The Knocking in the Gas Dual-fuel Engine with Liquid LPG Injection into the Intake Manifold

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***Abstract*—This article deals with a detection of the knocking in the gas dual-fuel engine converted from the original Cummins diesel (compression ignition – CI) engine. The dual-fuel engine is equipped with a Solaris (LPG-diesel) control system that adjusts the amount of LPG with diesel fuel to retain the same power as the original diesel engine. The maximal percentage of LPG supplied to the dual-fuel engine depends on the engine operating mode and prevents detonation in the engine cylinders. The combustion process of the fuel content and the detection of the knocking were checked by high-pressure indication in the cylinder. The knock-peak method is commonly used to detect knocking by the maximum pressure variation in working cycles. This is the absolute value of the maximum pressure oscillating at the high-pass filtered signal. The knock-peak limit is found to be 5 bar on the engine with Cummins dual-fuel using the knock-peak method. In general, this method can quickly detect the phenomenon of knocking and adjust the amount of LPG injection for improving engine power and reducing emissions.**

***Index Terms*—knocking, gas dual-fuel engine, LPG, diesel, compressed-ignition engine, measurement, the high-pressure indication**

I. Introduction

Along with advanced technology development, internal combustion engines (ICEs) have gradually been improved to enhance their efficiency and reduce emissions. ICEs have often used traditional fuels such as gasoline and diesel. Therefore, they have discarded a large amount of CO_2 emissions causing environmental pollution and the greenhouse effect, resulting in warming the earth [1-2]. Recently, the International Energy Agency introduced a draft law related to the reduction of CO_2 emissions of ICEs down to 95 g/km from 2020 and 75 g/km from 2025 [2]. Regulations on CO_2 emissions will become even more stringent in the future. Besides, the oil resources for producing gasoline and diesel are becoming exhausted. As a result, car manufacturers are forced to look for alternative fuels for ICEs and improving engine operation to achieve the highest efficiency.

One of the alternative fuels that has been mostly concerned by ICE manufacturers is LPG. For the diesel engine, a portion of diesel fuel was replaced by LPG fuel to create the dual-fuel (DF) LPG-diesel engine. LPG is injected and mixed with the air in the intake manifold of the engine. A small amount of diesel fuel is injected into the cylinder and it serves as the ignition source to burn the LPG-air mixture. LPG fuel is the main source of energy to keep up the DF engine operation. However, the DF engine can only be started with diesel fuel and subsequently switches to DF operation after briefly warming up the engine. The DF engines are easily converted based on the original diesel engines and can simply switch back to 100% original diesel mode without any modifications or settings.

Unlike diesel engines, DF engines have a knocking phenomenon when the combustion mixture contains a large amount of LPG fuel. The knocking is partly attributed to the physical and chemical properties of LPG causing in the combustion process. The knocking results in reduced performance of DF engines and increasing emissions. Moreover, it can cause destroying the piston mechanism assembly. The knocking is measured with an AVL Indimeter 619 indicating (cylinder pressure measurement) and is analyzed by the knock peak method.

The main purpose of this study is to evaluate the detonation occurring in the cylinder of DF engines. The research is carried out on the DF engine converted from the original Cummins diesel engine. The evaluation of the knocking of DF engines is necessary for improving their performance.

II. Theory

The fuel-air mixture burned in the engine cylinder has a decisive influence on the operating cycle parameters and the internal combustion engine operating characteristics. In addition to the physical quantities that describe the burning process (start of combustion, burning rate, total burning time, temperatures, and pressures in the cylinder), the stability of the combustion process (repeatability and reproducibility of the above-mentioned physical quantities) in each operating cycle of the engine is also essential for the operational cycle parameters. The characteristics of spark-ignition (SI) engines greatly vary in the combustion processes. They are manifested by the considerable variation of the cylinder pressure between operating cycles. The main reason is the difference between ignition energy and uneven energy distribution in the combustion chamber space at different working cycles. The great variability in

Manuscript received March 28, 2021; revised August 9, 2021.
This work was supported in part by the Ministry of Education, Youth and Sports of the Czech Republic under Grant SGS-2020-5015.

doi: 10.18178/ijmerr.10.12.694-701

the SI engine has a significant adverse effect on the performance parameters and emission parameters. Nowadays, the SI engine is operated mainly in medium- and high-load modes. The cycle-by-cycle variability of the combustion process at full engine load is necessary for conjunction with a predictive knock model [3-5].

