

Article citation info:

Biedrzycki J, Bukrejewski P, Chłopek Z, Skolniak M, Wójcik P, Wysoczarski D. Examining the physicochemical and operational properties of the LPG fuel with an addition of light aliphatic hydrocarbons. The Archives of Automotive Engineering – Archiwum Motoryzacji. 2016; 71(1): 21–37, <http://dx.doi.org/10.14669/AM.VOL71.ART2>

EXAMINING THE PHYSICOCHEMICAL AND OPERATIONAL PROPERTIES OF THE LPG FUEL WITH AN ADDITION OF LIGHT ALIPHATIC HYDROCARBONS

JACEK BIEDRZYCKI¹, PAWEŁ BUKREJEWSKI², ZDZISŁAW CHŁOPEK³,
MARTA SKOLNIAK⁴, PIOTR WÓJCIK⁵, DARIUSZ WYSOCZARSKI⁶

Automotive Industry Institute
Warsaw University of Technology

Summary

Results of comparative testing of the LPG (Liquefied Petroleum Gas) fuel and such a fuel with an addition of light aliphatic hydrocarbons, chiefly methane, in two versions have been presented. The tests were carried out in respect of the physicochemical properties of the fuels according to Standard PN-EN 589 and in respect of the performance characteristics of a motor vehicle powered with the fuels under test. The main purpose of the tests was to determine the acceptable fraction of light aliphatic hydrocarbons, predominantly methane, in the LPG fuel, whose basic components are C3 and C4 alkanes or alkenes. The addition of light aliphatic hydrocarbons to LPG may be of considerable importance for the fuel properties, primarily because of high values of the saturated vapour pressure of such admixtures. The fuel composition was determined with the use of the gas chromatography method. The methane additive content of the fuels under test was 0.1% m/m⁷ and 0.2% m/m and the ethane additive content was 0.2% m/m. The fuels met the requirements of Standard PN-EN 589. The performance of the motor vehicle was tested on a chassis dynamometer. No adverse effect of the addition of light aliphatic hydrocarbons to the LPG fuel on vehicle engine's effective power and pollutant emissions was revealed.

Keywords: internal combustion engines, LPG, light aliphatic hydrocarbons

¹ Automotive Industry Institute, ul. Jagiellońska 55, 03-301 Warszawa, Poland, e-mail: j.biedrzycki@pimot.eu

² Automotive Industry Institute, ul. Jagiellońska 55, 03-301 Warszawa, Poland, e-mail: p.bukrejewski@pimot.eu

³ Warsaw University of Technology, Faculty of Automotive and Construction Machinery Engineering, Institute of Vehicles, ul. Narbutta 84, 02-791 Warszawa, Poland, e-mail: zchlopek@simr.pw.edu.pl

⁴ Automotive Industry Institute, ul. Jagiellońska 55, 03-301 Warszawa, Poland, e-mail: m.skolniak@pimot.eu

⁵ Automotive Industry Institute, ul. Jagiellońska 55, 03-301 Warszawa, Poland, e-mail: p.wojcik@pimot.eu

⁶ Automotive Industry Institute, ul. Jagiellońska 55, 03-301 Warszawa, Poland, e-mail: d.wysoczarski@pimot.eu

⁷ %m/m = mass fraction

1. Introduction

The unconventional fuels for internal combustion (IC) engines are defined as those to which neither the mass-produced engines nor complete motor vehicles (within the scope of vehicle fuelling systems) are directly prepared by their manufacturers. This means that such fuels are understood to be those different from motor spirits (various petrol or gasoline grades) used for spark-ignition (SI) engines and diesel oils used for compression-ignition (CI) engines. Among the unconventional fuels, those being most popular are gaseous fuels, referred to as LPG (Liquefied Petroleum Gas) and stored in the liquefied phase under a pressure of about 0.3 MPa to 0.5 MPa [1, 2, 5, 10, 17], with their composition being based on petroleum-derivative gases. The major components of such fuels are propane and butane [1, 2, 5, 10, 17].

In the English-language literature, the LPG is also referred to as "autogas"; hence, polonized versions "autogaz" or "auto-gaz" of this term can be met in Poland. The high popularity of LPG chiefly results from its low price in comparison with the prices of the petrol and diesel oil grades available in the market.

LPG can be used for both spark-ignition and compression-ignition engines. The LPG-fuelled SI engines predominantly are bi-fuel units, with the petrol fuelling system being originally provided as the basic one. In such a system design, the petrol fuelling is used for cranking and heating the engine and then the fuelling system can be switched from petrol to LPG and vice versa. In the LPG fuelling mode, petrol is also periodically added to improve engine operation conditions, in consideration of both improved cooling of the engine combustion chamber due to vaporization of the liquid fuel and better lubrication properties of petrol as against the gaseous fuel [6, 10, 15, 16]. There are several technical generations of the LPG fuelling systems, from the simplest converter-and-mixer type systems to the systems where LPG in its liquid phase is directly injected to the engine combustion chamber [2]. For the LPG fuelling, the engine control algorithms (first of all, those used to control the fuel delivery) are implemented as modifications of the original algorithms designed for petrol fuelling [2]. Large SI engines, developed as modifications of original compression-ignition engines, are provided with mono-fuel systems, operating with LPG only [2], similarly as it is in large engines fuelled with CNG (Compressed Natural Gas). Designs of this kind have been used to power city buses.

