In-cylinder pressure peak position is used as a criterion of optimality for ignition timing calculation, and algorithm of propane/gasoline ratio variation allows keeping optimal spark advance as long as possible and preventing knock. The control method proposed is confirmed by test runs on MAHA LPS 3000 dyno stand. Experiments showed increase of engine power and torque. Knock, emissions and fuel cost were decreased.

Keywords: Modeling, supervision, control and diagnosis of automotive systems; Engine modeling and control; Automotive system identification and modeling.

1. INTRODUCTION

Due to rising oil prices accompanied by diminishing oil reserves, alternative fuels for car engines should be actively sought. Certain fuels (e.g. natural and associated gases, as well as various alcohols) have already found widespread use (Bechtold 2002, Morey 2011). This helps improve ecological and/or economic performance of existing internal combustion engine (ICE) design types, though resulting in deterioration of certain other indices (depending on the alternative fuel used) as compared to the use of traditional fuels. In order to eliminate such drawbacks, a number of leading producers and research institutes (among them: Bosch, Daimler, VAG, Delphi and many others) have been working hard to develop dual-fuel systems, which make use of two types of fuel at a time (as against single-fuel engines): two fuels are supplied to cylinders and combusted there simultaneously. Various fuel combinations are currently being studied, the most promising of which are diesel+gasoline, diesel+gaseous fuel and gasoline+gaseous fuel. In the Russian Federation, the mixture of gasoline and liquefied petroleum gas (LPG or propane) (binary fuel) has provided results in reducing the content of harmful substances in exhaust gases and increasing the service life of ICE components. The above research-and-development activities are supported by governmental bodies in different countries, and in the near future the development and manufacture of vehicles with dual-fuel systems is anticipated.

Since operating process control is important for ensuring high performance of modern automobile internal combustion engines, the most pertinent and valuable research is that pertaining to the controlling engines operating on various fuel mixtures. In case of dual-fuel engines (and engines making use of binary fuel, as well) control must be performed, among other things, with due regard to the supply balance between the two fuels. That is why it is of high importance to work out ICE control techniques, methods and algorithms which take this into account.

The work objective is to develop control methods for spark ignition ICEs that will improve their energy and economic performance when fueled by a mixture of propane and gasoline.

2. DETERMINING CONTROL ACTIONS

The object of control under study is the process of composite fuel combustion inside engine cylinders. This process may be controlled through a variation of the ignition angle and fuel supply, the latter including variation both of the air-fuel ratio and the ratio of fuel mixture components.

The control method suggested involves maintaining maximum pressure inside a cylinder within a specific RMP range, thus ensuring maximum performance. To this end, (see Fig. 1), the optimum ignition advance angle (IAA) is calculated based on input parameters and a specific model.

The input parameters include the following control unit sensor and calibration readings: m_{air} – mass of the air that has entered a cylinder, T_{air} – temperature of the air that has entered a cylinder; rpm – crankshaft revolutions; δ_{open} – rate of throttle opening; L – gasoline-propane ratio characteristic of a fuel; λ – equivalence ratio. Output (control) parameters: IA_{opt} – optimum ignition advance angle and tp_{open}, tg_{open} – propane and gasoline injectors opening time required for establishing the optimum ignition advance angle (IAA).