Knocking is one of the main factors limiting the efficiency of the SI engine. Knocking sound often occurs during incomplete combustion. In some places in the combustion chamber, energy is released locally and rapidly during combustion. It causes the overload of the engine parts. The knocking is partially attributed to an unburnt mixture at high pressure and temperature and the right conditions for the formation of the pre-flame reaction. This phenomenon is spontaneous combustion [6].

The piston damages due to pressure oscillations are shown in Fig. 1. The ICEs were operated at a lower part load and speed, and the piston is damaged due to the frequency of pressure oscillations when the detonation occurs. The piston rings vibrate and cause damage.

Figure 1. Piston damage due to pressure oscillations caused by knocking.

The typical and most common damage of the piston caused by knocking is the erosion on the piston's crown (see Fig. 2) [4]. The figure shows the piston damage by knocking under high load, where high heat transfer to the parts on the piston's crown caused deformations leading to the destruction of the individual components of the ICE.

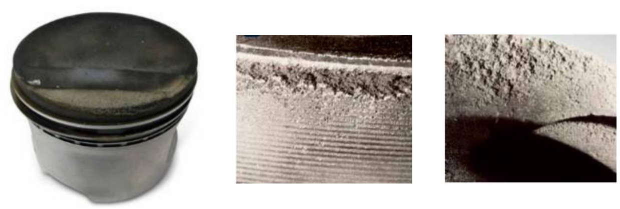

Figure 2. Piston damage due to high heat transfer (erosion on the crown of the piston) caused by knocking.

The knocking occurrence depends on temperature, pressure, fuel characteristics (fuel octane number), mixing and composition of the mixture, kinetic energy, and the time of the fuel mixture (fuel and air). The temperature and pressure in the combustion chamber may be affected by the compression ratio and sufficient cooling of the combustion chamber. A crucial parameter that affects the temperature and pressure in the cylinder is the ignition advance (only for SI engine). The in-cylinder flow fuel mixture is influenced by the shape, the length of the intake manifold, valve timing, and gas recirculation exhaust. The simplest way for the SI engine is to adjust the ignition timing. Currently, serial SI engines are equipped with a knock sensor. The ECU control system adjusts the ignition advance angle and the amount of fuel injected according to the knock signal [7]. The knock usually occurs in the SI engines and DF engines with LPG, CNG, or Hydro.

In the DF operation, the amount of injected LPG fuel is adjusted depending on the engine mode. However, it must satisfy the homogeneity of the LPG-air mixture without causing the detonation. The risk of knocking increases with an increasing richness of the LPG-air mixture and decreasing the intake temperature into the engine. The knocking can be reduced by injecting liquid LPG into the pipe behind the intake air cooler. The LPG injector end is heated, leading to the LPG-air temperature increase, thereby raising the engine performance. Nevertheless, the diesel fuel declines when increasing the LPG amount, resulting in overheating of the diesel injectors.

III. Experiment

A. *Experimental Setup*

The vehicle DF engine with liquid LPG injecting into the intake manifold is converted from the Cummins ISBe4 diesel engine. The CI engine is equipped with a Common Rail (2nd generation) injection system, ECM 850 electronic unit control, and injectors with an electromagnetic actuator. Details of the technical parameters [8] of the engine are listed in Table I.

TABLE I. Base Diesel Engine Specifications

Manufacturer	Cummins
Model	ISBE 150
Emissions specification	EURO 4
Applications in the type of vehicles	Transit Bus/Medium-Duty Truck/Tipper
Engine displacement	4500 cm^3
Fuel	Diesel
Turbocharging	Yes
Valvetrain	DOHC
Strokes/Cycle	4
The number of cylinders	4
Number of valves per cylinder	4
Compression ratio	17.3
Stroke/Bore	123.7/107.61 mm
Conrod	192 mm
Rated power/engine speed	152 kW (204 PS)/2500 rpm
Rated torque/engine speed	760 Nm/1500 rpm
Injection Timing	Electronic
Injection system	Common Rail
Electronic control unit	ECM 850

There are three phases of injecting diesel fuel into the cylinder. In the first phase, a minimal amount of diesel fuel is injected at approximately 30 °CA in front of TDC. Then, the large diesel amount is injected into the cylinder at about 10 °CA in front of TDC in the second phase. Finally, a small diesel amount is injected at approximately 30-50 °CA behind TDC in the third phase [9].

The DF engine operation is controlled by the Solaris (LPG-diesel) system. Liquid LPG fuel composition containing about 52% C_3H_8 and 48% C_4H_{10} is used for experimental measurements on the DF engine. The gas composition was stored in the pressure reservoir at 22.5 °C temperature under 6.5 bar pressure.