The compression-ignition engines fuelled with LPG, like the CNG-fuelled diesel engines, are built as bi-fuel units, using their original diesel oil fuelling system but with LPG being additionally fed [9].

Predominantly, LPG is used to fuel spark-ignition engines, i.e. chiefly for passenger cars and smaller light trucks (delivery vehicles).

The interest in using LPG for the fuelling of internal combustion engines is additionally stimulated by ecological considerations, i.e. the benefits typical for the use of gaseous fuels: reduction in pollutant emissions [3, 8, 12–19] and, for CI engines, noise reduction as well. A matter of considerable importance is also the possibility of utilizing other energy materials available in order to economize the consumption of conventional petroleum-derivative fuels.

Apart from evident good points, the use of LPG for the fuelling of IC engines has also some drawbacks. The most serious of the latter is the fact that neither engines nor motor vehicles are originally designed for LPG fuelling, which means that motor vehicles have to be additionally retrofitted with gas fuelling systems. At the present-day level of technological excellence of mass-manufactured products, including motor vehicles, the solution like this is dramatically unprofessional, even if procedures formally exist to authorize the modifications of this kind. Doubts about the professionalism of modifications of fuel feeding systems also arise from the fact that a success of the initiative to popularize the LPG fuelling of IC engines chiefly depends on the price of the additional devices needed. In such a situation, systems with the simplest technological solutions are usually installed, e.g. those where, as regards the system control, only the fuel delivery control algorithm is modified. The modification of original fuelling systems also causes adverse effects on the system safety, in result of which the indoor parking of LPG vehicles is often forbidden, although the LPG fuel is more volatile than petrol.

There are also other undesirable consequences of the use of LPG for vehicle fuelling. One of them is related to the combustion temperature being higher for gaseous fuels than that for liquid fuels and, in addition to this, practical lack of lubricity improvers. This results in increased wear of some engine components, in particular those exposed to heavy thermal loads, e.g. engine valves, especially exhaust valve heads and seats.

A problem related to vehicle operation is the susceptibility of LPG vapour pressure to ambient temperature due to a possibility of differences in fuel composition, as the saturated vapour pressure very rapidly drops with increasing number of carbon atoms in individual homologous series, e.g. in alkanes.

In spite of numerous critical opinions about the use of LPG for the fuelling of IC engines, the development of this technology has become a fact. Therefore, it is all the more purposeful to solve any problems in order to improve the performance characteristics of IC engines fuelled with LPG. Most often, the efforts are focused on the problem of increased fraction of light aliphatic hydrocarbons, first of all methane, in the LPG fuel. Methane has very high pressure of saturated vapour. Hence, it considerably affects fuel assessment parameters such as relative vapour pressure at a temperature of 40 °C and the temperature at which the relative vapour pressure is not less than 150 kPa. In respect of the temperature at which the relative vapour pressure is not less than 150 kPa, the addition of methane beneficially affects fuel quality; however, a methane addition may cause a significant growth in the relative vapour pressure at a temperature of 40 °C, so that the pressure would exceed 1550 kPa, which would pose a hazard of unsealing of the fuel system and, in consequence, an explosion risk as well.

2. LPG fuel

The petroleum-derivative gas is a mixture of chain hydrocarbons, chiefly the C₃ and C₄ alkanes and alkenes, with a small admixture of other chain hydrocarbons C₁ – C₇ [1, 6, 7, 10]. At the ambient temperature and a pressure of (0.3 ÷ 0.5) MPa, this gas is stored in liquid

state, hence its name "liquefied petroleum gas" and acronym "LPG", the latter being used in Polish as well.

The mass density of LPG is within limits of $(500 \div 600) \text{ kg/m}^3$ [1, 6]. The calorific value of this fuel is about 46 MJ/kg [1, 6] and its research octane number ranges from 102 to 108, and motor octane number – more than 89 [1, 6].

The petroleum-derivative gas is mostly obtained by degasolining of natural gas, stabilization of crude oil on an oil field, distillation of crude oil, catalytic cracking and hydrocracking, thermal processing, reforming, isomerisation, butadiene production, and production of ethers [10].

In the case of atmospheric distillation of crude oil, differences in the boiling point of individual organic compounds are utilized. Having been pre-cleaned, dewatered, and desalted, crude oil is heated in heat exchangers and then separated into fractions in a distillation column (tower) under atmospheric pressure. Neither this separation nor the subsequent one, carried out at a reduced pressure, changes the crude oil chemical composition; hence, these processes are counted among conservative methods. Thus, the pipe-still and tower distillation is a conservative method. The LPG fraction, obtained from the pipe-still and tower distillation, makes $(1 \div 2.5)\% \text{ m/m}$ of the crude oil. The LPG composition may vary depending on the raw material type used; as an example, the proportions between the major components of the LPG obtained from the REBCO oil are about 27% m/m of propane, 20% m/m of isobutane, and 51% m/m of n-butane.

