STUDY ON THE KNOCK PHENOMENON ON A DUAL-FUEL ENGINES USING RENEWABLE FUEL BIOCNG/DIESEL

Nguyen Phu Dong[1], Nguyen Thanh Tuan[1]*, Ho Duc Tuan[1], Nguyen Quang Huy[2]

[1]*Nha Trang University, Vietnam*

[2]*Buon Ma Thuot College, Vietnam*

*Corresponding author: nguyenthanhtuan@ntu.edu.vn

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Abstract - The article focuses on researching and evaluating the effect of knocking in biomethane/diesel dual-fuel operating modes. Knocking occurs because part of the biomethane fuel is compressed at high temperatures and pressure. All experiments were performed on four-stroke Cummins diesel engines with an AC_STAG electronic control unit operating in dual-fuel mode. The system is installed with Ac dyno-measuring devices and other pressure, temperature, and emission-measuring devices. By the Knock Peak method used in the AVL Indicom software, high-pressure analysis during fuel combustion showed knocking in the cylinders. The maximum pressure deviation is also known as the knock peak value (KNK_PK). Knocking can be observed at dual-fuel mode with different pressure curves, which are higher than in diesel. The CoV coefficient of dual-fuel operation is higher than that of CI engine diesel fuel operation. The knock limit of biomethane/diesel dual-fuel has been shown in this study.

Key words – The knocking; KNK_PK; the knock of dual-fuel engines; biomethane/diesel; bioCNG/diesel

1. Introduction

The EU Directive 2018/2001 of the European Parliament and the Council of 2018 on the promotion and use of energy from renewable sources establishes a common framework for Europe. The target by 2030 is for renewable energy sources to replace traditional energies by 32% [1]. It also sets sustainability and greenhouse gas emission reduction criteria for biogas, bio-liquids, and biomass fuels. To solve the above energy and environmental problems, most current research focuses on finding new energy sources from methyl esters and fatty acid ethyl esters (FAME) produced from vegetable oils, hydrogenated vegetable oils (HVO), dimethyl ether (DME), methanol, ethanol, butanol, biomethane (bioCNG), biofuels LPG, hydrogen, and other renewable energy sources can wholly or partially replace traditional fuels [2].

With the high thermal efficiency and low greenhouse gas emissions of diesel engines, it is being appreciated by users in the crisis of energy shortage and environmental pollution. Therefore, researchers are looking for other energy sources to partially replace the diesel in CI engines (compression ignition engines). In that context, biomethane is an important research subject that has always interested researchers. This fuel is used in bioCNG/diesel dual-fuel operating mode in CI engines [3].

Biomethane gas is a clean, and environmentally friendly fuel source. It hastechnical characteristics suitable for heat engines. When burned, it produces fewer toxic products. They are very renewable, and abundant raw fuel resources lead to low production and operating costs. Therefore, studying dual-fuel diesel engines running fuel from renewable sources, such as biomethane, to replace diesel is a suitable and feasible solution for real-life economics, and they meet the above conditions. The properties of bioCNG fuel from renewable sources and CNG from fossil sources are practically identical after bioCNG has been purified of impurities and has a methane concentration of approximately 95%, as described in Table 1 [4].

A dual-fuel engine means that a diesel engine uses two types of fuel simultaneously at different ratios to keep the engine running. In this case, part of the diesel fuel is replaced by biomethane gas, which is the main energy source to maintain the operation of dual-fuel engines. BioCNG gas is injected and mixed with the air in the intake manifold of the engine and is sucked into the cylinder; diesel fuel acts as the ignition source to ignite the bioCNG-air mixture [5].

Unlike diesel engines, dual-fuel engines have a knocking tendency at high speeds and loads. The knock appears partly due to the physicochemical properties of bioCNG fuel, which are caused during combustion at high pressure and temperature [6]. Continuous knocking will reduce the efficiency of dual-fuel engines and increase emissions due to incomplete combustion. Moreover, the strong local knock can cause damage to the piston and cylinder structure, leading to high operating and repair costs.