The DF engine was installed in the laboratory of the Vehicles and Engines Department of the Institute for Nanomaterials, Advanced Technologies, and Innovation at TU Liberec. The DF engine is mounted on a hydraulic Schenck D700 dynamometer with a control and measurement system using O.S. Windows. The DF engine is operated according to a programmed test mode with electronic data collecting from all standard engine operating quantities. In addition, special measurement techniques were used as the MGC Hottinger switchboard, the Horiba Mexa-One gaseous exhaust emission analyzer assembly, the EEPS TSI 3090 particle classification system to measure particulates (PM), and the AVL Indimeter 619 indicating apparatus (cylinder pressure measurement) with software AVL IndiCom. The LPG fuel system is formed from components of the VIALLE (pressurized fuel container with a pump, fuel distribution with pressure regulator, and electromagnetic injection valves).

The LPG injector ends are designed to heat electrically the outlet nozzle and to reduce the flow cross-section in the engine intake manifold. The assembly of the electromagnetic injector and its end part with the heated outlet nozzle is shown in Fig. 3. The installation of the LPG injectors into the intake manifold is described in Fig. 4.

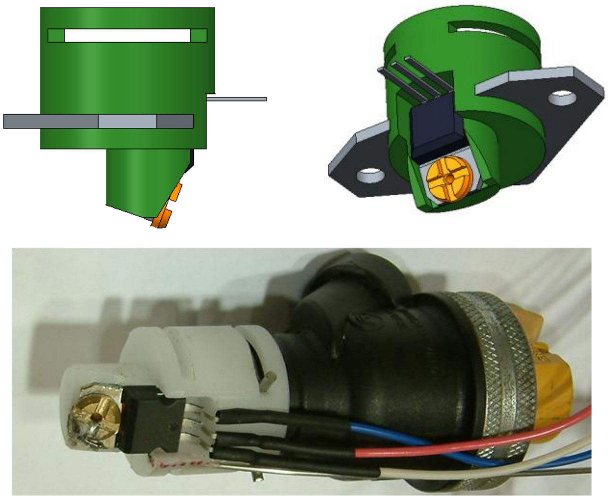

Figure 3. The assembly of the electromagnetic injector and its end part with the heated outlet nozzle.

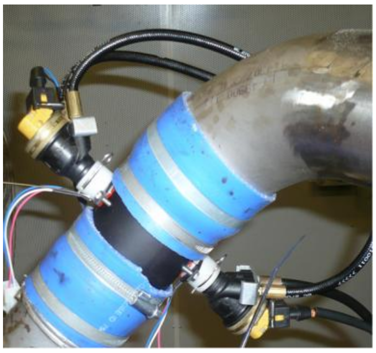

Figure 4. Installation of the LPG injectors into the intake pipe.

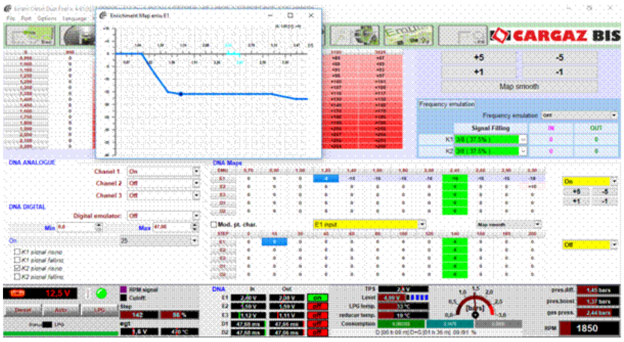

Figure 5. Monitor with S.W. electronic control units Solaris LPG-diesel.

The Solaris software system controls the switching between the diesel mode and the DF mode. After verifying the vehicle DF engine properties in real-time operation, the data are stored in the ECU control program. The experimental research is conducted on a functional sample of the Cummins DF engine. The data of the DF operation mode were not stored in Solaris ECU memory in Fig. 5. This engine is equipped with a gauge assembly that provides essential information for a comprehensive evaluation of the engine power, energy, thermodynamic, and emission parameters when comparing measurements on both diesel and DF engines [10-11]. The engine at the test site is shown in Fig. 6.

Figure 6. Gas DF engine Cummins with an injection of liquid LPG into the intake manifold.

Fig. 7 shows thermocouples measuring the exhaust gas temperature on the exhaust manifold of each engine cylinder. They are placed in front of the turbine.

Figure 7. Gas DF engine Cummins view of engine exhaust.

