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THE INFLUENCE OF INTAKE VALVE TIMING ON THE ENVIRONMENTAL PERFORMANCE OF THE SI ENGINE USING GASOLINE AND NATURAL GAS

Summary. The tightening of environmental requirements forces car manufacturers to look for various ways to reduce exhaust gas emissions. The existing structural solutions of internal combustion engines allow reducing this type of pollution by adjusting the intake valve timing. This is especially relevant when it comes to reducing SI engine emissions when using natural gas as a fuel. In this study, a wide range of intake valve timing adjustments from 24 to 54 degrees was taken at constant engine speed and various loads. The changes in O_2, CO, CO_2, NOx, CH_4 and 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 reduction in SI engines. It allows to increase the maximum power, but at the same time ensures lower fuel consumption (BSFC) and exhaust gas emissions (1). There is an ecological effect when replacing gasoline with natural gas. As the combustion speed slows down and the combustion temperature decreases, NOx 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 a fuel, play a fundamental role in the development of high-performance and environmentally friendly engines (4). The use of these technologies helps meet stricter emissions requirements while delivering efficient and powerful performance (5), paving the way for a more sustainable future of transportation (6). VVT is also used in hybrid cars that operate on the Atkinson cycle, while fuel economy could be increased up to 30 percent (7). A significant reduction in CO_2 emissions (about 25%) compared to a conventional spark-ignition engine fueled by gasoline was observed for transient driving cycles and natural gas as a fuel (8).

In combination with VVT, using The Skip Cycle Strategy (SCS) (where the engine valves are switched off at part load) the ecological effect increases and NOx concentration is reduced by 35.1%, 39.4% and 26.8%, and HC emissions are reduced by an average of 54.9%, 49.3% and 47.4% at BMEP values of 1, 2 and 3 bars (9).

The aim of this study was to investigate the intake valve close (IVC) timing adjustments from 24 to 54 degrees can impact the ecological performance of an engine when switching from gasoline (G) to natural gas (NG).

2. MATERIALS AND METHODS

Experimental tests were carried out in the internal combustion engine laboratory of the Vilnius Gediminas Technical University, with a Nissan HR16DE spark ignition (SI) engine equipped with a dual fuel supply system. The engine is adapted to operate with both liquid and gaseous fuels. Gasoline and gas injectors are installed in the intake manifold and their control is performed using open electronic control unit (ECU) Motec M800 as well as intake valve close (IVC) timing. The main characteristics of the engine shown in Table 1, while properties of gasoline and natural gas (10) presented in Table 2.

Tab. 1

Engine HR16DE specifications

Item	Content
Engine type	Four-stroke, naturally aspirated
Number of cylinder	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
Maximum power (kW)/Speed (rpm)	84/6000
Maximum 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 (G), Natural gas (NG)

The load for the engine is created by 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 (brake torque M_B = 40 Nm, M_B= 70 Nm, M_B = 100 Nm) and intake valve close timing were used. After calculating the engine load to break mean effective pressure (*BMEP*) the following values 0.31 MPa; 0.55 MPa and 0.79 MPa were obtained accordingly. The same excess air ratio (λ = 1) was fixed during all experimental tests.

Tab. 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

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

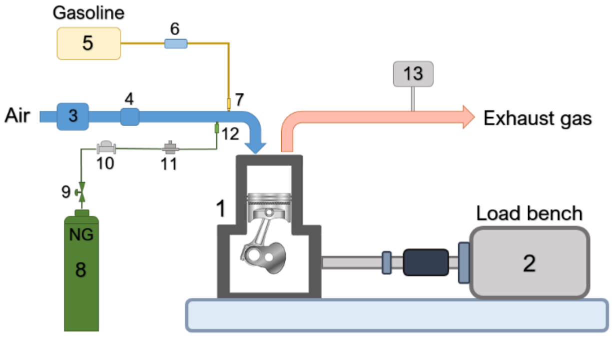


Fig. 1. Schematic diagram of internal combustion engine and experimental equipment: 1 - SI engine; 2 - load bench; 3 - air mass meter; 4 - throttle unit; 5 - fuel tank; 6 - fuel consumption meter; 7 - fuel injector; 8 - natural gas tank; 9 - valve; 10 - gas flow meter; 11 - high pressure reducer; 12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

Emissions were measured with gas analyser 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 crank angle degree. Exhaust gas analyser specifications are presented in Table 3.