The gas obtained from the separation process, predominantly consisting of propane and butane, is subjected to desulphurization, based on a chemical reaction between hydrogen sulphide and $(15 \div 20)\% \text{ V/V}^{\text{a}}$ solution of monoethanolamine, where the latter, reacting with the hydrogen sulphide at a temperature of $(25 \div 40) \text{ }^\circ\text{C}$ and under a high pressure, water-soluble salts.

In the coking processes, $(4 \div 6)\% \text{ m/m}$ of LPG, on the average, is obtained; the fluid coking and the Flexicoking processes yield up to 4% V/V and up to 7% V/V of LPG, respectively.

The catalytic cracking consists in reactions taking place in various oil fractions or vacuum oil distillates at temperatures of $(480 \div 540) \text{ }^\circ\text{C}$ and a relatively low pressure of about 0.05 MPa in the presence of aluminosilicates catalysts. The catalytic cracking makes it possible to obtain lighter hydrocarbons. The cracking reactions occur in the fluid phase. During the catalytic cracking process, chiefly the carbon-to-carbon bond breaking reactions take place, in result of which alkanes of lower molecular mass and, alkenes are formed. The catalytic cracking of vacuum oil distillates may yield $(18 \div 25)\% \text{ m/m}$ of LPG. In the LPG obtained from the catalytic cracking, sulphur occurs in the form of thiols (mercaptans), i.e. organic chemical compounds corresponding to alcohols where the oxygen atom of the hydroxyl group has been superseded by a sulphur atom. The thiols are removed from the LPG in the Merox process. The gas having been desulphurized is separated by rectification into propane, propylene, and butane fractions.

^a %V/V = volume fraction

Hydrocracking is a modification of the cracking process, where hydrogen at a high pressure ($3 \div 15$) MPa is applied and the process temperature is lowered to ($250 \div 450$) C, with molybdenum, nickel, and cobalt compounds as well as platinum and palladium being used as a catalyst. The products of hydrocracking of vacuum oil distillates are 1% m/m of LPG, (80% mole/mole⁹ of butanes and 20% mole/mole of propane), petrol, diesel oil, and fuel oil. The mass fraction of sulphur does not exceed 10 ppm¹⁰.

The hydrodesulphurization of petroleum feedstocks is the largest catalytic process that is run on an industrial basis, in terms of its scale and importance. In the modern refinery industry, practically all hydrocarbon fractions and streams are subjected to hydrorefining. In such processes, heteroatoms are removed from the petroleum feedstock and, the unsaturated bonds become saturated and the aromatic substances are hydrogenated. The main purpose of the hydrorefining is not to break the carbon-to-carbon bonds but instead, to break the carbon-to-heteroatom bonds or, at the same time, to hydrogenate the unsaturated bonds, chiefly the alkene bonds and, less frequently, the aromatic bonds. It is assumed that during the hydrorefining process, a reduction in molecular mass takes place in not more than 10% m/m of the feedstock. The hydrodesulphurization and hydrocracking of soft asphalt makes it possible to obtain ($1.5 \div 2.0$)% m/m of LPG (more than 50% m/m of that consists of the C3 and C4 fractions, there is no hydrogen sulphide, and the mass sulphur content is at a level of 50 ppm).

In the product of catalytic reforming, the LPG fraction makes ($0.8 \div 1.6$)% m/m, with 70% m/m of that consisting of propane and n-butane and 25% m/m being isobutane (the hydrogen sulphide content does not exceed 20 ppm by mass).

The composition and, in consequence, properties of the LPG fuel may vary within a wide range, depending on the feedstock types and process methods used. In this connection, specific quality requirements have been set for such a fuel, as laid down in Standard PN-EN 589 "Automotive fuels – LPG – Requirements and test methods".

3. Object and method of testing

The tests were carried out on the following fuels for spark ignition engines:

- commercially available standard LPG fuel;
- test fuel M1: commercially available standard LPG fuel with 0.1% m/m methane admixture;
- test fuel M2: commercially available standard LPG fuel with 0.2% m/m methane admixture.

The M1 and M2 fuels were prepared by adding commercial methane to the standard LPG fuel.

⁹ %mole/mole or % mole – mole fraction

¹⁰ ppm – parts per million, i.e. one-millionths part

Table 1. Composition of the fuels under test (continued)

Cis-2-butene	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Trans-2-butene	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Isobutylene	0.2	0.2	0.2	0.2	0.2	0.2
1-butene	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
n-butane	59.4	52.8	59.3	52.5	59.2	52.3
Isobutane	0.9	0.8	0.9	0.8	0.9	0.8
n-pentane	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
n-hexane	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Cyclobutane	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
3-methylpentane	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
1,3-butadiene	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Isopentane	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1

The main difference between the compositions of the fuels under test lies in the methane contents, which were as specified below:

- for the LPG fuel, less than 0.1% m/m;
- for the M1 fuel, 0.1% m/m;
- for the M2 fuel, 0.2% m/m.