B. Methodology

The sample engine was tested in low, medium, and high revolution load modes at 1500 rpm, 1900 rpm, and 2300 rpm under regular diesel and DF modes.

The DF operation mode was achieved in the following manner:

When the engine speed was constant under diesel-only operation, LPG was injected into the intake manifold. The diesel fuel injection of the DF engine was reduced gradually until reaching the same overall efficiency compared to that when running on diesel only.

This process was repeated for all speed conditions.

C. The Knock Peak Method

The combustion process of the fuel content and the detection of the knocking were checked by high-pressure indication in the cylinder. The high-pressure indication (high-pass signal) is filtered from the measured signal (all-pass) by discarding the low-pass signal (see Fig. 8).

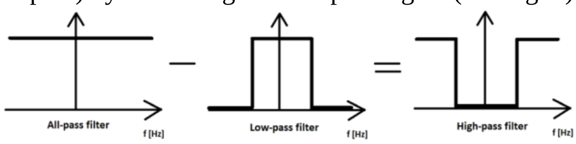

Figure 8. Splitting of the signal parts obtained from the knock sensor.

The maximum pressure deviations are considered as knock peak (KNK_PK) values and are determined by AVL IndiCom software [12]. They are the absolute values of the maximum pressure oscillating at the high-pass filtered signal. A mean-value filter is used to filtrate input signals according to Equation (1).

$$y_{FMA}{}^{(i)} = \frac{1}{1+2\cdot n} \cdot \sum_{i-n}^{i+n} y_{(i)} \tag{1}$$

For the DF engine, the mean-value filter is used as a filtering tool with the degree of 10 (5 values before and five values after) and the recommended sampling at 0.1 ℃A. The obtained KNK_PK value is only a single signal in each cycle. In addition to the in-cylinder pressure and detecting the presence of knocking, there was a need to check the coefficient of variation (CoV) for indicated mean effective pressure (IMEP) and P_{max} for all working cycles. Typical CoVs for IMEP and P_{max} of compressed-ignition engines are CoVIMEP (0.3-0.4%) and CoVp_{max} (0.3%). Currently, the KNK_PK method is being used more commonly to identify knocking than other analytical methods.

IV. Measurement Results

Measured results from selected samples in experiments using the DF engine are given below.

Figs. 9-11 show the brake-specific fuel consumption (BSFC) in the diesel modes with low, medium, and high revolution loads corresponding to 1500 rpm, 1900 rpm, and 2300 rpm. The diesel engine has very low fuel consumption at medium and high loads. The mean effective pressure value of the working cycle (BMEP) is 2.12 MPa at 100% load, which FMFR is fuel mass flow rate.

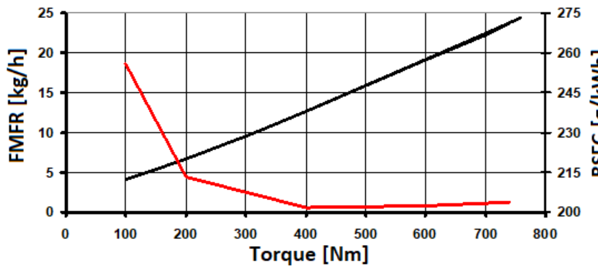

Figure 9. Diesel fuel consumption at the engine speed of 1500 rpm.

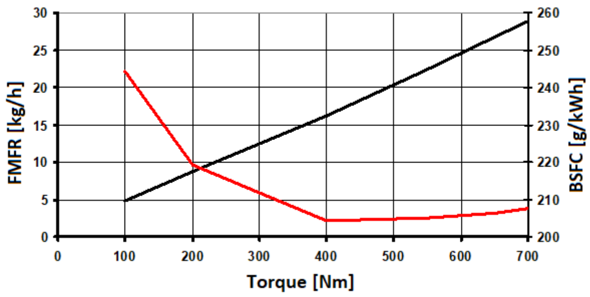

Figure 10. Diesel fuel consumption at the engine speed of 1900 rpm.

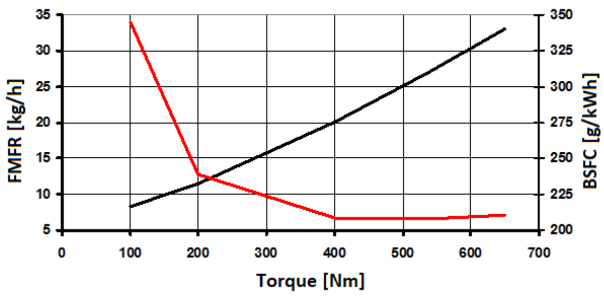

Figure 11. Diesel fuel consumption at the engine speed of 2300 rpm.