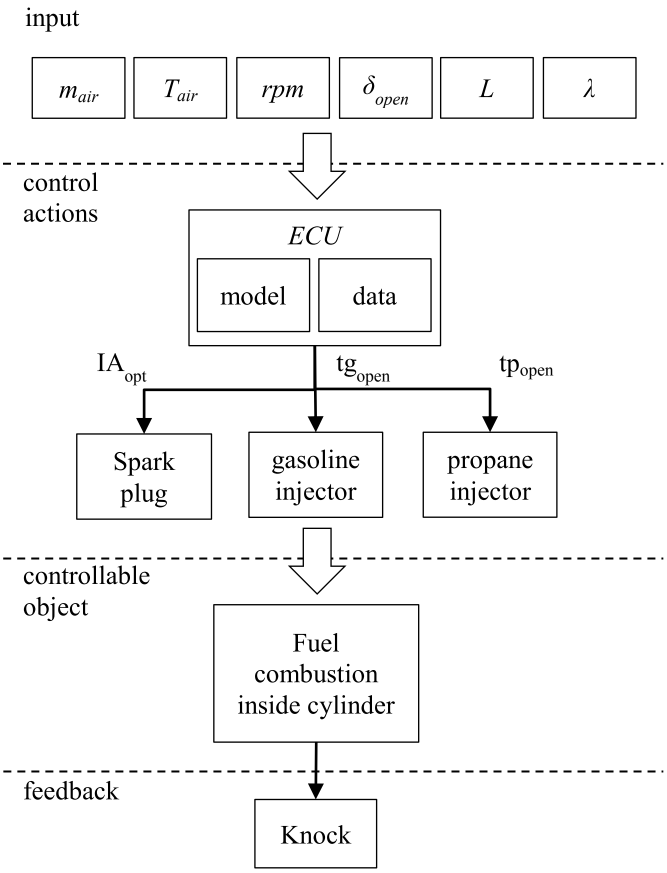

Fig. 1. Control chart.

After the angle is calculated, the electronic control unit (ECU) determines the propane and gasoline injector opening time needed for this angle. According to the results obtained from the IAA, the knock sensor readings are checked, and in case knock occurs, a two-level scheme of knock elimination is applied. The first step to improve the fuel knock rating is to top up the gasoline with propane. With that, the IAA remains optimum. If this is not enough, the IAA is adjusted.

3. MATHEMATICAL MODEL

Nowadays, the use of mathematical models has tended to supersede selection of pre-determined control parameters thanks to the observed improvement in the computing power of control units. As regards ICE control, the key task is to ensure the accuracy of calculations over a specific (relatively short) period of time.

Upon review of the works currently available, no method of released heat calculation for gasoline-propane mixtures has been found; for this reason a decision has been made to base calculations on the method, which is the closest to the required one (upon its modification). One of the most widely spread methods used today is method of heat calculation proposed by Wiebe (1962). Its main equation (1) applies to both gasoline and propane engines and was used as a basis.

$$\Delta x = e^{-6,908\times\left(\frac{\varphi_n}{\varphi_z}\right)^{m+1}} - e^{-6,908\times\left(\frac{\varphi_{n-1}}{\varphi_z}\right)^{m+1}}, \qquad (1)$$

where: φ_n, φ_{n-1} – limits of the range under consideration in degrees of crankshaft rotation; φ_z – fuel combustion duration in degrees of crankshaft rotation (CR); m – combustion character indicator.

According to Kuzmin (2008), it may be assumed that the combustion character indicator m does not depend on the type of fuel used and is determined by the following (2):

$$m = m_0 - 0,1(IA - IA_0), \qquad (2)$$

where: m_0 – combustion indicator, which corresponds to initial conditions and is obtained in the reference mode of ICE operation under 2000 rpm, ignition angle IA_0=25 °CR, and an equivalence ratio of 0,96.

The combustion duration is calculated by (3), which has been verified and proved by the studies of Fedyanova (1992).

$$\varphi_z = \varphi_{z0} + 0,25(IA - IA_0)^{1+0,52\frac{rpm}{rpm_0}}, \qquad (3)$$

where 0-index parameters correspond to the values obtained in the reference mode of operation.

The value of φ_{z0} varies for different gasoline-propane ratios of the binary fuel and will be adjusted according to experimental results.

After the heat release method and input/output data were determined, a calculation procedure was developed that included the following stages: the working medium condition indicators were calculated (during intake) with allowance for the binary fuel composition, engine and environmental parameters; the values obtained at intake valve closing were used as initial ones for the compression stage calculations; the combustion pressure and the working medium temperature inside the cylinder were calculated based on the compression data and the IAA; after the combustion stage calculations were performed, the pressure and temperature inside the cylinder were calculated for the expansion stroke.

Finally, the indicator diagram obtained was used to determine values of specific work, power, torque and other output parameters.

To take the effect of the propane temperature on the temperature of the air entering an ICE into account, T_0 is calculated according to the equation determining the intake stroke final temperature (4).

$$T_a = \frac{T_0 + \Delta T + \gamma T_r}{1+\gamma} = \left[\frac{\mu_{pb}C_{pb}t_{pb}^0 + \mu_v C_v t_v^0}{\mu_{pb}C_{pb} + \mu_v C_v} + \Delta T + \gamma T_r\right]\frac{1}{1+\gamma}, \qquad (4)$$

where: μ_{pb}, C_{pb}, t_{pb}^0 – molar mass, heat capacity and temperature of the propane; μ_v, C_v, t_v^0 – molar mass, heat capacity and temperature of the air.

