TRANSPORT PROBLEMS 2023 Volume 18 Issue 3
PROBLEMY TRANSPORTU DOI: 10.20858/tp.2023.18.3.15

Keywords: natural gas; intake valve timing; emissions; environmental performance

Tadas VIPARTAS[1]*, **Alfredas RIMKUS**[2], **Jonas MATIJOŠIUS**[3]

THE INFLUENCE OF INTAKE VALVE CLOSE TIMING ON THE ENVIRONMENTAL PERFORMANCE OF A SPARK IGNITION ENGINE USING GASOLINE AND NATURAL GAS

Summary. The tightening of environmental requirements has forced car manufacturers to look for various ways to reduce exhaust gas emissions. The existing structural solutions of internal combustion engines allow this type of pollution to be reduced by adjusting the intake valve timing. This is especially relevant when it comes to reducing spark ignition engine emissions when using natural gas as fuel. In this study, a wide range of intake valve timing adjustments from 24° to 54° every six crank angle degrees was taken at a constant engine speed ($n = 2500$ rpm) and different loads and fixed excess air ratios ($\lambda = 1$). The changes in oxygen (O_2), carbon monoxide (CO), carbon dioxide (CO_2), nitrous oxide (NO_x), methane (CH_4), and propane (C_3H_8) gas emissions were observed in the aforementioned intake valve timing range.

1. INTRODUCTION

Variable valve timing (VVT) is a modern technology that ensures emission reductions in spark ignition (SI) engines. The time at which the intake valves close can be adjusted in order to improve the efficiency of the engine, optimize the combustion process, and reduce the emissions of harmful pollutants. Increasing the amount of time that the intake valve is closed can lead to increased fuel flow, improved management of the combustion process, and a decrease in emissions. It allows an increase in the maximum power but, at the same time, ensures lower brake-specific fuel consumption and exhaust gas emissions [1].

The precise timing of the intake valve closure plays a crucial role in ensuring optimal fuel combustion and overall engine efficiency. Closure times that are too long or brief can result in uneven fuel combustion, fuel wastage, diminished engine performance, and heightened environmental pollutants. There is an ecological effect when replacing gasoline (G) with natural gas (NG). The specific timing with which the intake valve is closed influences the performance of an engine using natural gas as fuel. The aforementioned parameter possesses the potential for adjustment in order to achieve the optimal regulation of fuel flow and maximize combustion efficiency. In the context of using natural gas, it is common for the closure timing of the intake valve to deviate from that observed while exclusively employing gasoline. The observed disparity can be attributed to the distinct physical features and combustion characteristics inherent to gasoline and natural gas. As the combustion speed slows down and the combustion temperature decreases, NO_x emissions also decrease [2]. While using VVT, this tendency becomes even more pronounced [3]. The application of advanced engine technologies, such as VVT and natural gas as fuel, plays a crucial part in the advancement of high-performance and environmentally friendly engines [4].

---

[1] Vilnius Gediminas Technical University, Faculty of Transport Engineering; Plytinės Str. 25, LT-10105 Vilnius, Lithuania; e-mail: tadas.vipartas@vilniustech.lt; orcid.org/0000-0001-6686-0642

[2] Vilnius Gediminas Technical University, Faculty of Transport Engineering; Plytinės Str. 25, LT-10105 Vilnius, Lithuania; e-mail: alfredas.rimkus@vilniustech.lt; orcid.org/0000-0001-8995-7180

[3] Vilnius Gediminas Technical University, Faculty of Transport Engineering; Plytinės Str. 25, LT-10105 Vilnius, Lithuania; e-mail: jonas.matijosius@vilniustech.lt, orcid.org/ 0000-0001-6006-9470

* Corresponding author. E-mail: tadas.vipartas@vilniustech.lt

High-performance internal combustion systems promote emissions reduction through efficient fuel injection and exhaust cleaning systems [5]. The use of these technologies helps meet increasingly strict emissions requirements while delivering efficient and powerful performance [6], paving the way for a more sustainable future of transportation [7]. VVT is also used in hybrid cars that operate on the Atkinson cycle, while fuel economy could be increased by up to 30% [8]. There are multiple methodologies for lower emissions; nevertheless, a definitive alternative has yet to be identified for commercial use [9].

The primary characteristics and parameters of cognitive sustainability have been recognized, and a number of major study areas have been delineated [2]. A significant reduction in CO_2 emissions (about 25%) compared to a typical spark-ignition engine fueled by gasoline was observed for transient driving cycles and natural gas as fuel [8]. Contemporary laboratory measurement cycles are predicated upon a fixed methodology for replicating a given trajectory within specific measurement parameters [11]. In addition, hydrogen can be added to natural gas to reduce methane concentration in exhaust gas, which is identified as an important contribution to global warming [12]. Moreover, hydrogen and natural gas are renewable, emit fewer emissions, and could have significant benefits for the countries' economies compared to fossil fuels [13]. In combination with VVT, when using the skip cycle strategy (where the engine valves are switched off at part load), the ecological effect increases, NO_x concentration is reduced by ~35%, ~39%, and ~27%, and HC emissions are reduced by ~55%, ~49%, and ~47% at break mean effective pressure (BMEP) values of 1, 2 and 3 bars [9].

The investigation of the effects of VVT and the Miller cycle on hydrogen engine performance revealed that delayed intake valve close (IVC) timing improves brake thermal efficiency, optimizing intake and exhaust VVT and controlling NO_x emissions [15]. Cooling, heating, and power systems have been shown to enhance the integration of renewable energy sources, optimize the balance between energy supply and demand, and contribute to significant reductions in primary energy use. The implementation of VVT enhances the operational range of the system and effectively mitigates carbon dioxide emissions [16].

The influence of valve timing changes on engine performance and exhaust gas emissions were evaluated in the study, where three different valve overlaps (104°, 108°, and 112°) were chosen. The findings indicate that by decreasing the overlap period and increasing the compression ratio, both the overall performance and exhaust emissions are enhanced. This leads to an augmentation in volumetric efficiency and brake thermal efficiency [17]. Emission control catalysts are employed in order to mitigate total power emissions, yet they encounter challenges in effectively eliminating pollutants prior to the attainment of the engine's light-off temperature. The implementation of a variable valve control (VTC) system during engine initiation results in an extension of the valve overlap duration, leading to a reduction in engine-out emissions (EOE) and subsequent mitigation of EOE levels. Nevertheless, this particular approach necessitates a duration of three seconds for the application of hydraulic pressure, resulting in an elevation of the overall energy output. A novel VTC system with an optimal angular position locking mechanism has been developed. This innovative system successfully reduces engine-out emissions by enhancing valve overlap [18].