Results of testing the fuels for conformity with Standard PN-EN 589 have been shown in Table 2.

Table 2. Results of testing the fuels for conformity with Standard PN-EN 589

Parameter	Test method	Unit	Quality requirements ¹⁾	Fuel test results		
				LPG	M1	M2
Motor octane number	PN-EN 589+A1:2012 Annex B	-	min 89.0	92.0	91.7	91.2
Total diene content (incl. 1,3 butadiene)	PN-ISO 7941:1993/ API:2002	% mole	max 0.5	< 0.1	< 0.1	< 0.1
Hydrogen sulphide	PN-EN ISO 8819:2000	-	none	not detected*	not detected*	not detected*
Total sulphur content (with stenching agent added)	ASTM D 6667:2010	mg/kg	max 50	4.8	4.7	4.6

Table 2. Results of testing the fuels for conformity with Standard PN-EN 589 (continued)

Parameter	Test method	Unit	Quality requirements ¹⁾	Fuel test results		
				LPG	M1	M2
Copper strip corrosion test (1 h at 40 °C)	PN-EN ISO 6251:2001	corrosion class	class 1	class 1	class 1	class 1
Dry residue	PN-EN 15471:2009	mg/kg	max 60	-	-	-
Relative vapour pressure at 40 °C	PN-EN ISO 8973:2000 (with PN-EN 589 +A1:2012 Annex C)	kPa	max 1550	744	865	985
Temperature at which the relative vapour pressure is not less than 150 kPa	PN-EN ISO 8973:2000 (with PN-EN 589 +A1:2012 Annex C)	°C		0 (grade C)	-10 (grade A)	-10 (grade A)
Water content	PN-EN 15469:2009	-	not detected	OK**	OK**	OK**
Stench	PN-EN 589+A1:2012 Annex A, item 6.3	-	distinguishable and unpleasant, perceptible in air at a concentration of 20% of lower explosiveness limit	perceptible, unpleasant	perceptible, unpleasant	perceptible, unpleasant

1) Pursuant to Article 25, Clause 3, of the Act of 25 Aug. 2006 on fuel quality monitoring and inspection (Dz. U. No. 169 of 2006, item 1200, with later amendments), the results of sample testing shall be applicable to the quality of the whole batch of the fuel present in the tank from which the samples were taken.

* Pursuant to PN-EN ISO 8819:2000, the result "not detected" shall have the meaning that there was no hydrogen sulphide in the sample under test.

** Pursuant to PN-EN 15469:2009, the result "OK" shall have the meaning that no water was detected in the sample under test.

The test results have confirmed that even if a small amount of light aliphatic hydrocarbons, which are characterized by high vapour pressure [11], especially methane, is added to the LPG fuel then the fuel vapour pressure is significantly raised. All the fuels tested met the

requirements of Standard PN-EN 589, including the requirement regarding the relative vapour pressure, with a wide safety margin. The fuels with mass methane content of up to 0.2% m/m meet the criterion for fuel grade A, unlike the standard LPG fuel, which meets the criterion for fuel grade C (Table 3).

Table 3. Requirements for individual LPG fuel grades, according to PN-EN 589+A1:2012

Parameter	Unit	Requirements		Test method
		min	max	
Relative vapour pressure at 40 °C	kPa		1550	PN-EN ISO 4256 PN-EN ISO 8973 PN-EN 589, Annex C
Temperature at which the relative vapour pressure is not less than 150 kPa – Grade A – Grade B – Grade C – Grade D – Grade E	°C		-10 -5 0 10 20	PN-EN ISO 8973 PN-EN 589, Annex C

The relation between the relative vapour pressure at a temperature of 40 °C and the mass methane content of the LPG fuel has been shown in Fig. 1.

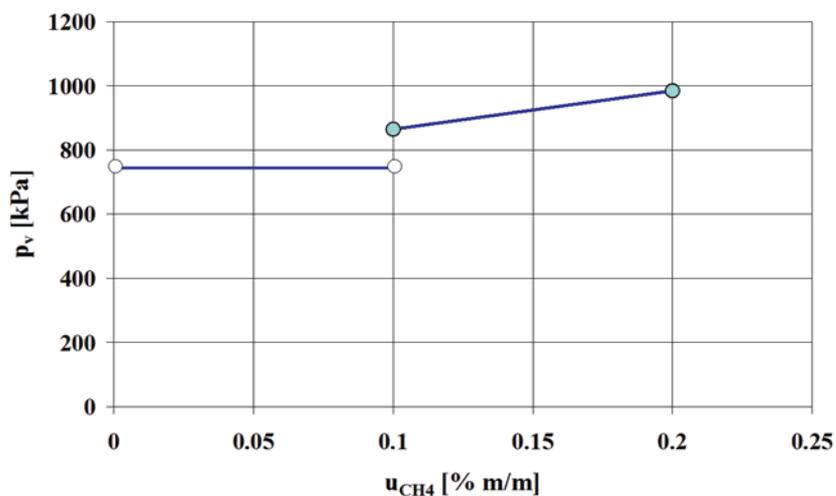


Fig. 1. Relative vapour pressure at a temperature of 40 °C and the mass methane content of the LPG fuel

To assess the impact of the methane addition to the LPG fuel, the relative vapour pressure at a temperature of 40 °C was determined by simulation tests carried out in accordance with the Dalton's law of partial pressures. The vapour pressure values of major LPG fuel components at temperatures from -5 °C to 40 °C, according to PN-EN 589+A1:2012, have been specified in Table 4.