The working medium pressure from intake valve closing until exhaust valve opening is determined in different ways for the stages of compression, combustion and expansion (see (5) below).

$$\begin{cases} p(\varphi) = p_a \left(\dfrac{V_a}{V(\varphi)}\right)^{n_1}, a < \varphi \leq y \\ p_n = \dfrac{2 \times q_{zbs} \times \Delta x + p_{n-1} \times (K\, v_{n-1} - v_n)}{K\, v_n - v_{n-1}}, \\ \qquad\qquad\qquad\qquad y < \varphi \leq z \\ p(\varphi) = p_z \left(\dfrac{\psi(\varphi)}{\psi_b}\right)^{n_2}, z < \varphi \leq b \end{cases} \quad (5)$$

where: φ – crankshaft rotation angle; a – intake valve closing angle; y – ignition angle; z – end of combustion angle; b – bottom dead point; n_1 –polytropic exponent of compression; V_a – working medium volume at a point; V – working medium volume at crankshaft rotation angle of φ, for which the pressure is determined; q_{zbs} – total specific heat of binary fuel combustion; Δx – portion of binary fuel that combusts during a period of crankshaft rotation from φ_{n-1} to φ_n; K – heat capacity factor; v_n – variable volume of the working medium at binary fuel burn-out; n_2 – polytropic exponent of expansion; $\psi(\varphi)$ – kinematic function of cylinder volume changing.

When determining the cylinder pressure during fuel combustion, bear in mind that heat values of gasoline and propane are different. For that purpose it has been suggested that the total specific heat of binary fuel mixture combustion be calculated as a sum of total specific heat values of the fuel components in proportion to their percentage in the binary fuel:

$$\begin{aligned} q_{zbs} &= L_b q_{zb} + L_{pb} q_{zpb} \\ &= \frac{g\xi}{(1+\gamma)}\left[L_b \times \frac{H_{smb}}{1 + \alpha_{vt}\lambda_{vb}} + L_{pb} \times \frac{H_{smpb}}{1 + \alpha_{vt}\lambda_{vpb}}\right], \end{aligned} \quad (6)$$

where: L_b – share of gasoline in the binary fuel; L_{pb} – share of propane in the binary fuel; ξ – combustion efficiency ratio; λ_{vb}, λ_{vpb} – air-gasoline and air-propane ratios; H_{smb}, H_{smpb} – volumetric heat capacities of gasoline and propane, correspondingly.

After all calculations are performed for the main stages, indicators and efficient indices are determined: cycle work, indicated pressure, efficiency and ICE torque.

4. IGNITION ADVANCE ANGLE CONTROL AND KNOCK ELIMINATION

An algorithm (Beresnev et. al. 2011) and a program (Beresnev & Beresnev 2010) have been developed to determine the IAA that will ensure peak pressure within a specific range. According to measurement results, the run time of the program on 1GHz processor varies from 1,1×10-4 to 1,25×10-4 s. When a modern 200MHz ECU is used, the run time does not exceed 5×10-4 s, and the time available for calculation at 6000 rpm amounts to ≈ 2×10-3 s. Consequently, the program developed may be executed in real-time mode.

Since often it is impossible to ensure optimum IAA due to knock, which results in a significant deterioration in engine performance, it is suggested that potential knock be avoided and prevented through the use of a predictive two-level scheme shown in Figure 2:

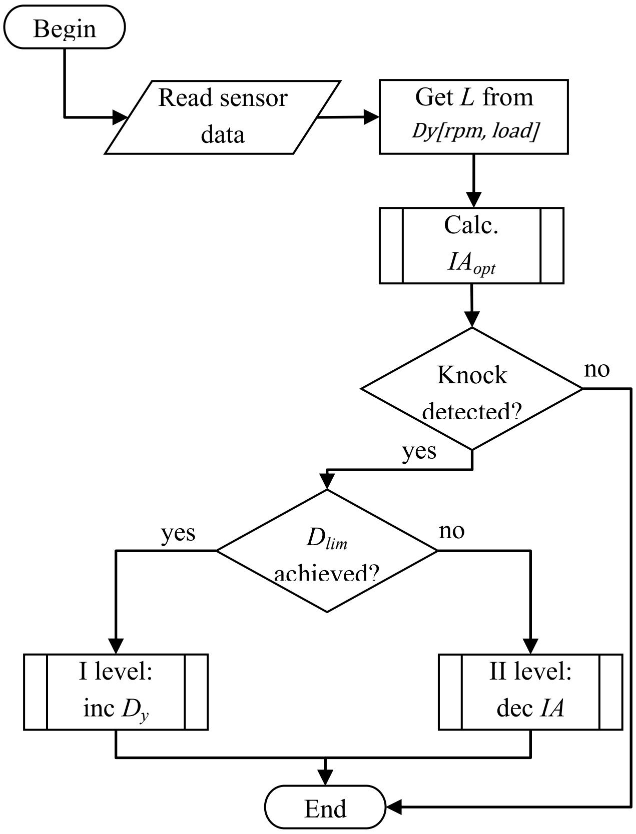

Fig. 2. Procedure for preventing knock.

To eliminate knock through the use of a binary fuel a variation is recommended in the gasoline-propane ratio of the latter. Since when two fuels are mixed together, the octane number of the mixture is calculated according to Bobrovich et. al. (1992) using equation (7), gasoline being topped up with high octane propane, this will improve the binary fuel knock rating.

$$ON_{bin.f.} = ON_g + x(ON_p - ON_g), \quad (7)$$

where: ON_g – gasoline octane number; ON_p – propane octane number; x – share of propane in the binary fuel (%/100).

Here the opportunity arises to both perform predictive control of fuel composition to raise the octane number in those cases when the knock probability is the highest, and to eliminate knock by increasing the supply of propane without changing the optimum IAA. Three matrices are applied to implement the above approach: initialization matrix D_{init}, value matrix D_v and limit matrix D_{lim}. These matrices are a set of values of the binary fuel composition for various RPM and loads.

Initial values of the binary fuel composition are entered into the initialization matrix, whose (initial values) are used for the RMP and the load specified. It is natural that during ICE operation these values change under the algorithm outlined below. The value matrix is used to store these changes. In order to distinguish the area of knock elimination through the use of propane from that achieved thanks to IAA adjustment, a limit matrix is used to specify propane content limits for the binary fuel under various conditions.

5. FUEL COMPOSITION CONTROL

Based on the results of ICE energy and environmental simulation performed for various gasoline-propane ratios of the composite fuel, a procedure of fuel composition control has been proposed (see Fig. 3). Fuel composition is marked as *L*. It shows propane and gasoline percentage in binary fuel. E.g. *L*=60/40 indicates that fuel consist of 60% of propane and 40% of gasoline. Factor *L* is varied depending on the RMP and load in order to ensure:

- reliability of engine start and minimum idling emission;
- maximum economic and environmental performance at part-load operation (statistically – the most commonly used mode);
- a balance between fuel costs, the engine torque and the content of harmful substances in exhaust gases at average-load operation;
- maximum possible engine torque at high-load operation.

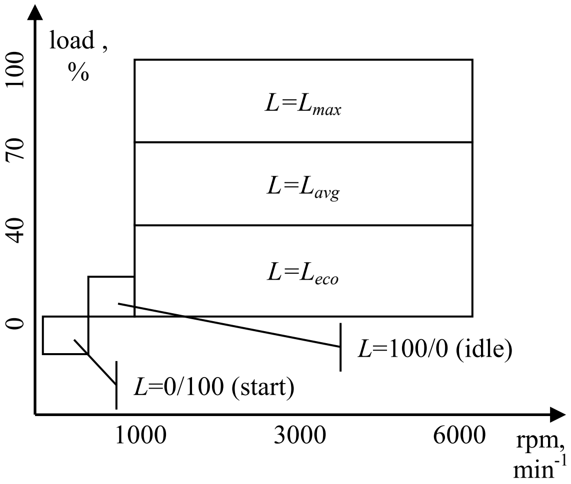

Fig. 3. Binary fuel composition control

Proceeding from these requirements, the following binary fuel compositions have been determined for the modes used:

- L_{eco}=10/90 (provides for high reliability, economic and environmental performance);
- L_{avg} is taken dependent on the load according to (8);
- L_{max}=60/40 (characterized by maximum torque).

$$L_{avg} = \begin{cases} 30/70, \text{when } 40\% < \text{load} \le 50\% \\ 40/60, \text{when } 50\% < \text{load} \le 60\% \\ 50/50, \text{when } 60\% < \text{load} < 70\% \end{cases} \qquad (8)$$

At engine start, pure gasoline is used, which ensures its high reliability, and at idle speed (when engine is warned up), pure propane is used, which provides for minimum emission.