The Cummins engine is assumed that it has the same overall performance in the DF operation as in the diesel-only operation (see the black line in Figs. 12-14).

Therefore, the dual and diesel engines have the same input thermal energy. The operating status of the dual engine is indicated by the red arrow in Figs. 12-14. The released diesel energy is described as the red horizontal line in Figs. 12-14, and the LPG is depicted as the red vertical line.

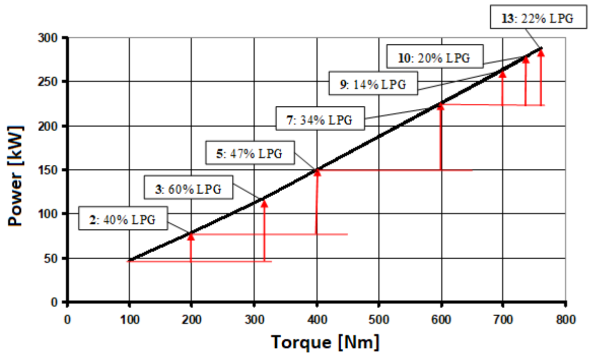

Figure 12. Engine heat input at the engine speed of 1500 rpm: diesel and LPG shares in the DF mode.

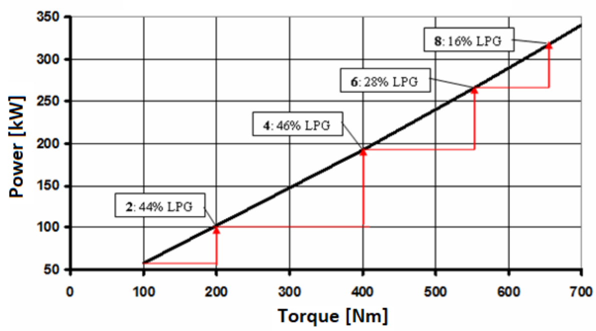

Figure 13. Engine heat input at the engine speed of 1900 rpm: diesel and LPG shares in the DF mode.

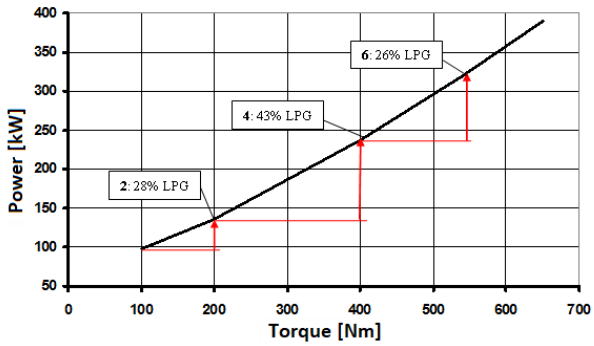

Figure 14. Engine heat input at the engine speed of 2300 rpm: diesel and LPG shares in the DF mode.

When increasing the engine torque at all speeds, the amount of LPG fuel substituted for diesel decreases. The main reason is that the amount of injected LPG fuel is limited by the detonation condition. The maximal percentage of LPG covered for diesel is injected so that the weak detonation is within the permissible detonation limit.

Figs. 15-17 show the average (avg) values of the maximum combustion pressures in the cylinder in load characteristic modes determined by high-pressure indication on the diesel and dual engine. The average combustion pressure in the DF operation is higher than that in the diesel-only operation. This is attributed to the adjustment of the early injected angle of the diesel between 10-14 °CA before TDC with a minimal pre-fuel injection rate and flammable LPG-air mixture. The increase in the combustion pressure in the DF operation does not considerably affect the technical quality of the original diesel engine.

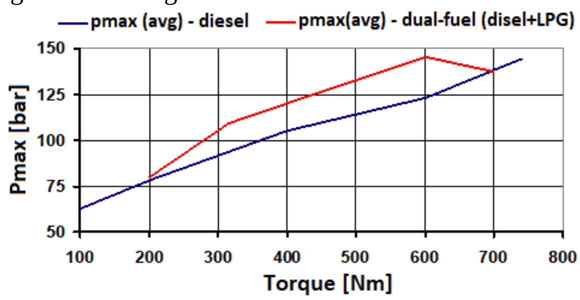

Figure 15. Maximal combustion pressure curves at the engine speed of 1500 rpm.