The main purpose of this study is to compare and evaluate the knocking phenomenon that occurs when diesel engines operate dual-fuel bioCNG/diesel, and improve their performance.

2. Materials and methods

2.1. Properties of renewable alternative fuels

EU legislation considers alternative engine fuels for dual-fuel engines, particularly biomethane (bioCNG) or compressed natural gas (CNG), as described in Table 1. The main component of natural gas (CNG) is methane. Methane content in natural gas at different extraction sites ranges from 80% to 99% [7]. Other components of natural gas are hydrocarbons, nitrogen, carbon dioxide, and small amounts of other gases [8]. The main advantages of using natural gas as an automotive fuel over gasoline and diesel are generally oil savings, less environmental impact due to harmful emissions, and lower CO_{2eq} production assessed in the WtW test cycle [2]. The downside is that they are fossil-based, and with vehicle development and over-exploitation rates, they will gradually run out in the coming years.

***Table 1.** Basic parameters of diesel fuel, CNG, and bioCNG [2]*

Parameter [unit]	Diesel	CNG	BioCNG
C content [% mass]	86.2	74.7	74.7
H content [% mass]	13.5	24.9	24.9
Other elements [% mass]	0.3	0.4	0.4
Density at 20^0C [kg/m^3]	835	0.68	0.68
Calorific value [kWh/kg]	11.94	13.9	13.9
Octane number [-]	-	125	125
WtW [kg CO_{2eq}/kg]	3.84	3.28	0.36 - 0.83

Biomethane (bioCNG) is produced from biogas. Biogas is made from the biodegradation of organic matter under anaerobic conditions, known as anaerobic methane fermentation of organic materials. Biogas is not considered landfill gas; it contains less harmful gases. Methane fermentation is created by a mixture of gases and residues of fermented organic matter. The gas mixture contains two main gases, methane CH_4, about 60 - 70%, and carbon dioxide CO_2, about 30 - 40% [9]. Biomethane is obtained by refining biogas, using membrane separation technology to achieve the same quality and purity as fossil-derived natural gas. Biomethane must contain a minimum of 95% methane concentration. The fuel characteristics of biomethane from renewable sources and fossil-derived natural gas are practically the same.

2.2. Method of determining the knocking phenomenon

The knocking in engine cylinders is one of the factors caused by bioCNG fuel in dual-fuel engines. During the combustion process, energy is released locally in some places, leading to overload for engine parts and adversely affecting the overall combustion in the cylinder. Knocking usually occurs when the fuel mixture is not burned completely. This phenomenon occurs partly due to the excess bioCNG-air mixture (the unburned mixture remaining in the cylinder) at high pressure and temperature, where the right conditions exist for pre-combustion to form. This phenomenon is self-igniting and uncontrolled combustion. In addition, it depends on the characteristics of the fuel, such as the fuel's octane number or mixture ratio and mixing time. The higher the bioCNG replacement ratio for diesel, the easier it is to cause knock in the combustion process. When knocking occurs, a pressure wave is generated in the combustion chamber, propagating through it, and can be measured.

The peak pressure measurement method is often used to determine the knocking phenomenon in the cylinder, also known as the Knock Peak Method (KNK_PK). The AVLx-ion device can measure the combustion pressure in the engine, and the knock is analyzed by the high-pressure indicator in the engine cylinder, supported by Indicom software. High-pass pressure indications are filtered within the all-pass pressure indications range by eliminating low-pass pressure indications. After analysis, the KNK_PK value gives only one value for one cylinder combustion pressure measurement cycle. The maximum high-pass pressure deviation is compared with the knock limit or average value filter to determine whether the motor appears to knock. For this study on dual-fuel engines, the mean value filter was used to compare with the high-pass pressure values. The filter value is ten (five values before and five after), with the crankshaft angle measurement value as small as 0.1°CA. The mean value filter is based on Eq. (1) [6].

$$Y_{FIR}{}^{i} = \sum_{j=i-n}^{j+n} k_j . Y_j \tag{1}$$

$$k_j = h_j . C_j$$
$$h_j = \frac{1}{2}\left(1 + \cos\left(\frac{2.\pi.j}{2.n+1}\right)\right) \tag{2}$$

where: n = number of elements [-]; i, j = order of element [-]; y = general values [-].