The purpose of this investigation was to determine how the IVC timing change from 24° to 54° at intervals of 6° can affect the environmental performance of an internal combustion engine running on conventional gasoline and natural gas.

2. MATERIALS AND METHODS

Experiments were run in the internal combustion engine laboratory at Vilnius Gediminas Technical University using a Nissan HR16DE SI engine that was outfitted with a dual fuel delivery system. The engine was modified to operate with both liquid and gaseous fuels. The gasoline and gas injectors are controlled by an open electronic control unit (Motec M800), which is also used in conjunction with intake valve close (IVC) timing. These injectors are mounted in the intake manifold of the vehicle. Table 1 presents the technical specs of the SI engine, while the properties of G and NG [10] are presented in Table 2.

The load for the engine is created by an eddy-current-type bench AMX200/100 through the shaft with a maximum brake torque of 480 Nm. In order to evaluate the change in ecological indicators, engine speed (n = 2500 rpm), different load (M_B = 40, 70, 100 Nm ($BMEP$ = 0.31, 0.55, 0.79 MPa)) and intake valve close timing were used, while the excess air ratio (λ = 1) was fixed during all experimental tests.

Six different timings for the IVC were used: 24°, 30°, 36°, 42°, 48°, and 54° (crank angle degrees) after bottom dead center (CAD aBDC). The SI engine operated on E95 gasoline after replacement with natural gas during the experimental tests. Gasoline was supplied from the fuel tank by a low-pressure pump, while natural gas entered the intake manifold from a high-pressure tank through a valve and reducer. The amount of fresh air entering the engine was controlled by the throttle valve. A Coriolis mass flowmeter (RHEONIK RHM 015) was used to evaluate the consumption of natural gas, while gasoline consumption was measured with a fuel mass meter. Fig. 1 presents a principal diagram of the SI engine and its associated equipment.

Table 1

Specifications of the HR16DE engine

Parameter	Value
Engine type	Four-stroke, naturally aspirated
Number of cylinders	4
Cylinder arrangement	In-line
Firing order	1-3-4-2
Displacement (cm^3)	1598
Bore (mm)	78.0
Stroke (mm)	83.6
Compression ratio	10.7
Max. power (kW)/speed (rpm)	84/6000
Max. torque (Nm)/speed (rpm)	156/4400
Gas distribution system	DOHC
Intake valve timing (°)	228
Exhaust valve timing (°)	208
Injection mode	Port fuel injection
Fuel type	Gasoline, natural gas

Table 2

Fuel properties

Properties	Unit	Gasoline	Natural gas
Density	kg/m^3	740	~0.74
Lowering heat value (LHV)	MJ/kg	44	47.5
Air/fuel ratio (stoichiometric)	-	14.7	17.2
C/H ratio		6.13	3.16
Flame propagation speed	m/s	0.415	0.41
Ignition energy	mJ	0.24	0.3
Self-ignition temperature	°C	~400	~540
Quantity of methane (CH_4), by volume	%	-	91.9

Emissions were measured with gas analyzer MRU MGAprime before the catalyst converter in the engine exhaust system. Data of oxygen (O_2), carbon dioxide (CO_2), carbon monoxide (CO), nitrous oxide (NO_x), methane (CH_4), and propane (C_3H_8) were recorded at a fixed engine speed, load, and intake valve close timing crank angle degree. The characteristics of the exhaust gas analyzer are outlined in Table 3.

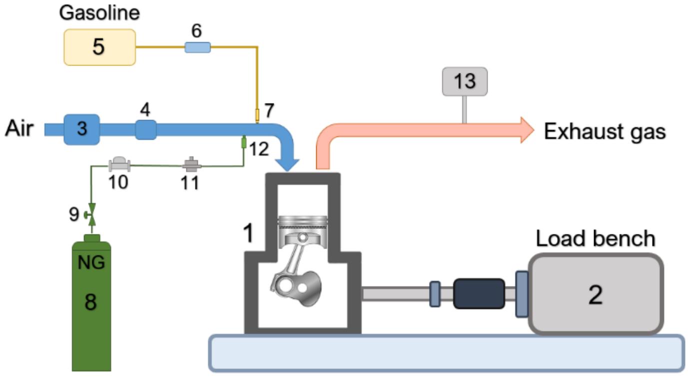


Fig. 1. Principal diagram of internal combustion engine and experimental equipment: 1 - SI engine; 2 - load bench; 3 - air mass meter; 4 - throttle unit; 5 - gasoline tank; 6 - gasoline consumption meter; 7 - fuel injector; 8 - natural gas tank; 9 - valve; 10 - gas flow meter; 11 - high-pressure reducer; 12 - gas injector; 13 - exhaust gas analyzer

Table 3

The specs of an exhaust gas analyzer

Gas type	Scope of measurement min/max	Resolution	Repeatability
O_2	0 ... 25/100%	0.01%	0.1% (1% reading)
CO_2	0 ... 40%	0.01 Vol%	0.2% (1% reading)
CO	0 ... 175/10.000 ppm	0.1 ppm	2 ppm (1% reading)
NO_x	0 ... 200/4.000 ppm	0.1 ppm	2 ppm (1% reading)
CH_4	0 ... 500/10.000 ppm	0.1 ppm	10 ppm (1% reading)
C_3H_8	0 ... 200/5.000 ppm	0.1 ppm	2 ppm (1% reading)

Before each test, the engine ran to reach the operating temperature to ensure the stabilization of data, repeatability, and reliability. The exhaust gas concentration was fixed for 1 min every 3 s.

3. RESULTS AND DISCUSSION

The increasing stringency of environmental regulations compels automobile makers to investigate a variety of strategies that can cut down on the emissions of exhaust gases. Adjusting the timing of the intake valves is one of the structural solutions already available in internal combustion engines that makes it possible to reduce this kind of pollution. When it comes to the reduction of emissions produced by SI engines when using natural gas as fuel, this is essential.