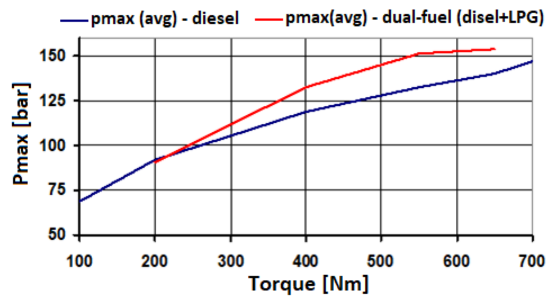

Figure 16. Maximal combustion pressure curves at the engine speed of 1900 rpm.

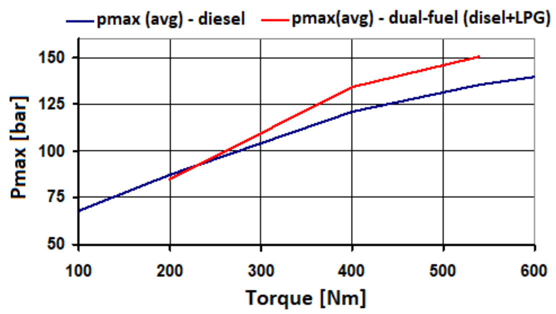

Figure 17. Maximal combustion pressure curves at the engine speed of 2300 rpm.

The peak values of cylinder pressure curves in the operating modes of the DF engine are indicated in Figs. 18-20.

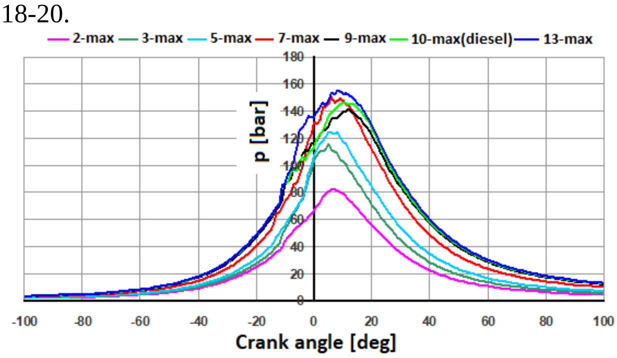

Figure 18. Cylinder pressure curves in the DF mode for engine speed 1500 rpm.

As observed in Fig. 18, the pressure curves of modes No. 3 and No. 7 show relatively weak knocking. This is a minimal increase pressure above the average pressures in the cylinder over 100 working cycles. The pressure curve of No. 10 shows that the cylinder pressure curve of diesel-only operation for comparison.

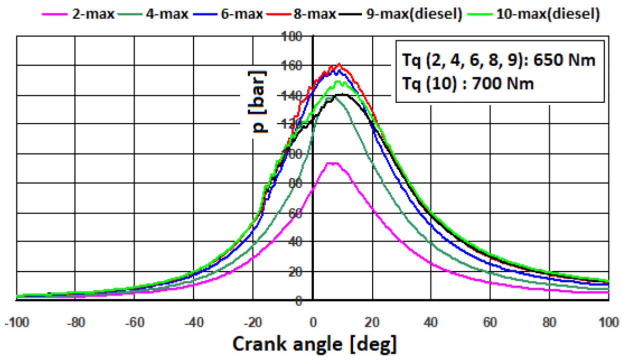

Figure 19. Cylinder pressure curves in the DF mode at the engine speed of 1900 rpm.

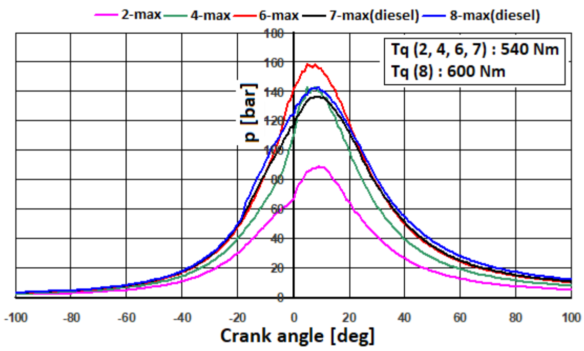

Figure 20. Cylinder pressure curves in the DF mode at the engine speed of 2300 rpm.

As observed in Fig. 21, the peaks of cylinder pressure curves in the same engine mode (speed and load) during the DF operation (No. 7: 63% diesel and 37% LPG) and diesel-only operation (No. 8) indicate marked differences during the in-cylinder combustion.