Tab. 3

Exhaust gas analyser specifications

Gas measurement	**Measuring range min./max.**	**Resolution**	**Repeatability**
Oxygen (O_2)	0 ... 25/100%	0,01%	0.1% or 1% reading
Carbon dioxide (CO_2)	0 ... 40%	0.01 Vol%	0.2% or 1% reading
Carbon monoxide (CO)	0 ... 175/10.000 ppm	0.1 ppm	2 ppm or 1% reading
Nitrous oxide (NO_x)	0 ... 200/4.000 ppm	0.1 ppm	2 ppm or 1% reading
Methane (CH_4)	0 ... 500/10.000 ppm	0.1 ppm	10 ppm or 1% reading
Propane (C_3H_8)	0 ... 200/5.000 ppm	0.1 ppm	2 ppm or 1% reading

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

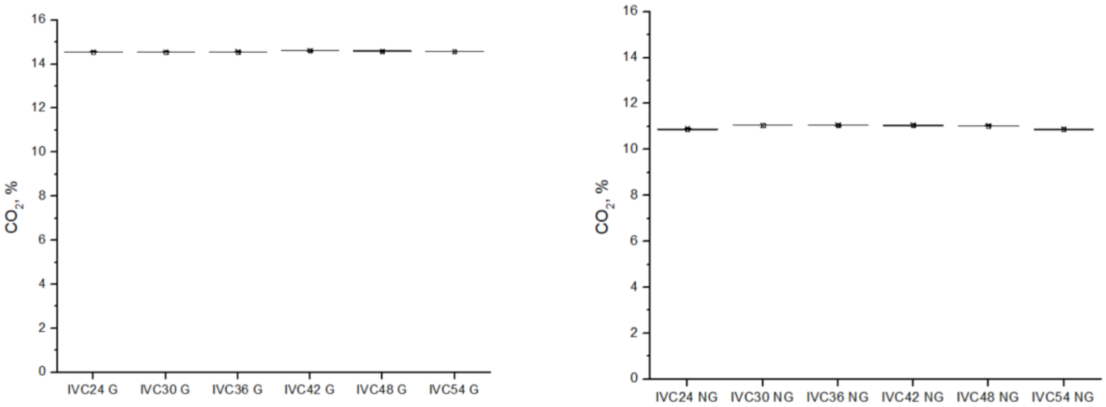
3. RESULTS AND DISCUSSION

Greenhouse gases – carbon dioxide (CO_2) concentration changes little (~14.6%) when the engine is running on Gasoline fuel at all tested loads (Fig. 2), because the stoichiometric fuel mixture ($\lambda = 1$) is maintained. When changing IVC timing from 24 CAD aBDC to 54 CAD aBDC, the variation in CO_2 concentration is not significant. When the engine is running on natural gas, a CO_2 concentration of ~10.9% was determined. The concentration of NG CO_2 is 25% lower, because the C/H ratio (~3) of NG fuel is ~49% lower compared to gasoline (~6) (Table 2).

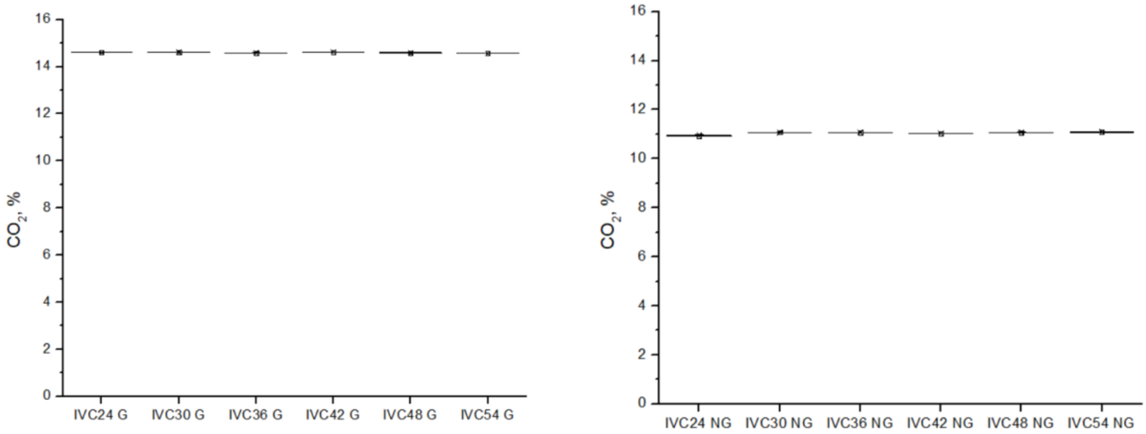
The concentration of O_2 in the exhaust gas for both Gasoline and NG at all tested loads ranged from 0.6% to 0.8% (Fig. 3) and this shows that a stoichiometric mixture was ensured.