The percentage of carbon dioxide (CO_2) in greenhouse gases experiences minimal fluctuations (about 14.6%) during engine operation for G fuel across all evaluated loads (refer to Fig. 2). This can be attributed to the maintenance of a stoichiometric fuel mixture ($\lambda = 1$).

Changing IVC timing causes no substantial difference in the concentration of carbon dioxide (CO_2). However, it is worth noting that when an SI engine is operating on natural gas, there is a decrease in CO_2 concentration of around 10.9%. A carbon dioxide (CO_2) concentration of around 10.9% was measured when the engine was operated on NG as fuel.

The concentration of carbon dioxide (CO_2) in natural gas is 25% lower than in gasoline due to the lower carbon-to-hydrogen (C/H) ratio of NG fuel (~3) compared to gasoline (~6), as shown in Table 2.

The exhaust gas from both G and NG exhibits a concentration range of 0.6% to 0.8% for O_2, as depicted in Fig. 3. This observation indicates that a stoichiometric mixture is effectively maintained.

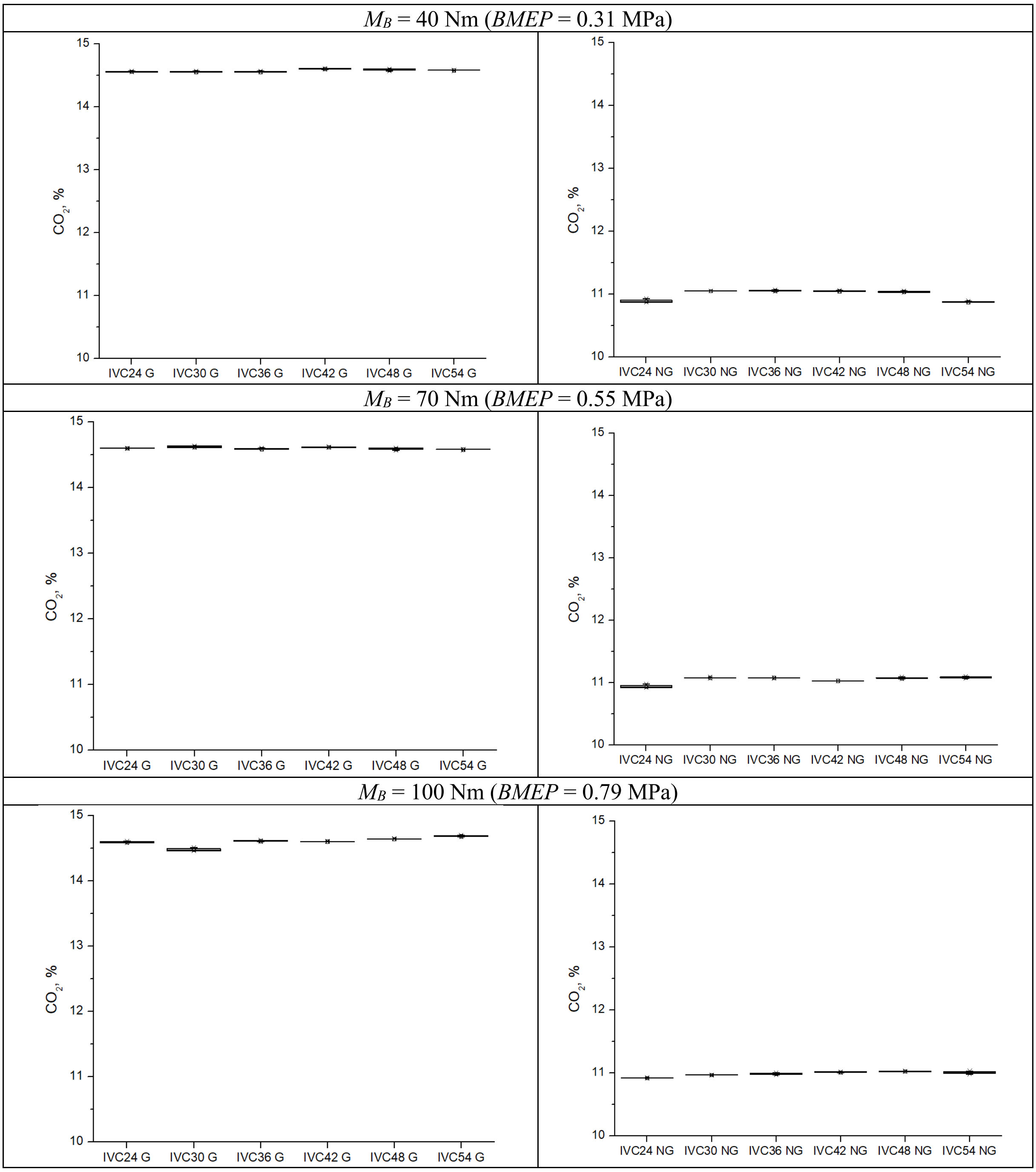
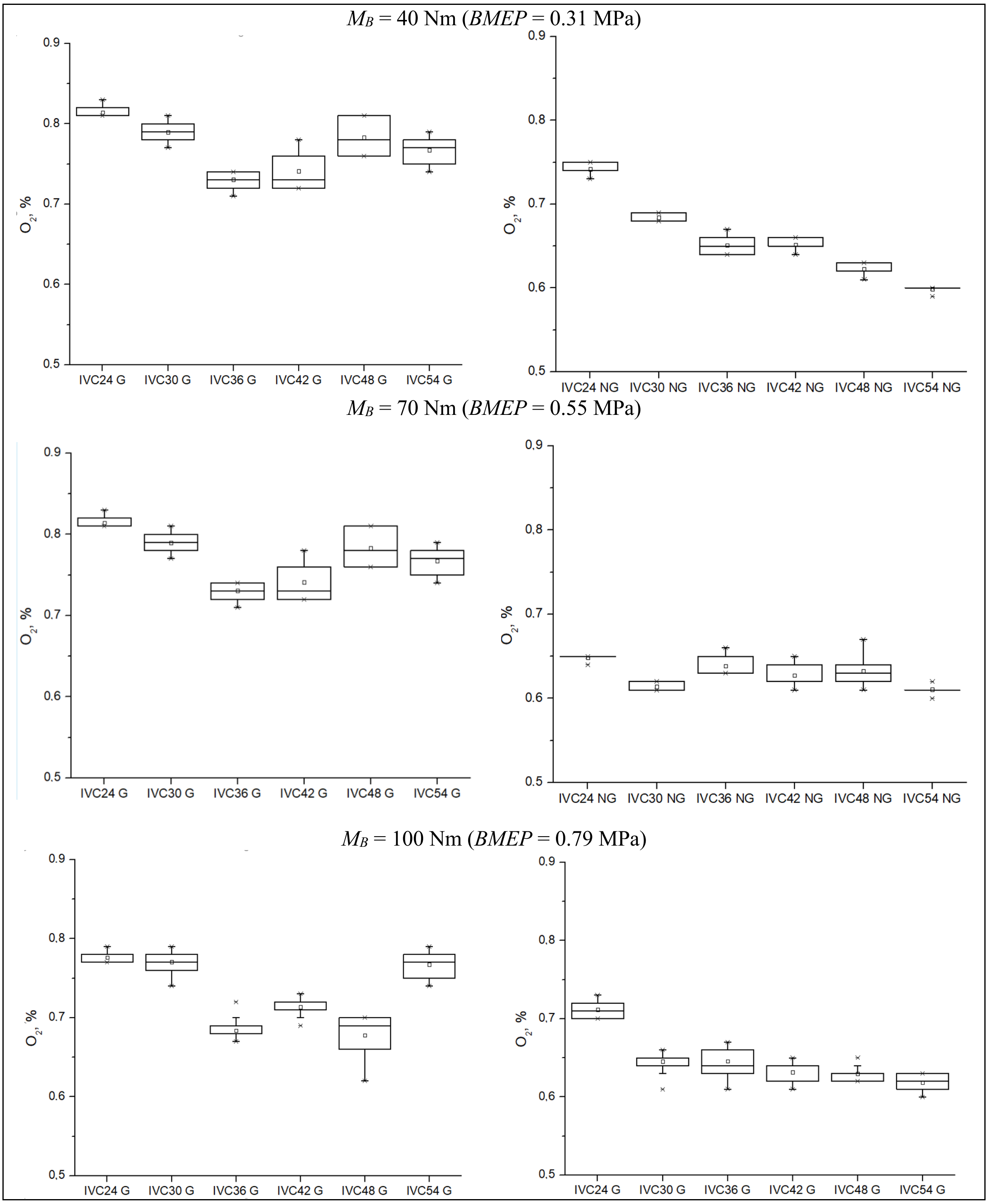