Table 4. Vapour pressure values of major LPG fuel components at temperatures from -5 °C to 40 °C, according to PN-EN 589+A1:2012

Component name	T_{LPG} [°C]					
	-10	-5	0	10	20	40
p_v [kPa]						
Methane	21334	22742	24211	27333	30707	38230
Ethane	1873	2128	2407	3040	3781	5613
Propane	346	405	472	630	826	1353
Isobutylene	90.17	109.5	131.9	187.6	259.9	466
n-butane	71.26	86.64	104.5	149.2	207.6	376.9
Isobutane	109.9	132.3	158.1	221.4	302.7	531

Fig. 2 shows the vapour pressure of the LPG fuel with methane admixture at temperatures from -5 °C to 40 °C.

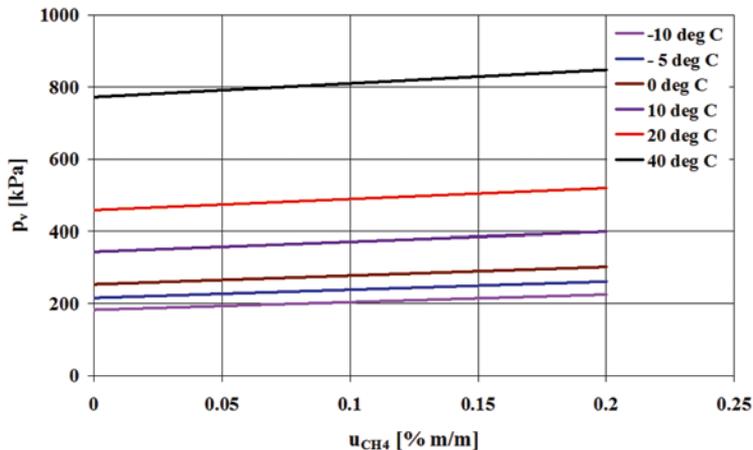


Fig. 2. Vapour pressure of the LPG fuel with methane admixture

To determine the limit value of the methane content of the LPG fuel under test with respect to the criterion of maximum relative vapour pressure, simulation tests of the vapour pressure of LPG fuel and methane mixtures at a temperature of 40 °C were carried out. The simulation results have been presented in Fig. 3.

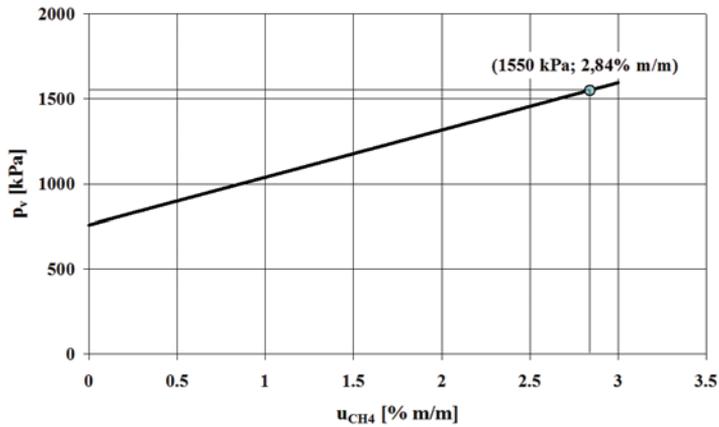


Fig. 3. Vapour pressure of the LPG fuel with methane admixture at a temperature of 40 °C

Based on the simulation test results presented, the requirement defining the maximum methane admixture to the LPG fuel according to Standard PN-EN 589 is met by an LPG fuel blend with a methane content of up to 2.08% m/m.

Figs. 4 and 5 show effective power and torque vs. engine speed, respectively, in the conditions of vehicle acceleration in fourth gear.

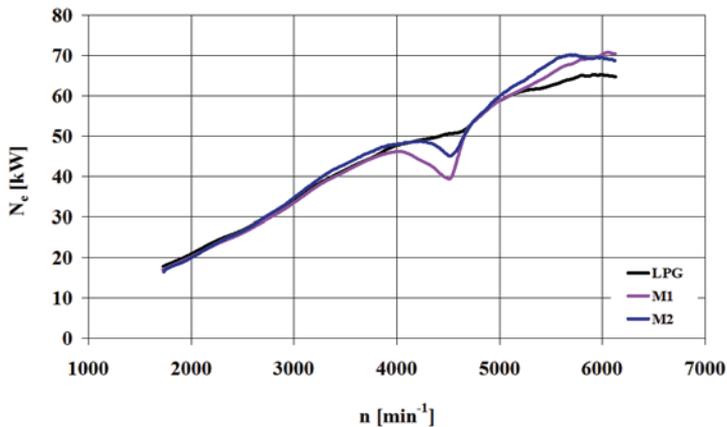


Fig. 4. Effective power vs. engine speed in the conditions of vehicle acceleration in fourth gear