It can be observed that when the engine is operating under low and medium load (*BMEP* = 0.31 ... 55 MPa), and when changing the IVC timing, the concentration of O_2 does not show any significant change trends, but when the load is increased to 0.79 MPa, it decreases. In the case of NG, the decrease in O_2 concentration is more intense, because stoichiometric gas combustion requires ~17% more air (Table 2). In addition, due to the lower density of NG, the inertia of the air-gas mixture decreases and the volumetric efficiency deteriorates. The amount of NG injected is sufficient to overcome the set load, but a slight lack of oxidizer is observed in 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)

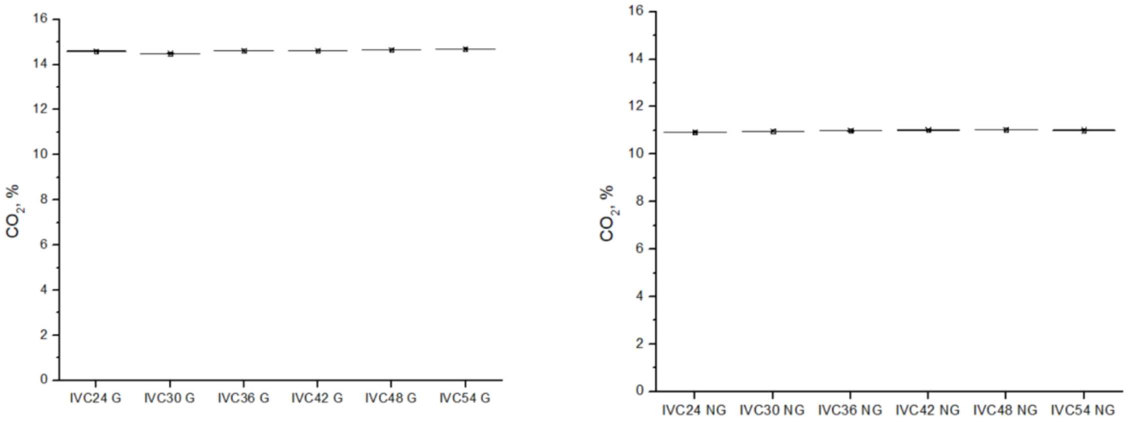
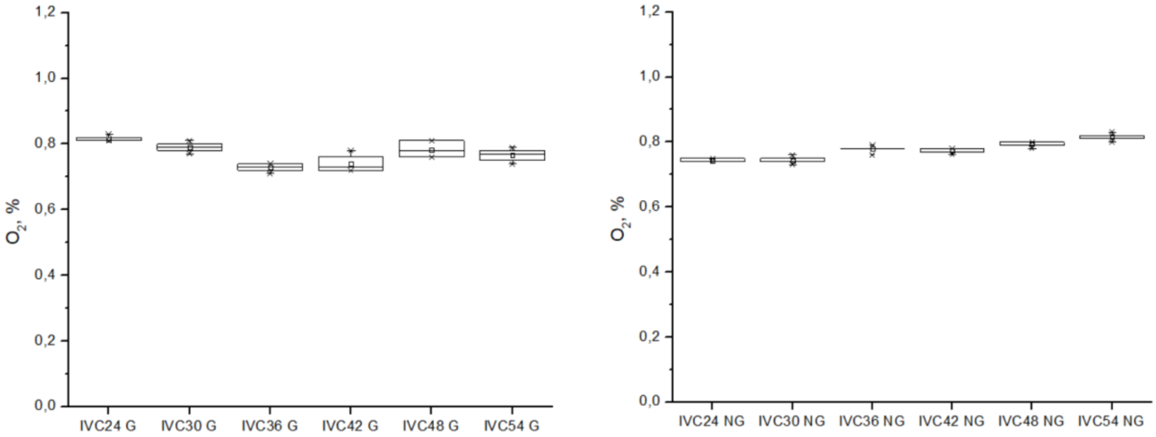


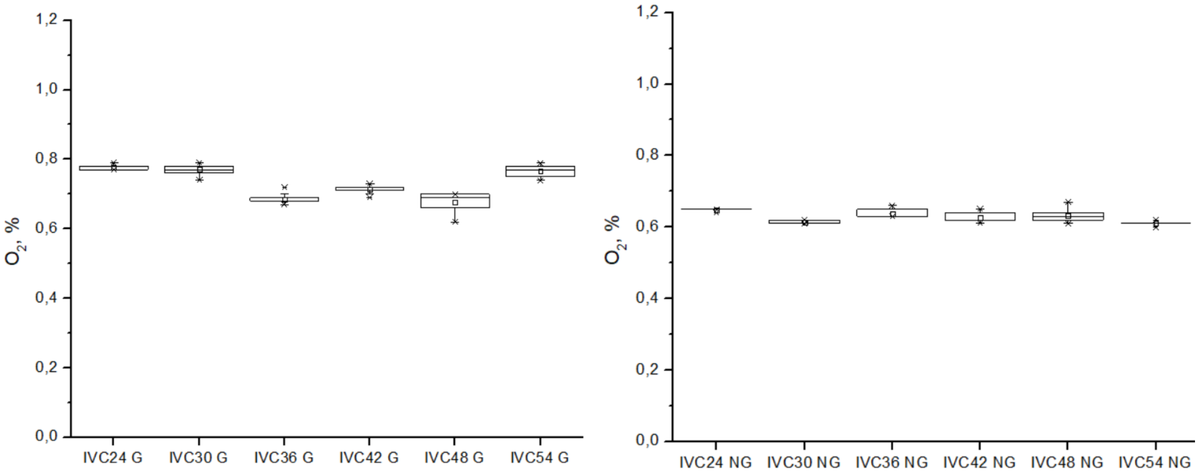
Fig. 2. Carbon dioxide concentration in the exhaust gas when the engine is running on Gasoline (G) or natural gas (NG) when the IVC timing is adjusted