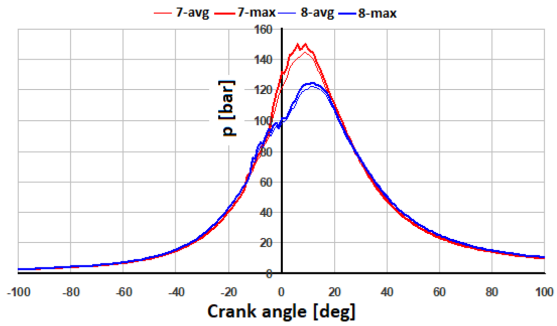

Figure 21. Comparison of cylinder pressure curves for n=1500 rpm and Tq=600 NM when engine running on diesel (No. 8) and in DF (No.7) operation.

The LPG mixed homogeneously with air in the combustion chamber. The diesel fuel injected into the combustion chamber created a heterogeneous mixture in which diesel is burned diffusely. The combustion kinetic reaction occurs rapidly during the delayed ignition period. The response is described by the slight undulation at the pressure curves at about 10 °CA before TDC. The difference of the maximum pressure in the cylinder between the DF and diesel-only operations is ascribed to the variation of burning rate (see Figs. 18-20).

A typical cycle was selected to analyze the detonation in 100 working cycles. The detonation signal was determined using the knock peak method throughout AVL_Concerto software. Fig. 22 shows the operating cycle of the DF and diesel-only engines with the same speed of 1500 rpm and the torque of 600 Nm.

For the DF operation, the knock can be observed in pressure curve No. 1, but it is not detected in pressure curve No. 2. The reason is that these two modes used different ratios of LPG/diesel fuel. The pressure curve No. 3 shows the diesel-only engine without detonation. The attached table indicates the CoV for p_{max} and IMEP in percentage. The CoVs in the DF operation are two times lower than those in the diesel-only operation. The detonation limit for dual fuel is determined at 5 bar pressure and is described by a horizontal light red line No. 4. However, the pressure is only about 2.5 bar in the non-knocking working cycle (see lines 2-3 in Fig. 22).

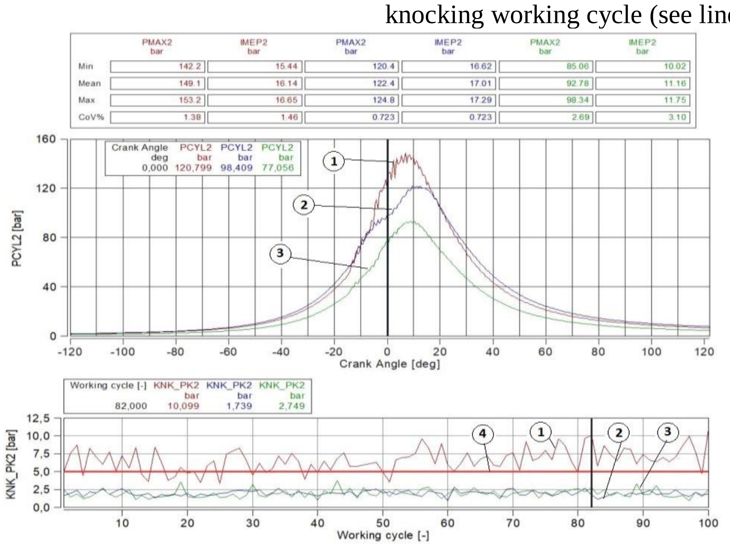

Figure 22. Comparison of a knock when engine running on diesel and DF operation.

V. Conclusion

The paper presents detecting the knocking in a modified diesel engine using LPG-diesel fuel. The engine has installed the injector with the LPG heated outlet nozzle. With the same performance parameters of the DF engine and the diesel engine, LPG fuel can substitute for 60% diesel at medium loads despite the maximum pressure increases in the combustion chamber. The use of substituted LPG leads to a significant reduction in CO_2 emissions and fuel consumption.

The measured results show that the limit of the knock peak was 5 bar pressure in the DF engine. Therefore, the knocking in the working cycle with the knock peak value higher than the limit was found.

The measurement and analysis in this paper can partially help to reduce the cost and time for developing the DF engine.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

RP conducted and designed the research on the knocking topic; AD and TZ prepared experiments and measured the data; RP, AD and DNP analyzed the literature and wrote the paper. RP, AD and TZ analyzed the data.; AD, DNP and TZ reviewed and corrected the paper; all authors had approved the final version.

Acknowledgment

This publication was written at the Technical University of Liberec as part of the Project SGS-2020-5015 - Simulation of the cycle-by-cycle variability of the spark-ignition with the support of the Specific University Research Grant, provided by the Ministry of Education, Youth and Sports of the Czech Republic in 2021.