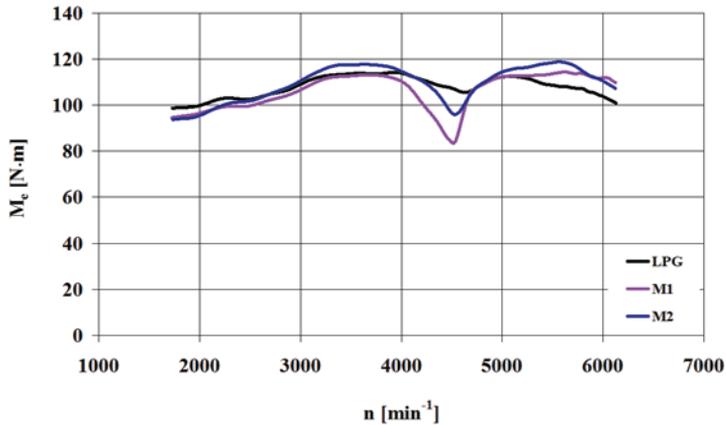


Fig. 5. Torque vs. engine speed in the conditions of vehicle acceleration in fourth gear

In both of the graphs above, an engine speed range can be clearly seen where the fuelling system is switched from LPG to petrol: LPG fuel – 4600 min^{-1} , M1 fuel – 4530 min^{-1} , M2 fuel – 4550 min^{-1} . In the engine speed range where the engine is fed with gaseous fuels, there are no considerable differences in the performance curves for the fuels under test. This means that a methane addition to LPG at a level of about $(0.1 \div 0.2)\% \text{ m/m}$ has no substantial impact on engine's energy characteristics in terms of its effective power and output torque and on dynamic performance of the engine in terms of vehicle acceleration.

The specific distance emission values determined in the UDC, EUDC, and NEDC tests have been presented in Figs. 6–9.

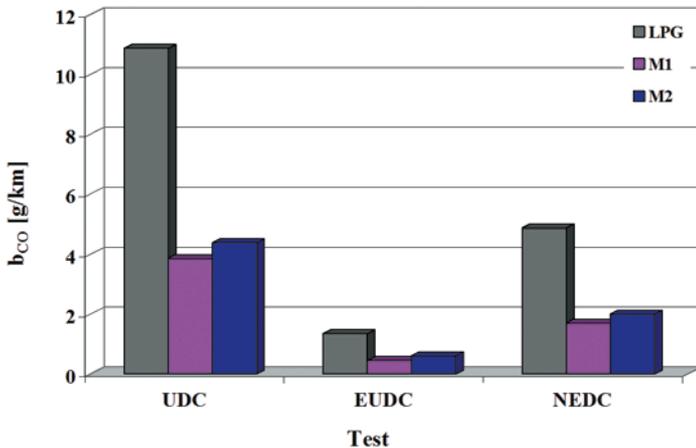


Fig. 6. Specific distance emission of carbon monoxide in the UDC, EUDC, and NEDC tests

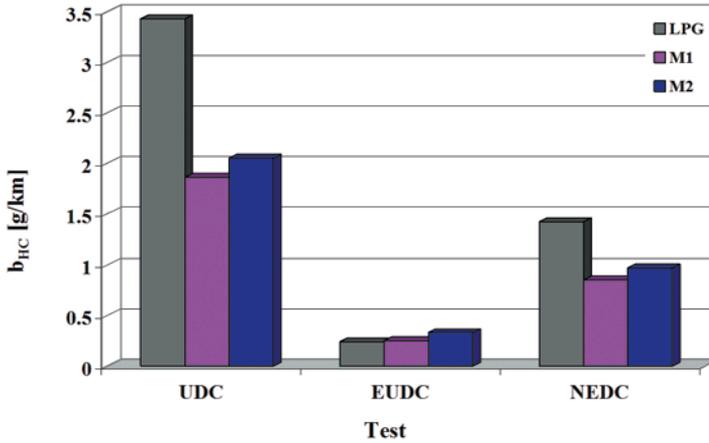


Fig. 7. Specific distance emission of hydrocarbons in the UDC, EUDC, and NEDC tests

Interestingly, a methane addition to LPG causes a reduction in the specific distance emission of hydrocarbons in the urban traffic conditions, while in the extra-urban traffic, the specific distance emission of hydrocarbons is slightly raised when methane is added to LPG.