Carbon monoxide (CO), a product of incomplete combustion, also tends to increase with increasing load and delaying IVC timing up to 54 CAD aBDC (Fig. 4). This is more significant when the engine runs on NG fuel and when the load is increased to BMEP = 0.79 MPa. Delaying the IVC reduces the actual compression ratio and lowers the combustion temperature, which worsens the combustion process. In the case of a higher load, the throttle is opened more, a larger amount of fresh mixture enters the cylinder compared to the fuel, and this cools the compressed mixture more. The reduced concentration of O_2 in the exhaust gas (Fig. 3) indicates that even a slight lack of oxygen impairs NG combustion.

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



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



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

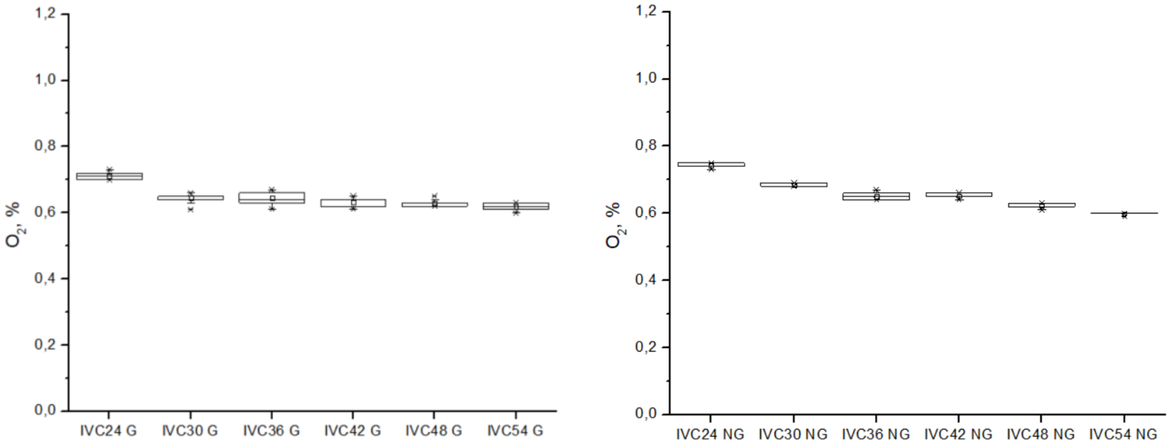
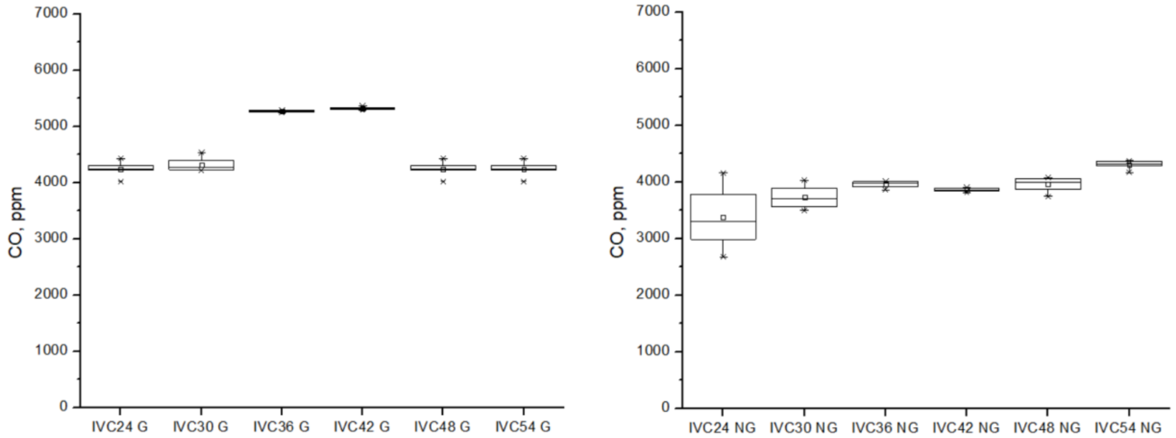