Fig. 2. Carbon dioxide (CO_2) emissions in exhaust gas. The engine was operated on G and NG when the IVC timing was adjusted

During the operation of the engine at low and medium load conditions (*BMEP* = 0.31 ... 55 MPa) and when altering the IVC timing, there is no notable observable trend in the concentration of O_2. However, when the load is increased to 0.79 MPa, there is a reduction in the concentration of O_2. In the instance of NG, the reduction in O_2 concentration is more pronounced because stoichiometric gas burning necessitates approximately 17% additional air, as indicated in Table 2.

Furthermore, as a result of the decreased density of natural gas, the inertia of the combination of air and gas is reduced, leading to a decline in volumetric efficiency [19, 20]. The quantity of natural gas injected is adequate to surpass the designated load; nonetheless, a minor insufficiency of oxygen is detected inside the air.



M_B = 40 Nm (*BMEP* = 0.31 MPa)

M_B = 70 Nm (*BMEP* = 0.55 MPa)

M_B = 100 Nm (*BMEP* = 0.79 MPa)

Fig. 3. Oxygen (O_2) emissions in exhaust gas. The engine was operated on G and NG when the IVC timing was adjusted

Furthermore, as a result of the decreased density of natural gas, the inertia of the combination of air and gas is reduced, leading to a decline in volumetric efficiency [19, 20]. The quantity of natural gas injected is adequate to surpass the designated load; nonetheless, a minor insufficiency of oxygen is detected inside the air.

Carbon monoxide (CO), which is generated as a result of incomplete combustion, also exhibits a tendency to rise when the load increases and the IVC time is delayed up to 54 CAD aBDC (see Fig. 4).