Low-pass pressure indications

$$C_j = \frac{\sin\left(2.\pi.\frac{f_c}{f_s}.j\right)}{\pi.j} \qquad C_0 = 2.\frac{f_c}{f_s} \tag{3}$$

High-pass pressure indications

$$C_j = -\frac{\sin\left(2.\pi.\frac{f_c}{f_s}.j\right)}{\pi.j} \qquad C_0 = 1 - 2.\frac{f_c}{f_s} \tag{4}$$

where: f_c - selected frequency [Hz]; f_s - sampling frequency [Hz].

2.3. Percentage of biomethane substitution fuel

It is important to determine the alternative fuel ratio so that the biomethane-air mixture is poor and the amount of diesel is minimal to maintain stable engine operation. Biomethane fuel is in a gaseous state, while diesel is in a liquid state. Usually, the percentage of energy replaced determines the ratio of biomethane substitution because the total energy input is the same in both cases (biomethane/diesel dual-fuel and diesel-only operation) [10]. This energy replacement ratio has a major impact on the combustion and emissions of dual-fuel engines. The symbol CCR (Co-Combustion ratio) is defined as the percentage of bioCNG energy to the total dual-fuel energy, as shown in Eq. (5) [11]:

$$CCR = \frac{\dot{m}_{bioCNG}.H_{ubioCNG}}{\dot{m}_{bioNG}.H_{ubioCNG} + \dot{m}_D.H_{uD}}.100\% \tag{5}$$

where: $\dot{m}_D$ and $\dot{m}_{NG}$ represent the pilot diesel fuel and bioNG consumption per cycle [mg/cyc], while $H_{ubioCNG}$: 49,54 [MJ/kg] and H_{uD}: 42,5 [MJ/kg] denote the lower heating value.

3. Experimental setup

At the laboratory of the Faculty of Vehicles and Engines of the Liberec Technical University, a prototype dual-fuel engine was designed based on an existing diesel engine. The dual-fuel engine has been converted from the Cummins ISBe4 diesel engine (specs are listed in Table 2), with the common rail fuel system and controlled by a capable ECM 850 controller that injects diesel in three different phases into the cylinder, with a main injection dose of approximately 10°C before top dead center (TDC).

Table 2. *Engine parameters specified for laboratory measurements [12]*

Description	Value
Type	Cummins ISBE/ CI/ EURO 4/ 4 cylinder inline/ turbocharged/ aftercooled/ DOHC
Engine displacement	4.5 dm3
Stroke/Bore	119/102 mm
Compression ratio	17.3:1
Maximum power	152 kW
Maximum torque	760 Nm
Cooling system	water

The diesel engine is equipped with a dual-fuel supply system electronically controlled by Ac STAG-Diesel. The accompanying equipment includes a gas pressure regulator, an air release valve, an bioCNG-air mixer, a control unit, and sensors for various operating parameters, depicted in Figure 1. The dual-fuel Cummins engine was installed on a test bed equipped with a dyno AC, engine cooling system, air temperature control, and other external measuring devices (temperature, pressure, flue gas analysis). The fuel combustion pressure of the engine was measured by an AVL X-ion device, which was then analyzed for high-pass pressure indication by AVL-Indicom software [13].