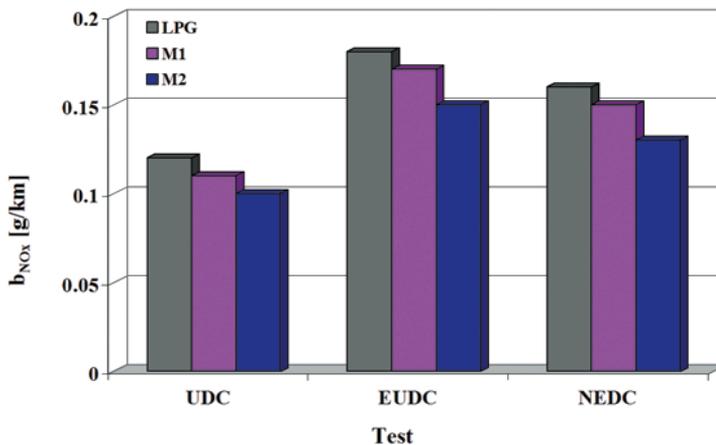


Fig. 8. Specific distance emission of nitrogen oxides in the UDC, EUDC, and NEDC tests

An approximately linear reduction can be observed in the specific distance emission of nitrogen oxides with increasing methane content of the LPG fuel.

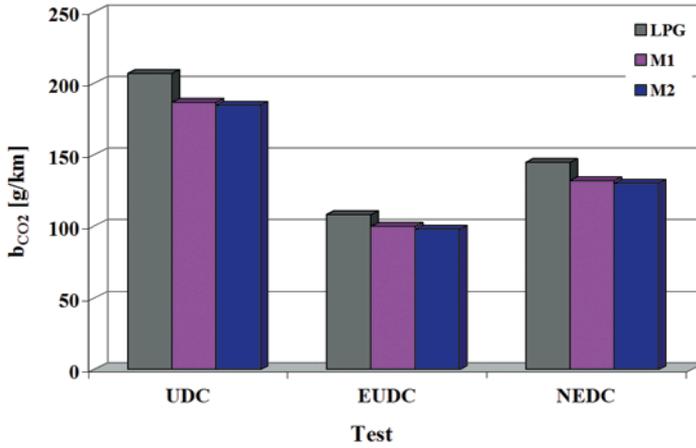


Fig. 9. Specific distance emission of carbon dioxide in the UDC, EUDC, and NEDC tests

The specific distance emission of carbon dioxide also declines with increasing methane content of the LPG fuel.

The operational fuel consumption in the UDC, EUDC, and NEDC tests has been shown in Fig. 10.

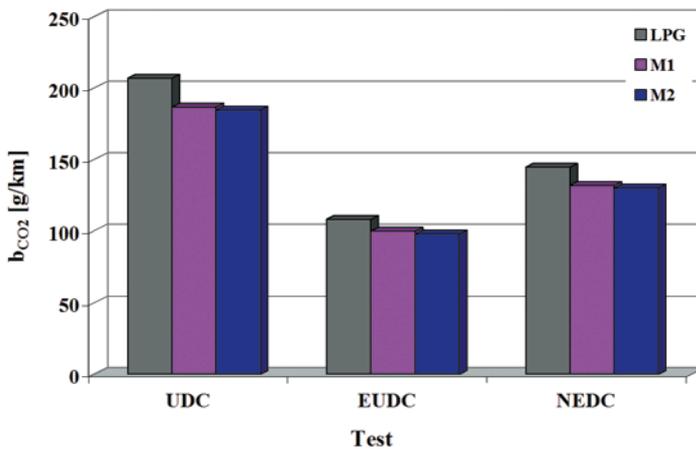


Fig. 10. Operational fuel consumption in the UDC, EUDC, and NEDC tests

As in the case of the specific distance emission of carbon dioxide, the operational fuel consumption declines, too, with increasing methane content of the LPG fuel.

The operational energy consumption in the UDC, EUDC, and NEDC tests has been shown in Fig. 11.

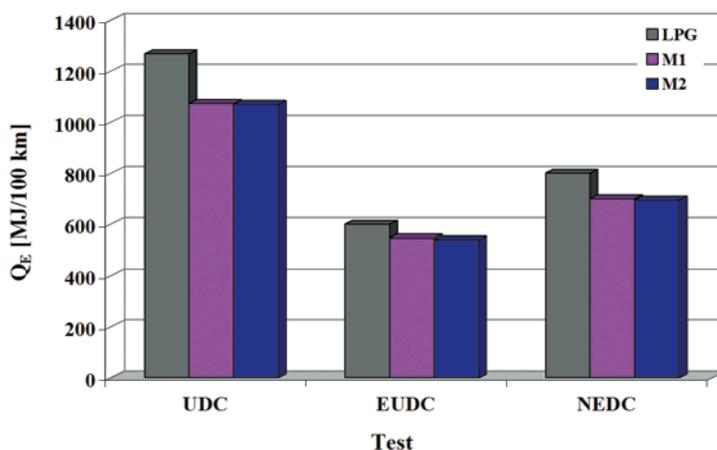


Fig. 11. Operational energy consumption in the UDC, EUDC, and NEDC tests

As in the case of the specific distance emission of carbon dioxide, the operational fuel and energy consumption declines, too, with increasing methane content of the LPG fuel.