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Radek Procházka was born in Jeseník, Czech Republic, in March 1993. He graduated in May 2012 at Gymnasium in Jeseník, Czech Republic. After that, he started to study Mechanical engineering at the Brno University of Technology, Czech Republic. He received the B. S. degree (Bc. title - bachelor) in 2015 in the field of Construction of Machines and Equipment. The M.S. degree (Ing. Title – engineer) he received in 2017 from study Mechanical engineering at the Technical University of Ostrava, Czech Republic, with a specialization in vehicles. His diploma thesis was Thermodynamic analysis of internal combustion engines.

By his master's studies, he worked from 2016 to 2017, as a development designer in 3D CAD Catia V5 in Hella Autotechnik Nova s.r.o., Design Office of Science and Technology center in Ostrava, Czech Republic. He is currently pursuing a Ph.D. degree from 2017 in Mechanical engineering at Technical University of Liberec, Czech Republic, specializing in internal combustion engines. His dissertation thesis is on the theme Simulation of cycle-by-cycle variability of the combustion process of the spark-ignition engine. From his Ph.D. study in 2017, he also works at the Technical University of Liberec as a Junior researcher. He works on several public and private projects as a full-fledged member of the team and also as a leader. He still works from 2018 as application support for the development of the racing engine in company ŠKODA AUTO a.s. – ŠKODA Motorsport, in Mladá Boleslav, Czech Republic.

Ing. Procházka is mainly focused on functional and longtime tests on internal combustion engines, different measurements from indication, temperatures, pressures, torque, work with the open electronic control unit, visualization, simulations, and subsequent evaluation of measured data. During his doctoral studies, from 2017, he published as an author or co-author about 10 publications.

Aleš Dittrich was born in November 1985 in Turnov – Czechoslovakia. He graduated from Gymnasium in Mnichovo Hradiště, Czech Republic, in 2005. After that started to study Mechanical engineering at the Technical University of Liberec, Czech Republic, he finished his studies in 2010 as an engineer in the field of internal combustion engines, and then he started to study Ph.D. at the same university and finished his Ph.D. in 2018 in the field of internal combustion engines. From 2011 to 2013, he completed pedagogical studies and became Ing. PAED.IGIP. Aleš used to work in several companies during his studies as a mechanic for ŠKODA AUTO company. After he finished his master thesis, he started to work at the Technical University of Liberec as a junior researcher. He used to work on several public and also private projects as a member of the team and also as a team leader. He was also a member of the project for educating the youth people, where he worked as a lecturer. During 2011 to 2017 he was employed in ŠKODA AUTO R&D center in Mladá Boleslav, Czech Republic. From 2017 to 2018, he worked on a specific project in The Institute of Information Theory and Automation (UTIA) - a public non-university research institution that administratively falls under the Czech Academy of Sciences. Since 2018 he has worked as an assistant professor at the Department of vehicles and engines at the Technical University of Liberec, Czech

Republic. His field of research is internal combustion engines. Between 2010 and 2020, he published as an author or co-author over 50 papers. He is also a co-author of the patent.

Tomáš Zvolský was born in July 1979 in Liberec – Czechoslovakia. He graduated from Secondary Technical School in Liberec, Czech Republic, in 1998. After that, he started studying Mechanical Engineering at the Technical University of Liberec, Czech Republic. He received the B. S. degree (Bc. title - bachelor) in 2002 in the field of Machines and Equipment. After bachelor graduating, he started working for MSV Systems Liberec as a machine designer. In 2003, he started studying Electrical Engineering and Computer Science at the Technical University of Liberec, Czech Republic. He received the M.S. degree (Ing. Title – engineer) in 2007. In 2013, he started studying Ph.D. at the same university, Faculty of Mechanical Engineering and finished his Ph.D. in 2020 in the field of electronic in internal combustion engines. In 2014, he started working at the Technical University of Liberec as a junior researcher. He used to work on several public and also private projects as a member of the team. Ing. Zvolský Ph.D. is mainly focused on functional and longtime tests of drive units and gearboxes. He also focuses on electronic control and measurement systems. Between 2014 and 2020, he published as an author or co-author over 30 papers or research reports. He is also a co-author of several patents and utility models.

Dong Nguyen Phu was born in Vietnam. He obtained his master's degree from the Technical University of Liberec in 2013. He has conducted his Ph.D. study at this university since 2019. His research focuses on alternative fuels on dual-fual engines as an author or a co-author published five publications.