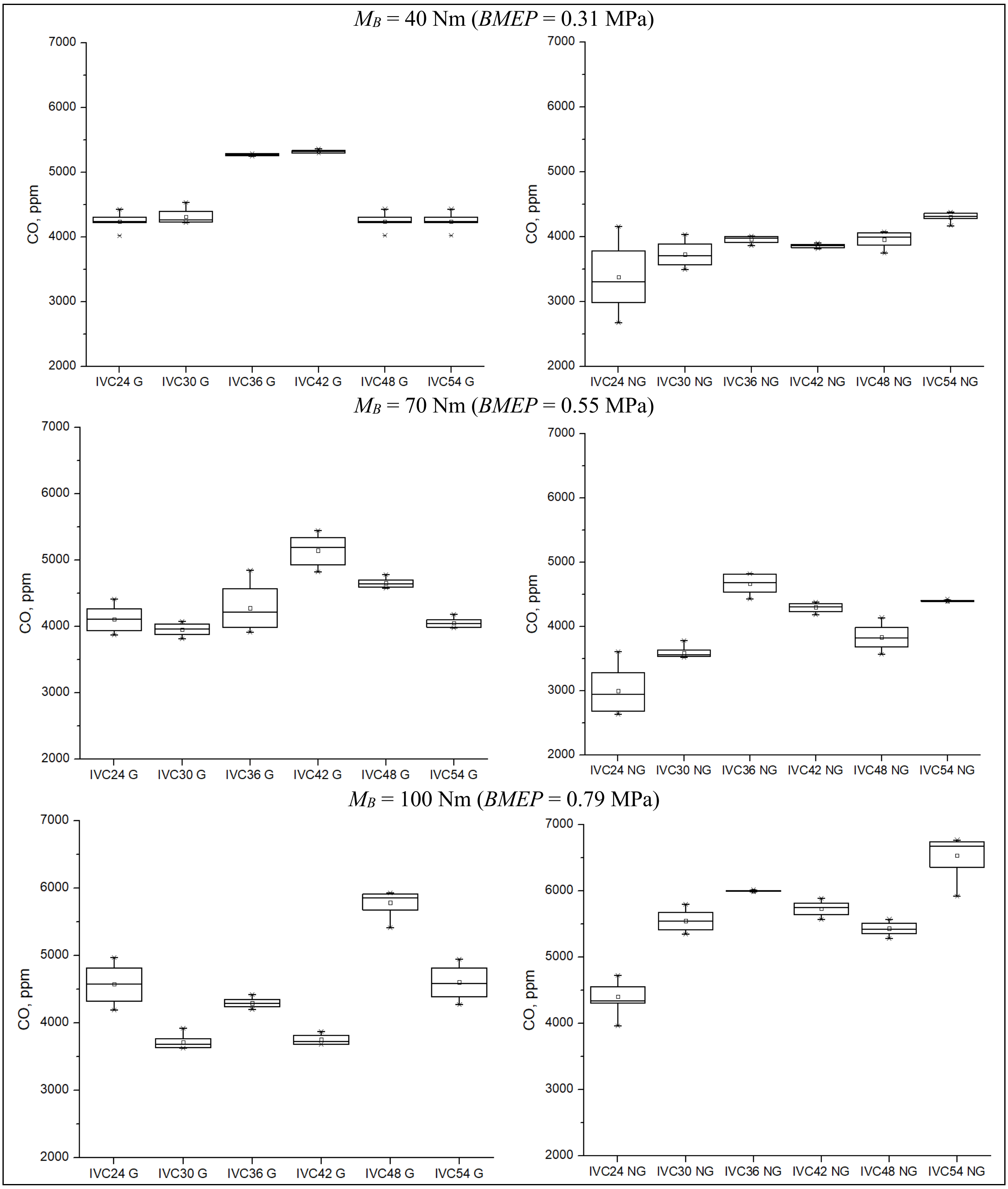


Fig. 4. Carbon monoxide (CO) emissions in the exhaust gas. The engine was operated on G and NG when the IVC timing was adjusted

when the IVC timing was adjusted

The significance of this phenomenon becomes more pronounced when the engine operates on natural gas fuel and when the load is elevated to a brake mean effective pressure (BMEP) of 0.79 megapascals (MPa). The act of postponing the IVC results in a decrease in the effective compression ratio and a reduction in the temperature of