5. Recapitulation

In result of the tests carried out, it has been found that an addition of light aliphatic hydrocarbons to the commercially available standard LPG fuel, in a proportion resulting in the mass methane content of the fuel being of up to 0.2% m/m, causes no considerable changes in the physicochemical fuel properties, such that they would adversely affect the suitability of the fuels under test for the powering of spark-ignition engines. In respect of the criterion of the temperature at which the relative vapour pressure is not less than 150 kPa, the fuels with an addition of light aliphatic hydrocarbons meet the criterion for fuel grade A, unlike the standard LPG fuel, which meets the criterion for fuel grade C. The requirements regarding the relative vapour pressure at a temperature of 40 °C are also met by the fuels with an addition of light aliphatic hydrocarbons, and with a wide safety margin at that. Simulation tests have indicated that the vapour pressure at a temperature of 40 °C reaches its upper acceptable limit when the methane content is as high as 2.08% m/m.

The addition of light aliphatic hydrocarbons to the standard LPG fuel does not cause any considerable changes in IC engine characteristics in terms of its effective power and output torque and in the dynamic performance of the engine in terms of vehicle acceleration.

In result of the tests carried out, it has been found that even a small amount of light aliphatic hydrocarbons added to the LPG fuel causes a significant reduction in the specific distance emissions of air pollutants, especially carbon monoxide and hydrocarbons, from a vehicle engine in type-approval driving tests. A small reduction in the fuel consumption has also been found to result from the addition of light aliphatic hydrocarbons to the LPG fuel.

The results of the research carried out show the reasonability of checking the impact of larger methane amounts being added to the LPG fuel on engine's performance characteristics. It also seems that it would be interesting to extend the scope of the research programme so that it would cover the addition of hydrogen to the LPG fuel.

The full text of the Article is available in Polish online on the website <http://archiwummotoryzacji.pl>.

Tekst artykułu w polskiej wersji językowej dostępny jest na stronie <http://archiwummotoryzacji.pl>.

References

- [1] Astm D1835-11: Standard specification for liquefied petroleum (LP) gases. American Society for Testing & Materials.
- [2] Auto-gas.net: Generations of autogas systems [cited 2015 Sep 15]. Available from <http://www.auto-gas.net/technology/system-types>.
- [3] Chłopek Z, Bardziński W, Jarczewski M, Sar H. Badania porównawcze samochodu osobowego zasilanego benzyną i skroplonym gazem ropopochodnym (LPG). Zeszyty Naukowe Politechniki Częstochowskiej. 2006; 111-120.
- [4] Davis SC, Diegel SW, Boundy RG. Transportation energy data book: edition 33. Oak Ridge National Laboratory. Oak Ridge, Tennessee, USA. 2014.
- [5] Delphi. Worldwide emission standards. Passenger cars and light duty vehicles. Innovation for the real world. 2015/2016.
- [6] Falkiner RJ. Liquefied petroleum gas. In "Fuels and lubricants handbook: technology, properties, performance, and testing". 2nd edition: ASTM International 2003. West Conshohocken.
- [7] Górski W. Stan normalizacji LPG w Polsce – Gatunek A czy B?: Nafta-Gaz. 2010 (2): 121-127.
- [8] Lee JW, et al. Effect of various LPG supply systems on exhaust particle emission in spark-ignited combustion engine: International Journal of Automotive Technology. 2010; 11(6): 793-800.
- [9] Luft S. Dwupaliwowy silnik o zaplonie samoczynnym zasilany wtryskowo paliwem LPG w fazie ciekłej: The Archives of Automotive Engineering – Archiwum Motoryzacji. 2005; 2: 153-163.
- [10] Meyers R. Handbook of petrochemicals production processes: McGraw-Hill. 2004.
- [11] Pubchem compound [cited 2015 Sep 12]. Available from <http://www.ncbi.nlm.nih.gov/pccompound>.
- [12] Qi D, et al. Combustion and exhaust emission characteristics of a compression ignition engine using liquefied petroleum gas-fuel-oil blended fuel: Energy Conversion and Management. 2006; 48(2): 500-509.
- [13] Saraf RR, Thipse SS, Saxena PK. Comparative emission analysis of gasoline/LPG automotive bifuel engine: World Academy of Science, Engineering and Technology. 2009; 3.
- [14] Tasic T, et al. Gasoline and LPG exhaust emissions comparison. Advances in Production Engineering & Management 2011. 6(2): 87-94.

-
- [15] Vijayabalan P, Nagarajan G. Performance, emission and combustion of LPG diesel dual fuel engine using glow plug: *Jordan Journal of Mechanical and Industrial Engineering*. 2009; 3(2): 105–110.
- [16] World LP gas association. *Clearing the air a technical guide on autogas. Emissions, test methods, standards and technology*. 2002; Paris.
- [17] World LP gas association. *Health effects and costs of vehicle emissions*. 2005; Paris.
- [18] Wu YY, Chen B-CH, Tran A-T. Pollutant emission reduction and engine performance improvement by using a semi-direct injection spark ignition engine fueled by LPG: *Aerosol and Air Quality Research*. 2012; 12: 1289–1297.
- [19] Zhang Ch, et al. A study on an electronically controlled liquefied petroleum gas-diesel dual-fuel automobile: *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*. 2005; 219(2): 207–213.