To have a basis for comparing the parameters of dual-fuel engines operating with bioCNG/diesel or diesel, it is first necessary to establish the operating parameter conditions, such as: The total energy supplied to the engine in both cases is the same; the engine coolant and air temperatures need to be controlled similarly. Therefore, when the engine operates on dual-fuel with different bioCNG substitution ratios, the diesel and bioCNG injection amounts must follow a predetermined and calculated injection map. Those parameters are set in the software's injection map. In this study, the bioCNG substitution ratio for diesel was set with the maximum injection map for each engine operating mode, increasing from low to maximum load, and speeds of 1,500 rpm, 1,900 rpm, and 2,300 rpm.

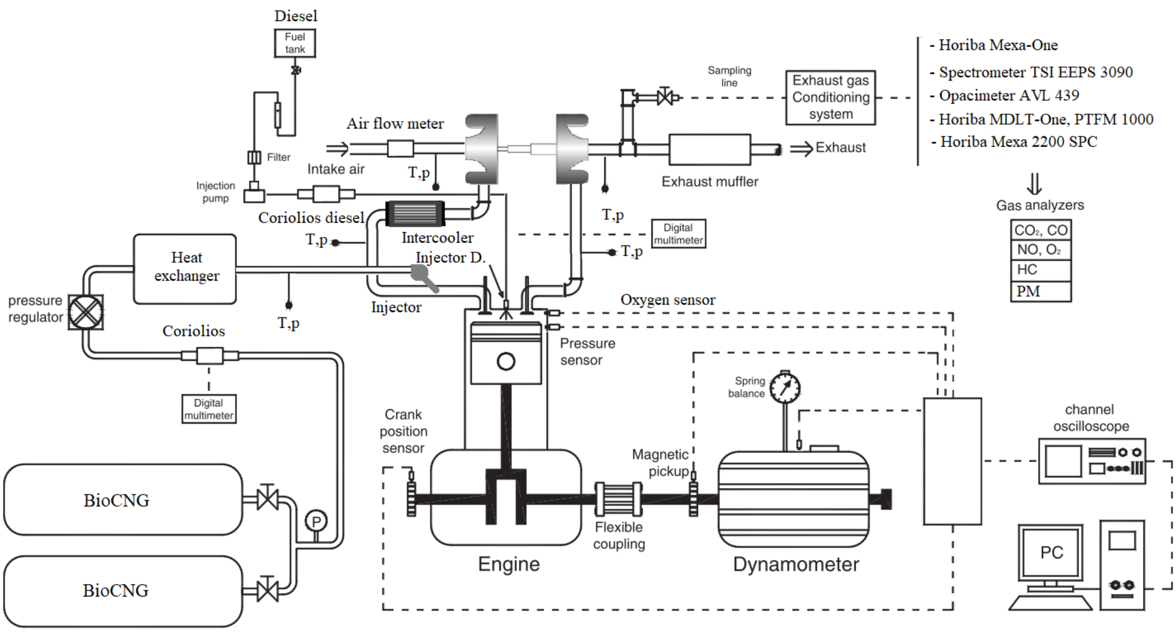

Figure 1. *Diagram of the experimental setup and dual-fuel Cummins engine*

4. Results and discussion

This paper describes the knocking phenomenon of the dual-fuel engine using a speed of 1900 rpm and the maximum load. The measurement is performed so that the load increases gradually for each fixed measurement speed, from an initial load of 100 Nm to the maximum load of 600 Nm (the deviation between the measured values is 100 Nm).

To increase the accuracy of measurement results or eliminate random errors, all the above test cases need to be retested many times under the same engine operating conditions, with one measurement being 200 cycles. Initially, the Cummins engine operates in full diesel mode; when the engine operates stably, it switches to dual-fuel mode. The bioCNG energy substitution ratio is gradually increased until the engine begins to exhibit knocking phenomena, after which the engine is adjusted to operate stably and measured.

In Figure 3, the dual-fuel diesel engine's bioCNG substitution ratio decreases linearly in the opposite direction with load. This means that at the lowest load, the bioCNG substitution ratio is the largest, and vice versa occurs at all engine speeds. In this case, the bioCNG energy substitution ratio is relatively high, with a maximum of 81% at 2,300 rpm and 74% at 1,900 rpm when operating at a load of 100 Nm. This may result in some weak knocking, but they are still within acceptable limits. Thanks to the good physical and chemical properties of bioCNG fuel, such as a high-octane number (125), the substitution ratio of bioCNG has increased more than that of other renewable fuels.