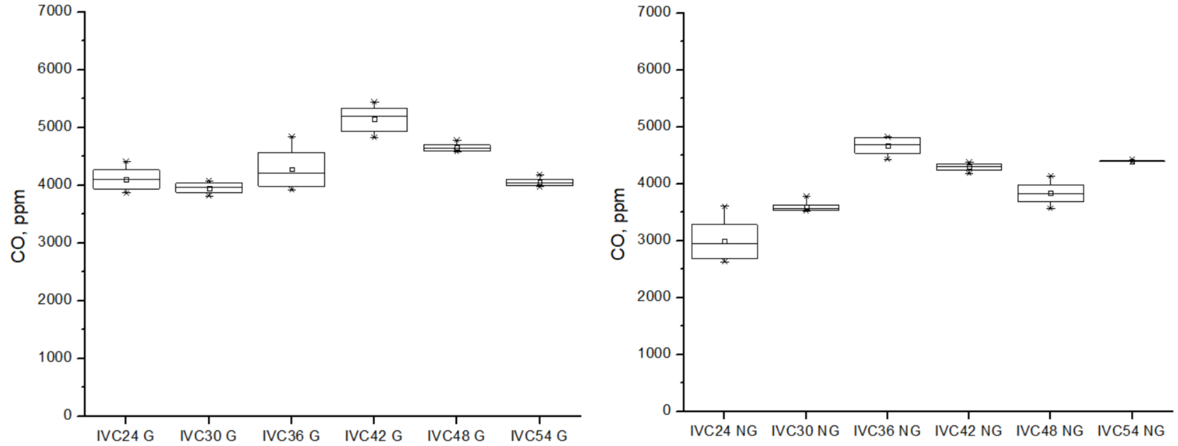
Fig. 3. Oxygen concentration in the exhaust gas when the engine is running on Gasoline (G) or natural gas (NG) when the IVC timing is adjusted

The concentration of other incomplete combustion products - non-methane hydrocarbons (C_3H_8) in the exhaust gases is significantly different, when the engine is running on Gasoline and NG fuel - the concentration of C_3H_8 is 8 ... 10 times higher than when the engine is running on Gasoline (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)

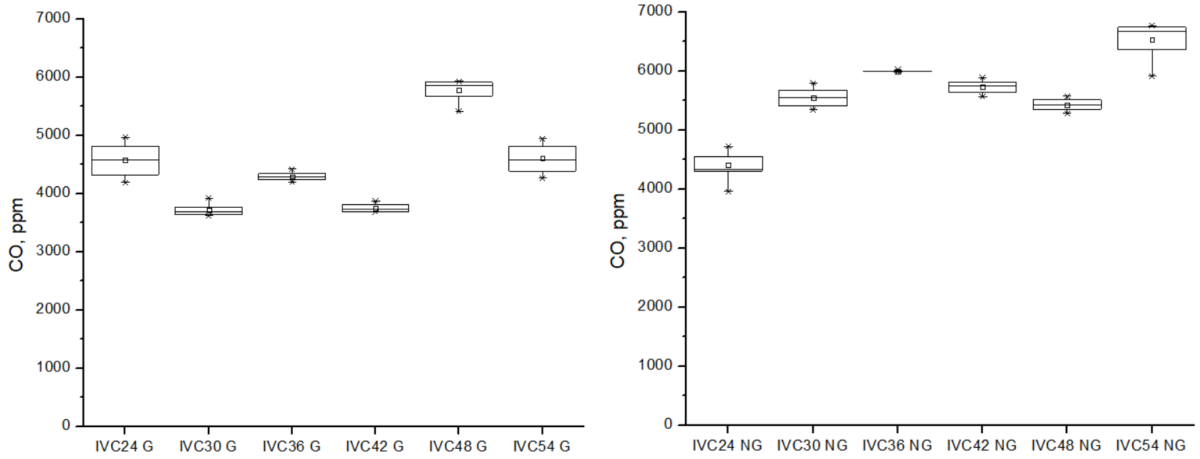
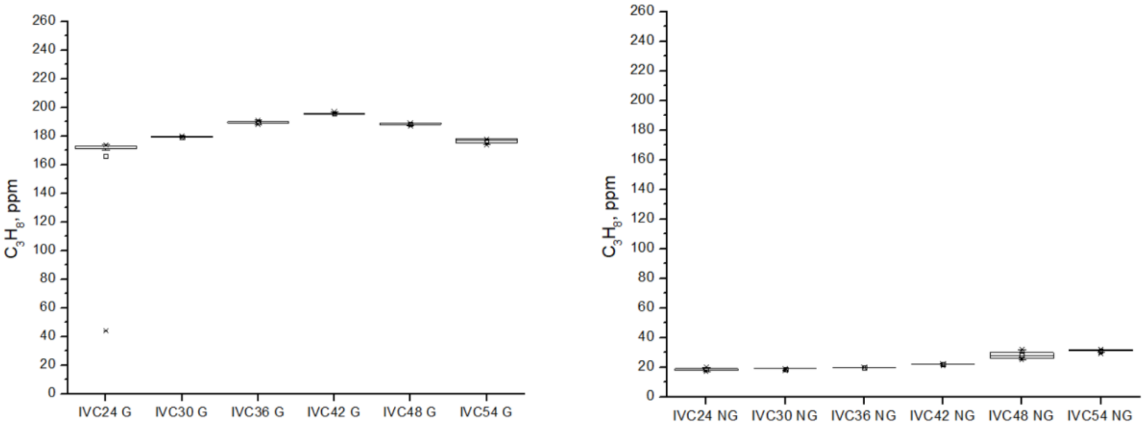