combustion, exacerbating the combustion process. When confronted with an increased load, the throttle aperture is widened, resulting in a greater influx of the fresh mixture into the cylinder relative to the fuel. Consequently, this leads to a more pronounced cooling effect on the compressed mixture. The diminished concentration of oxygen in the exhaust stream, as depicted in Fig. 3, suggests that even a minor deficiency of oxygen hampers the burning of natural gas.

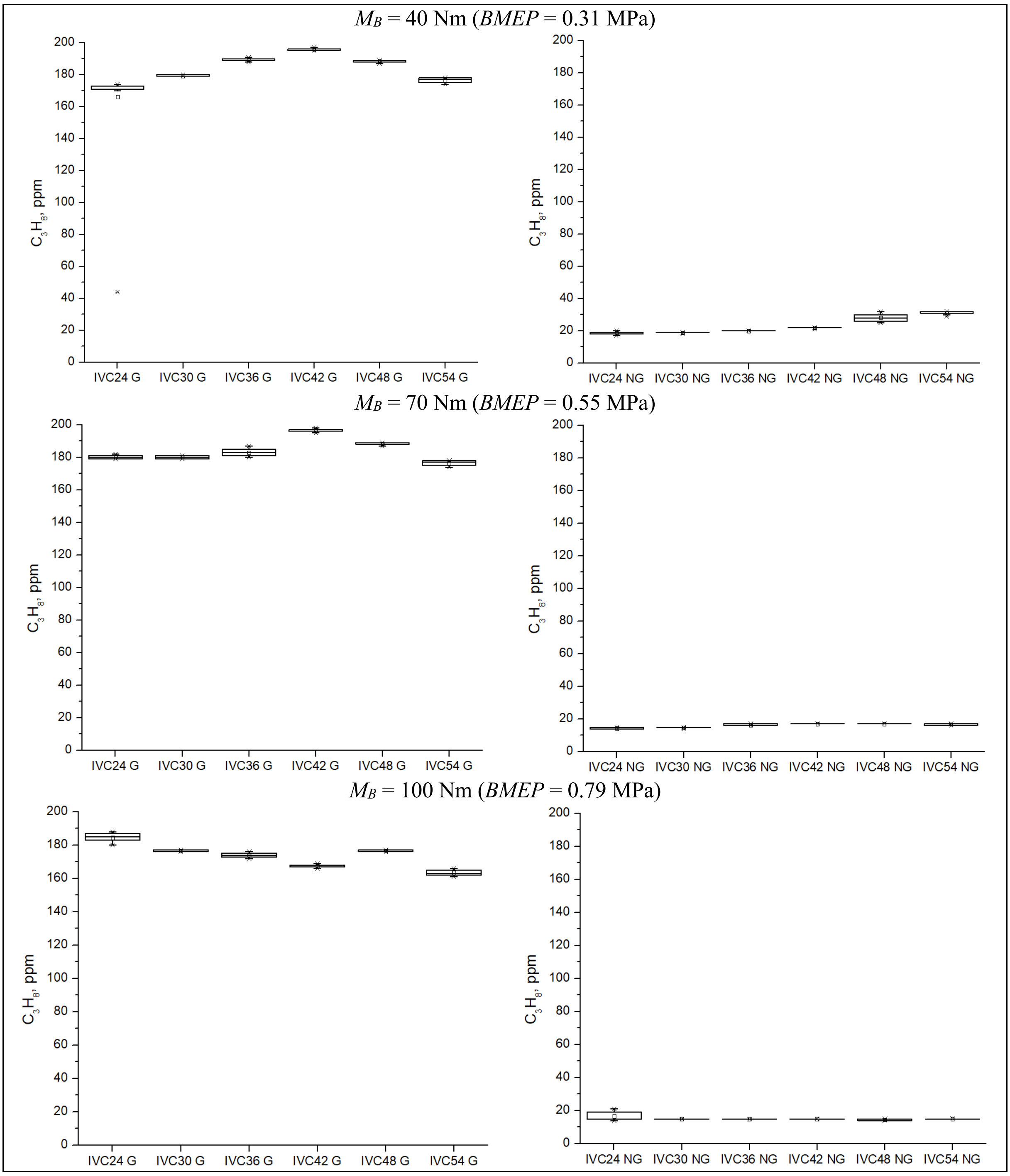
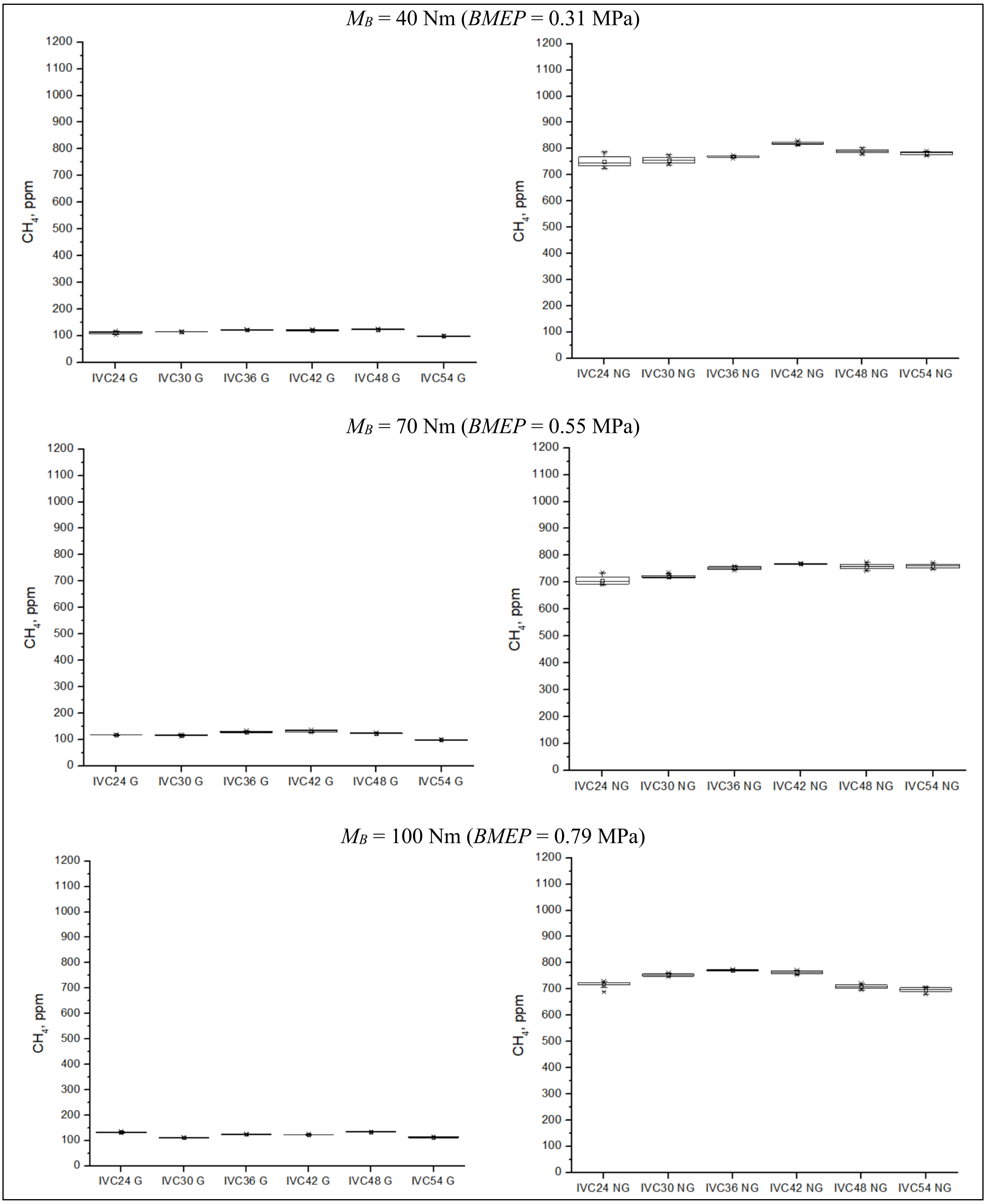