Figure 2. *Functional sample of a dual-fuel engine in the laboratory*

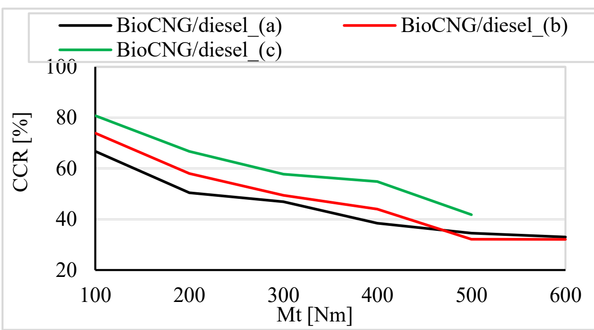

Figure 3. *Energy substitution percentage of bioCNG for diesel according to engine loads (a) 1500 rpm, (b) 1900 rpm, (c)2300 rpm*

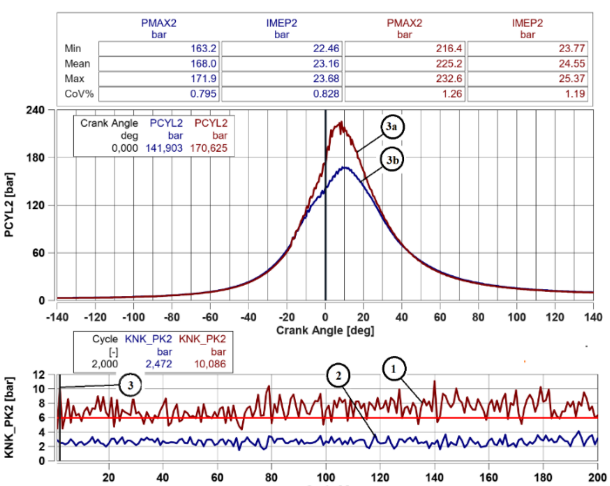

Figure 4. *Cylinder pressure curve when operating bioCNG/ diesel, knocking was analyzed by KNK_PK2 - With knocking*

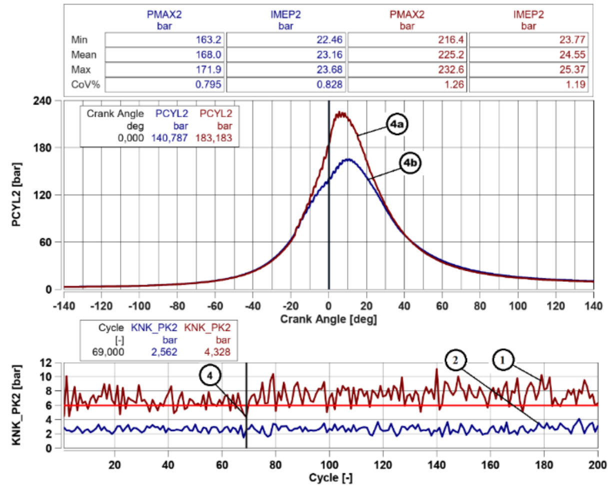

Figure 5. *Cylinder pressure curve when operating bioCNG/diesel, knocking was analyzed by KNK_PK2 - Without knocking*

1 - high-pass pressure indicator of bioCNG/diesel; 2 - high-pass pressure indicator of diesel; 3 and 4 - The cycle with the knock is selected for analysis; 3a, 3b are the maximum pressure curves with knocking and 4a, 4b without knocking of bioCNG/diesel and diesel, respectively