Fig. 4. Carbon monoxide concentration in the exhaust gas when the engine is running on Gasoline (G) or natural gas (NG) when the IVC timing is adjusted

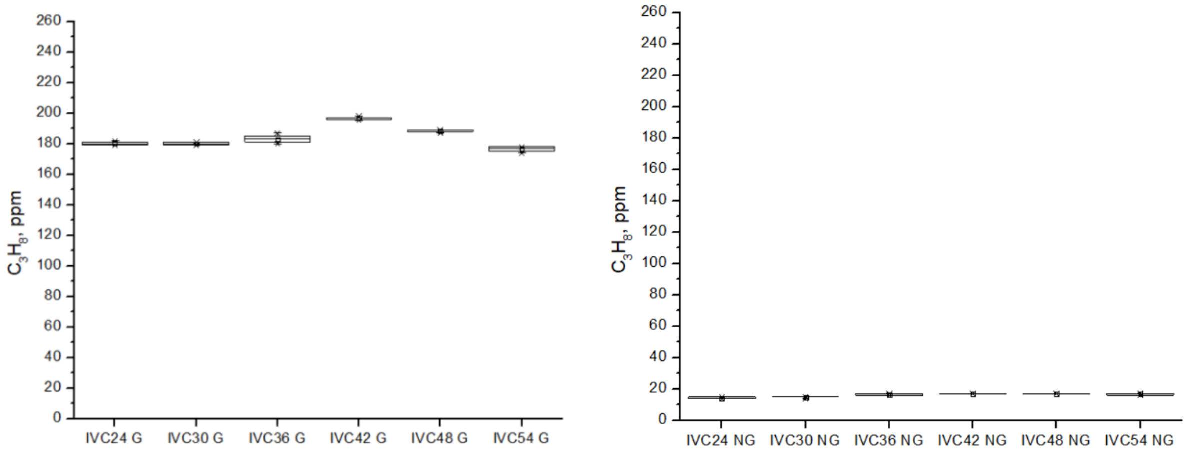
When using Gasoline and increasing the load, a tendency to decrease the concentration of C_3H_8 is observed, because the combustion temperature increases. In the case of NG, the concentration of C_3H_8 also decreases insignificantly when increasing the load, but when the IVC timing is delayed more than 42 CAD aBDC, the concentration of non-methane hydrocarbons starts to increase due to the decreasing real compression ratio.

The concentration of methane hydrocarbons (CH_4) when the engine is running on Gasoline fuel is 7 to 8 times lower compared to NG (Fig. 6).