Fig. 5. Emissions of non-methane hydrocarbons (C_3H_8) in exhaust gas. The engine was operated on G and NG

The percentage of non-methane hydrocarbons (C_3H_8), which are incomplete combustion products, exhibits a notable disparity in the exhaust gases when the engine operates on gasoline compared to natural gas. Specifically, the concentration of C_3H_8 is approximately eight to 10 times greater when the engine is fueled by gasoline, as depicted in Fig. 5.


M_B = 40 Nm (*BMEP* = 0.31 MPa)

M_B = 70 Nm (*BMEP* = 0.55 MPa)

M_B = 100 Nm (*BMEP* = 0.79 MPa)

Fig. 6. The emissions of methane hydrocarbons (CH_4) in the exhaust gases. The engine was operated on G and NG when the IVC timing was adjusted

A decrease in the concentration of C_3H_8 is observed when using gasoline and increasing the load, which can be attributed to the rise in combustion temperature. In the scenario involving NG, it is observed that the concentration of C_3H_8 exhibits a slight drop when the load is increased. However, when the IVC timing is delayed beyond 42 CAD aBDC, the concentration of non-methane hydrocarbons begins to rise. This increase can be attributed to the declining real compression ratio.

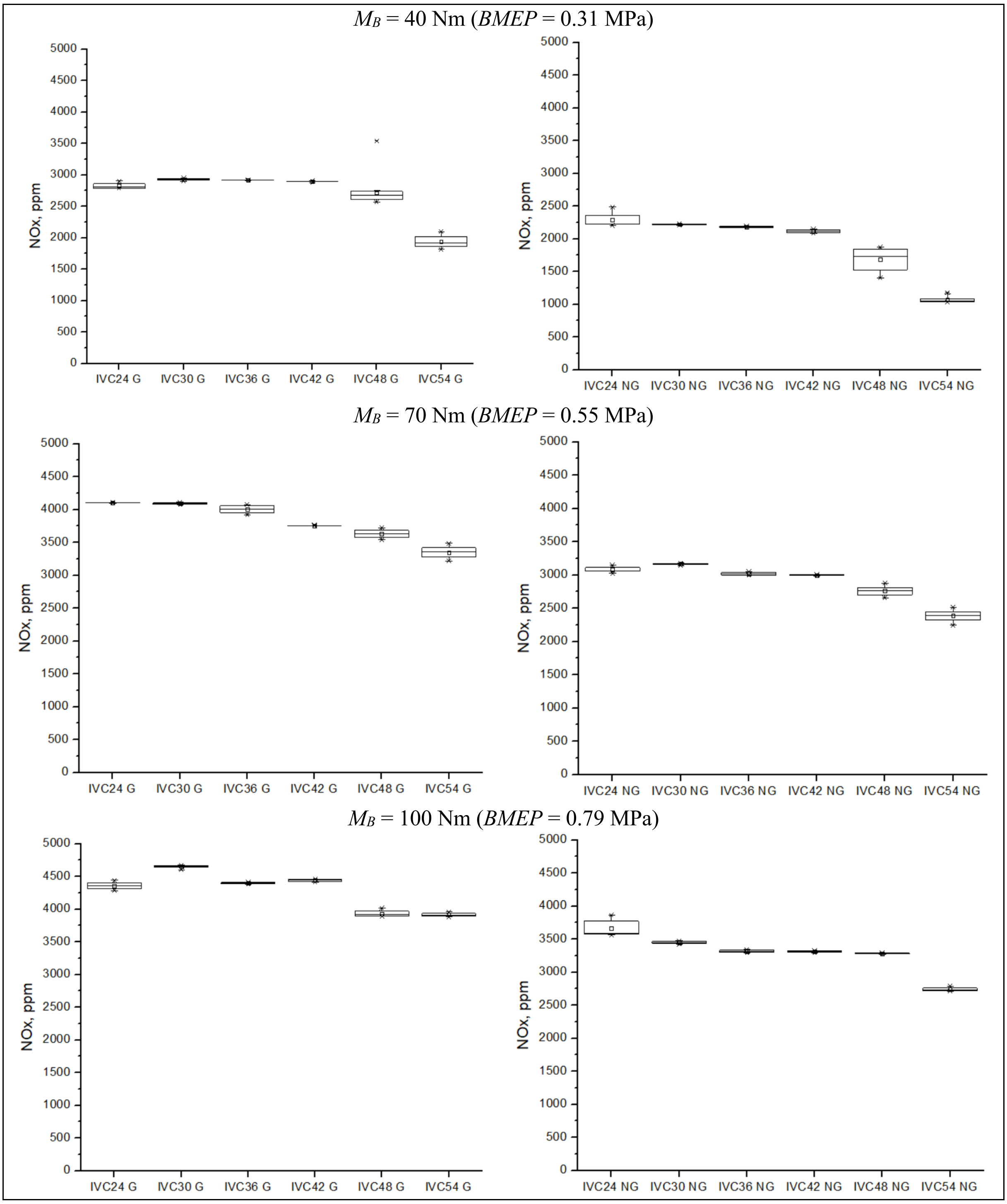


Fig. 7. Emissions of nitrous oxide (NO_x) in exhaust gas. The engine was operated on G and NG when the IVC timing was adjusted

The concentration of methane hydrocarbons (CH_4) when the engine runs on G is seven to eight times lower compared to NG (Fig. 6). When the internal combustion engine is running on gasoline as fuel, there is a minor increase in the concentration of CH_4 with higher engine load. Additionally, IVC timing does not exert a significant influence on this phenomenon.

When using natural gas in SI engine, it is observed that there is no substantial impact on CH_4 concentration when engine load is increased. However, an increase in CH_4 concentration is observed after the delay of IVC timing, and this can be seen in other studies [21]. As the IVC time experiences additional delays, there is a subsequent decrease in methane (CH_4) concentration, particularly when the load is increased.

The variation in nitrogen oxide (NO_x) content in the exhaust flow is notably influenced by different types of fuels, engine load, and IVC timing, as depicted in Fig. 7. The correlation between the optimal closing time of the intake valve and the effective management of fuel burn and combustion control has been established. The incorrect timing of the intake valve might give rise to suboptimal combustion, subsequently leading to an escalation in the emission of nitrogen oxide (NO_x). This phenomenon may arise when the timing of fuel injection is not synchronized with other engine parameters, such as the composition of combustion air and the ratio of air to fuel mixture.

In all instances, elevating the engine load leads to a rise in NO_x emissions due to the concurrent increase in combustion temperature. The substitution of gasoline with natural gas results in a reduction in NO_x concentration by around 22% to 32%. This decrease can be attributed to the slower combustion rate of natural gas, which leads to a decrease in the maximum combustion temperature and a shift toward the exhaust. A notable decrease in nitrogen oxide (NO_x) emissions by 32% is found when utilizing natural gas at lower loads, accompanied by reduced volumetric efficiency.

In all instances, elevating the engine load leads to a rise in NO_x emissions due to the concurrent increase in combustion temperature. The substitution of gasoline with natural gas results in a reduction in NO_x concentration by around 22% to 32%. This decrease can be attributed to the slower combustion rate of natural gas, which leads to a decrease in the maximum combustion temperature and a shift toward the exhaust. A notable decrease of 32% in nitrogen oxide (NO_x) emissions is found when utilizing natural gas at lower loads, accompanied by reduced volumetric efficiency.

When the IVC timing is extended from 24 CAD aBDC to 42 CAD aBDC, minimal change is observed in the concentration of NO_x for both G and NG, as depicted in Fig. 7. By increasing the IVC timing to a maximum of 54 CAD aBDC, the concentration of nitrogen oxide falls by approximately 12% to 20% for gasoline and 25% to 50% for natural gas. The observed phenomenon can be attributed to the decrease in combustion temperature resulting from the reduction in the actual compression ratio [22]. In the case of NG, the concentration of NO_x drops mostly as a result of the anticipated reduction in cylinder air volume. This is because the engine is operating at a relatively low speed (n = 2500 rpm) and the development of air flow inertia, which limits the favorable impact of late IVC timing, is insufficient. According to Table 2, NG necessitates around 17% additional air.