Figures 4 and 5 show the maximum combustion pressure curve (PCYL2) versus crankshaft angle of the engine with different fuels; the graph below shows the peak knock pressure (KNK-PK2). The maximum combustion pressure and peak knock pressure of dual-fuel are shown in dark red, and diesel in green. The maximum combustion pressure curve is selected to represent one cycle in 200 consecutive cycles. From the figures below, it is easy to see that the maximum combustion pressure of bioCNG/diesel in dual-fuel engines is higher when operating only one liquefied fuel (diesel) in all modes of engine load and speed. The maximum combustion pressure of dual fuel is higher and has a peak closer to TDC than diesel fuel because the combustion of the bioCNG fuel mixture is faster than that of diesel fuel. The calorific value of bioCNG is also higher than that of diesel.

The AVL-Concerto software supports the calculation method of the mean value filter, which gives the knock limit value for the dual-fuel engine as 6bar. The bright red horizontal indicator line in the KNK-PK2 graph depicts this value. The KNK_PK2 indicator is higher when operating dual fuel (bioCNG/diesel symbol number 1) than when operating liquid fuel (diesel symbol number 2). Most dual-fuel combustion cycles have peak knock pressure indications higher than the knock limit value with a continuous frequency of 200 measurement cycles. Part of the reason is that a large amount of bioCNG fuel replaces diesel at a high percentage, at high speeds and high loads, resulting in large amounts of unburned or incompletely burned bioCNG fuel combined with high pressure and temperature conditions that are prone to knocking.

CoV_Pmax and CoV_IMEP [%] are parameters that help analyze the quality of the combustion process. The value of this parameter is low to demonstrate the stability of the combustion process and help the engine operate better. From the table above, graphs 4 and 5 show that the Cummins engine operating with single diesel and dual-fuel bioCNG/diesel has CoV_Pmax and CoV_IMEP values that are much lower than those of gasoline engines (the average value of gasoline engine CoV_Pmax = 8-9% and CoV_IMEP = 2%); with the diesel engine operating, CoV_Pmax = 0.795% and CoV_IMEP = 0.828%; and the engine operating with dual-fuel bioCNG/diesel CoV_Pmax = 1.26% and CoV_IMEP = 1.19%. This proves that the combustion process of dual-fuel bioCNG/diesel in a diesel engine is good, as it does not affect the stability of engine operation.

Typically, gasoline engines have a higher CoV% than diesel engines, partly due to changes in the ignition process and the influence of fuel chemistry. The same is true for dual-fuel engines, as the ignition and flame propagation with biomethane are highly variable. However, combustion stability can be improved by increasing the intake temperature or introducing hot EGR at low engine loads [14]. It can also be seen that as the engine load increases, the CoV% decreases. At low engine loads, the bioCNG/air mixture is very lean, resulting in large cycle changes. While the engine load increases, the excess air coefficient decreases and at the same time the temperature in the cylinder increases, so the flame spreads faster and the combustion time is shorter, thus reducing the CoV%.

5. Conclusion

From the above results, the dual-fuel engine has determined the knock limit and the knock frequency. Specifically, in this study, the knock limit value is 6 bar. From there, it is possible to adjust the ratio of bioCNG fuel to replace diesel fuel to suit each different speed and load without knocking in the engine. The study showed that the knocking phenomenon occurred frequently when replacing the largest bioCNG fuel energy ratio, about 33.5%, at the maximum load of 600 Nm and speed of 1900 rpm in 200 test cycles. The knocking phenomenon occurred but was still within the allowable limits, with CoV_{pmax} and $CoV_{\_IMEP}$ having small values of 1.26% and 1.19%, respectively.

On the other hand, the method of heating the bioCNG-air fuel mixture on the intake manifold helps to increase the efficiency of the combustion process and, to some extent, also helps to reduce knocking in the engine. With the dual-fuel engine model, it is easy to switch from the diesel engines available on the market with low cost, low fuel operating costs, and a sharp reduction in CO_2 exhaust emissions and particulate emissions. BioCNG fuel is a new, environmentally friendly fuel source that contributes to ensuring future energy security.

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