6. EXPERIMENTS

Experimental part of the work included identifying combustion duration for various binary fuel compositions, research of 2-level scheme of knock elimination and measuring engine performance using proposed control method. The test bench layout is presented in Figure 4.

For test purposes, cars were equipped with an original binary fuel supply system (ELPIGAS-based) the propane injectors 6 of which were connected to the modified engine electronic control unit (ECU) 15 instead of to the propane ECU, in order to ensure coordinated control of propane and gasoline injectors.

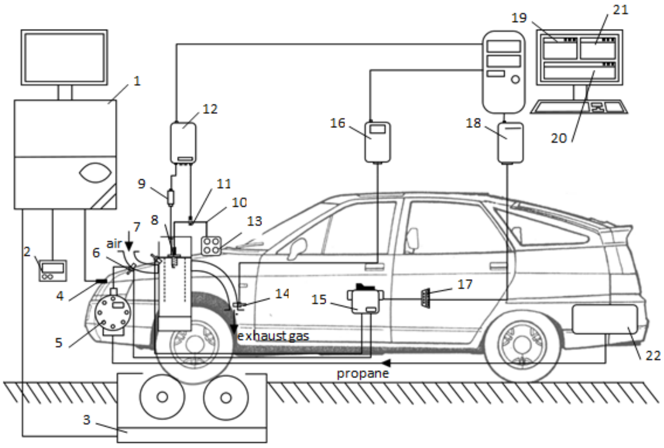

Fig. 4. Test bench layout: 1 – control console of the MAHA LPS 3000 dyno; 2 – weather station; 3 – roller unit R101; 4 – air temperature sensor (for the air that enters the intake manifold); 5 – propane vaporizer; 6 – propane injectors; 7 – gasoline injectors; 8 – ignition spark plug integrated with a lead for a cylinder peak pressure registration sensor; 9 – Quantex 16/100 atm pressure sensor; 10 – high voltage wire; 11 – Motodoc synchro sensor; 12 – Motodoc II engine tester; 13 – ignition module; 14 – Innovate wideband oxygen sensor; 15 – engineering electronic control unit based on Yanvar' 5.1; 16 – LM-01 controller; 17 – OBD II adapter; 18 – K–line adapter; 19 – Motodoc software; 20 – Injector online software; 21 – software for IAA calculation; 22 – propane cylinder.

The first experiment saw the binary fuel combustion duration φ_{z0} being identified in the reference mode for various fuel compositions (*L*=80/20, 70/30, 60/40, 50/50, 40/60). After that, a full-load curve of the Lada 21108M (1.8 liter 16 valve) was formed for the above compositions. Measuring was performed over a one-day period to ensure identical environmental conditions. In the course of measuring a comparable coolant temperature was maintained.

The experimental results correspond closely to the math simulation outcome (see Table 1). The difference in torques ΔM does not exceed 5%. After the binary fuel combustion duration φ_{z0} was identified, the difference between design and experimental data was less that 1%. Values of the combustion duration before and upon identification are shown in Table 1.

Table 1. Combustion duration values of various binary fuel compositions identified in the reference mode before and after identification.

	φ_{z0},°		ΔM, %	
L	before*	after	before	after
80/20	55	55	0,82	0,82
70/30	50	47,5	1,6	0,30
60/40	45	40	3,27	0,02
50/50	50	45	3,75	0,05
40/60	55	50	4,54	0,25

* – the first value of φ_{z0} for different binary fuel compositions was a hypothesis, based on propane and gasoline property analysis.