4. CONCLUSIONS

When the SI engine is running on liquid and gaseous (G and NG) fuels, a stoichiometric air/fuel mixture, set speed, and various loads while adjusting the IVC timing, the change in the concentration of exhaust gas components has the following trends:

1. NG CO_2 concentration is ~25% lower than G due to the lower C/H ratio. Engine load and IVC timing have no significant effect.
2. The O_2 concentration changes slightly, but when the load is increased ($BMEP$ = 0.79 MPa) and the IVC timing is delayed (especially in the case of NG), the O_2 concentration decreases. NG fuel requires more air than G, but the late IVC timing at low engine speed (n = 2500 rpm) reduces volumetric efficiency.
3. CO concentration does not differ significantly in G and NG cases. With a higher load and delay in IVC timing, CO increases (especially in the case of NG), as the real compression ratio decreases and the combustion temperature decreases. A lower reduction in the amount of oxidant also has an influence.
4. In the case of gasoline, the concentration of non-methane hydrocarbons (C_3H_8) is eight to 10 times higher, but the concentration of methane hydrocarbons (CH_4) is seven to eight times lower compared to NG. IVC timing does not significantly affect the concentration of unburned hydrocarbons.
5. Changing G to NG reduces the NO_x concentration by 22% to 32% because the combustion process is slower. As the load increases, the NO_x concentration increases, but as the IVC timing is further

delayed (48 to 54 CAD aBDC), NO_x G decreases by 12% to 20% due to a decrease in the real compression ratio. In the case of NG, it decreases by 25 to 50% because the additional influence is caused by a slight decrease in the amount of oxygen.

References

1. Menzel, C & Torresan, C. & Knight, J. & Raines, C. & Sapp, D. & Patel, M. & et al. Electronic Continuous Variable Valve Timing for Small SI Engine. SAE Technical Paper. 2008. No. 2008-01-1778.
2. Matijošius, J. & Juciūtė, A. & Rimkus, A. & Zaranka, J. Investigation of the concentration of particles generated by public transport gas (CNG) buses. *CogSust*. 2022. Vol. 1(1). Available at: https://www.cogsust.com/index.php/real/article/view/10.
3. Ghazal, OHM & Najjar, YSH & Al-Khishali, KJM. Modeling the Effect of Variable Timing of the Exhaust Valves on SI Engine Emissions for Greener Vehicles. *EPE*. 2013. Vol. 05(03). P. 181-189.
4. Alger, T. & Wooldridge, S. Measurement and Analysis of the Residual Gas Fraction in an SI Engine with Variable Cam Timing. *SAE Transactions*. 2004. Vol. 113. P. 860-869.
5. Vrublevskyi, O. & Wierzbicki, S. Analysis of potential improvements in the performance of solenoid injectors in diesel engines. *Eksploatacja i Niezawodność – Maintenance and Reliability.* 2023. Vol. 25(3). 11 p.
6. Rimkus, A. & Vipartas, T. & Kriaučiūnas, D. & Matijošius, J. & Ragauskas, T. The effect of intake valve timing on spark-ignition engine performances fueled by natural gas at low power. *Energies*. 2022. Vol. 15(2). No. 398. 21 p.
7. Caban, J. & Droździel, P. & Ignaciuk, P. & Kordos, P. The impact of changing the fuel dose on chosen parameters of the diesel engine start-up process. *Transport Problems.* 2019. Vol. 14(4). P. 51-62.
8. Takahashi, D. & Nakata, K. & Yoshihara, Y. & Ohta, Y. & Nishiura, H. Combustion Development to Achieve Engine Thermal Efficiency of 40% for Hybrid Vehicles. *SAE International.* 2015. Report No. 2015-01-1254.
9. Zöldy, M. Investigation of Correlation Between Diesel Fuel Cold Operability and Standardized Cold Flow Properties. *Periodica Polytechnica Transportation Engineering.* 2019. DOI: 10.3311/PPtr.14148.
10. Payri, R. & Novella, R. & Barbery, I. & Bori-Fabra, O. Numerical and experimental evaluation of the passive pre-chamber concept for future CNG SI engines. *Applied Thermal Engineering*. 2023. No. 120754.
11. Borucka, A. & Wiśniowski, P. & Mazurkiewicz, D. & Świderski, A. Laboratory measurements of vehicle exhaust emissions in conditions reproducing real traffic. *Measurement*. 2021. Vol. 174. No. 108998.
12. Chen, H. & He, J. & Zhong, X. Engine combustion and emission fuelled with natural gas: A review. *Journal of the Energy Institute*. 2019. Vol. 92(4). P. 1123-1136.
13. Prasad, RK. & Agarwal, AK. Development and comparative experimental investigations of laser plasma and spark plasma ignited hydrogen enriched compressed natural gas fueled engine. *Energy.* 2021. Vol. 216. No. 119282.
14. Li, Q & Liu, J. & Fu, J. & Zhou, X. & Liao, C. Comparative study on the pumping losses between continuous variable valve lift (CVVL) engine and variable valve timing (VVT) engine. *Applied Thermal Engineering.* 2018. Vol. 137. P. 710-720.
15. Ji, C. & Hong, C. & Wang, S. & Xin, G. & Meng, H. & Yang, J. et al. Evaluation of the variable valve timing strategy in a direct-injection hydrogen engine with the Miller cycle under lean conditions. *Fuel*. 2023. Vol. 343. No. 127932.
16. Li, Y. & Han, D. & Wang, Z. & Bi, C. & Jing, Y. & Sui, J. et al. A novel combined throttle opening and variable valve timing strategy for combined cooling, heating, and power system flexibility. *Applied Thermal Engineering.* 2023. Vol. 219. No. 119688.

17. Khudhur, S. & Saleh, A. & Chaichan, M. The Effect of Variable Valve Timing on SIE Performance and Emissions. *International Journal of Scientific & Engineering Research*. 2015. Vol. 6. P. 173-179.
18. Miura, T. & Aoyama, S. & Onogawa, K. & Fujia, T. & Murata, T. & Ariga, K. et al. Development of a Hydraulic Variable Valve Timing Control System with an Optimum Angular Position Locking Mechanism. SAE International. 2012. *Report* No. 2012-01-0416.
19. Heywood, JB. *Internal combustion engine fundamentals.* Second edition. New York: McGraw-Hill Education; 2018. 1028 p.
20. Kim, S. & Park, C. & Jang, H. & Kim, C. & Kim, Y. Effect of boosting on a performance and emissions in a port fuel injection natural gas engine with variable intake and exhaust valve timing. *Energy Reports.* 2021. Vol. 7. P. 4941-4950.
21. Wang, J. & Duan, X. & Wang, W. & Guan, J. & Li, Y. & Liu, J. Effects of the continuous variable valve lift system and Miller cycle strategy on the performance behavior of the lean-burn natural gas spark ignition engine. *Fuel*. 2021. Vol. 297. No. 120762.

Received 25.01.2022; accepted in revised form 05.09.2023