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



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



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

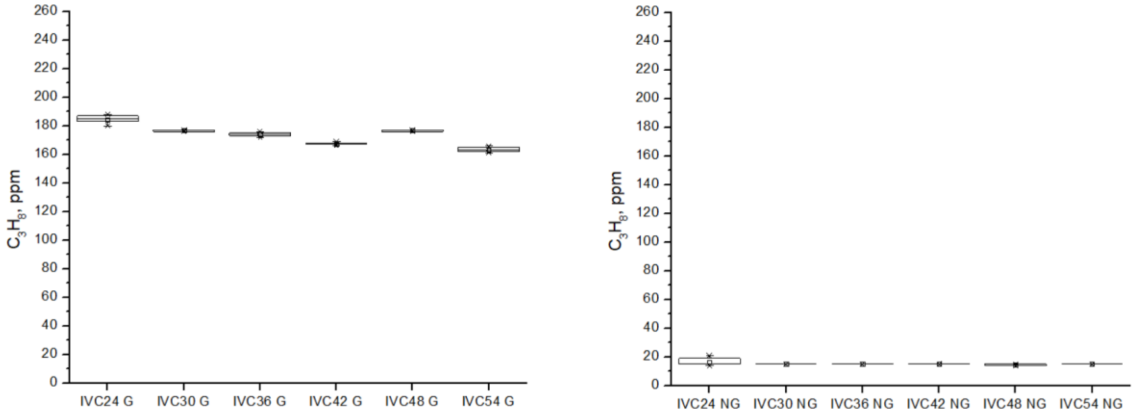
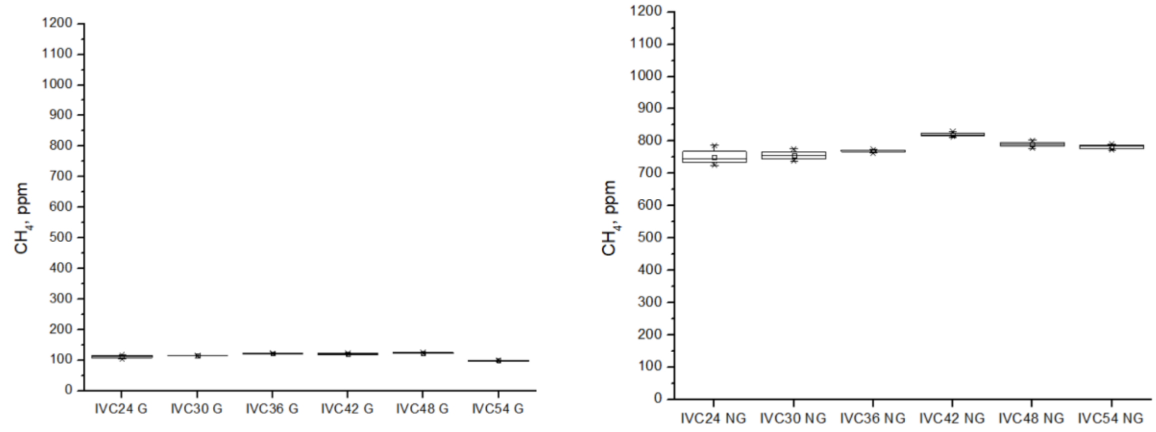


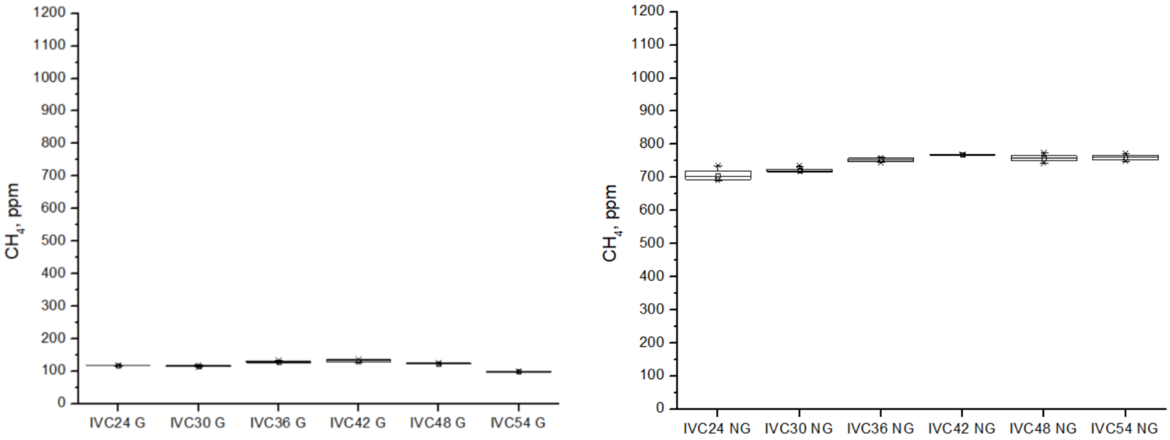
Fig. 5. The concentration of non-methane hydrocarbons in the exhaust gas when the engine is running on Gasoline (G) or natural gas (NG) when IVC timing is adjusted

When the engine is running on gasoline, the concentration of CH_4 increases slightly with increasing engine load, IVC timing also has no significant effect. In the case of NG, increasing engine load has no significant effect on CH_4 concentration, but increases after delaying IVC timing to 42 CAD aBDC. As the IVC timing is further delayed, the CH_4 concentration decreases again, especially as the load increases.