In order to check how the addition of propane affects knock, in the second experiment, the ECU of the Lada 2112 (engine: 21124, 1.6 liter 16 valve) was adjusted for IAAs, which most likely cause knock; after that, values of the full load power and torque were measured for gasoline (Fig. 5a, curves 2 and 4) and binary fuel L=70/30 (Fig. 5a, curves 1 and 3).

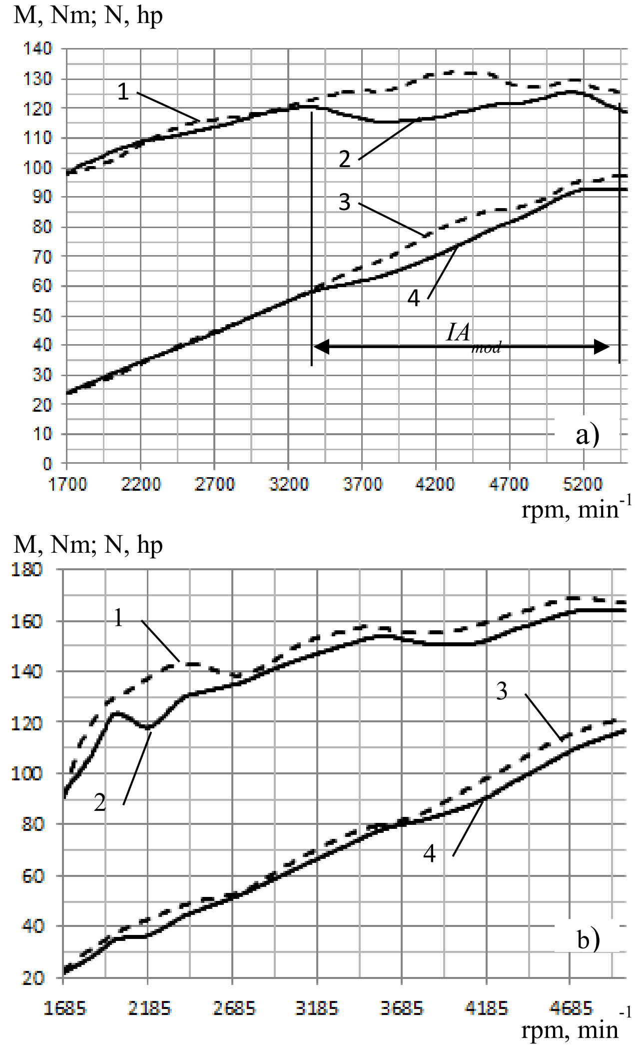

Fig. 5. – a) use of propane to reduce knock. b) use of the method proposed

To mitigate the negative impact of the experiment for the ICE, the angle values were modified within the range of IA_{mod}, only. The curves evidence the contribution of the control system, which reduced the IAA when knock occurred in the car running on gasoline. Here, the torque was reduced, as well (it can be easily seen on frequencies from 3200 up to 5500 rpm). After propane was added, the IAA was ensured and no knock occurred, which was evidenced by the increased power and torque.

According to the experimental results, application of the proposed control method leads to the torque increasing within the whole crankshaft rpm range and reaching its peak value of 173.1 Nm, this being an increment of 5.7% as compared to the peak torque of 164.2 Nm reached when standard IAA values are used. Moreover, the lower crankshaft rpm range (2000-2600 rpm) sees the torque increasing by up to 11.6%, the curve becoming straighter. The measurement accuracy is ±2%. After comparing the specific fuel consumption rates for the method suggested and for the standard rate, it has become evident that the proposed method provides for an average reduction in the consumption rate of 6.1%. Car emission is down by 9.9%.

The next experiment produced a full-load curve of a Lada 21108M being formed for standard IAAs (factory default values) and those determined by the suggested method. The comparative power and torque curves are presented in Figure 5b (IAA standard values correspond to curves 2 and 4, and the method suggested – to curves 1 and 3).

6. CONCLUSIONS

According to the research results, a control method for spark ignition internal combustion engines has been suggested which ensures improvement of ICE performance when an alternative composite fuel (gasoline + propane) is used. A mathematical model has been developed that enables the calculation of control actions during engine operation and accounts for composite fuel component ratios. A procedure to avoid knock has been produced, which is based on a variation in composite fuel component ratios, and another procedure has been developed to control fuel composition, thus providing an improvement in ICE environmental performance, as well as a reduction in fuel costs.

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