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



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



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

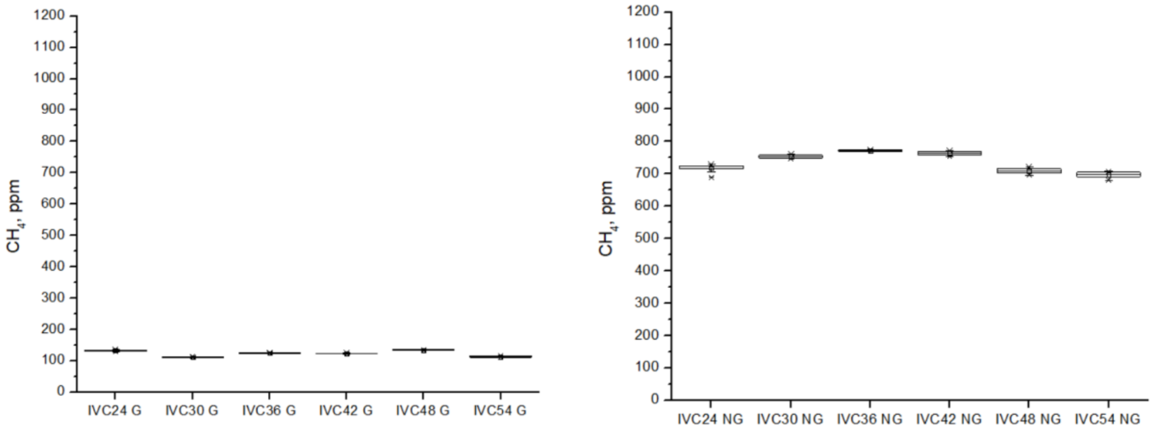
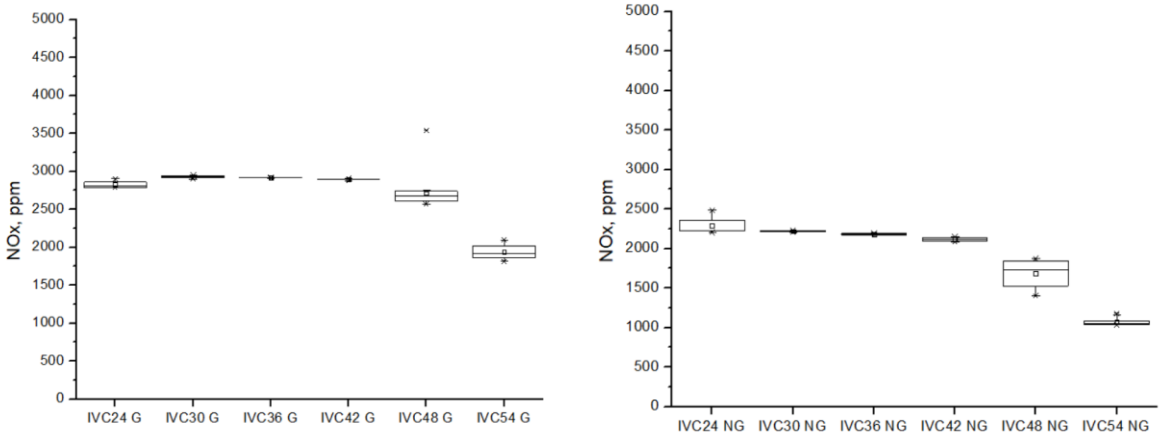


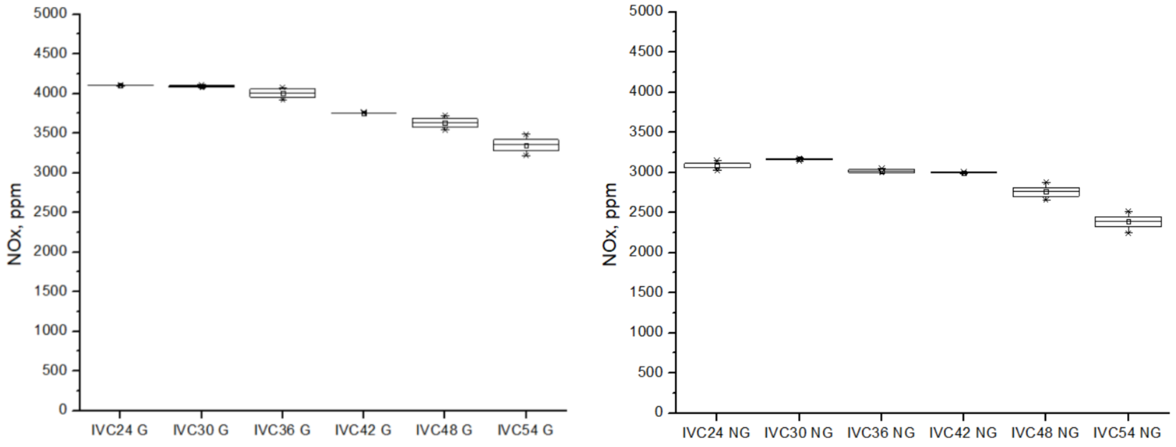
Fig. 6. The concentration of methane hydrocarbons in the exhaust gases when the engine is running on Gasoline (G) or natural gas (NG) when the IVC timing is adjusted

The concentration of nitrogen oxides (NOx) in the exhaust gas is significantly changed by different fuels, engine load, and IVC timing (Fig. 7). Increasing the engine load in all cases increases NOx because the combustion temperature increases. After replacing Gasoline with NG fuel, the NOx concentration decreases by 22 ... 32%, because the gas burns more slowly and the maximum combustion temperature decreases and shifts towards the exhaust. A more significant NOx reduction (32%) with NG is observed at low loads with lower volumetric efficiency.

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



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



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

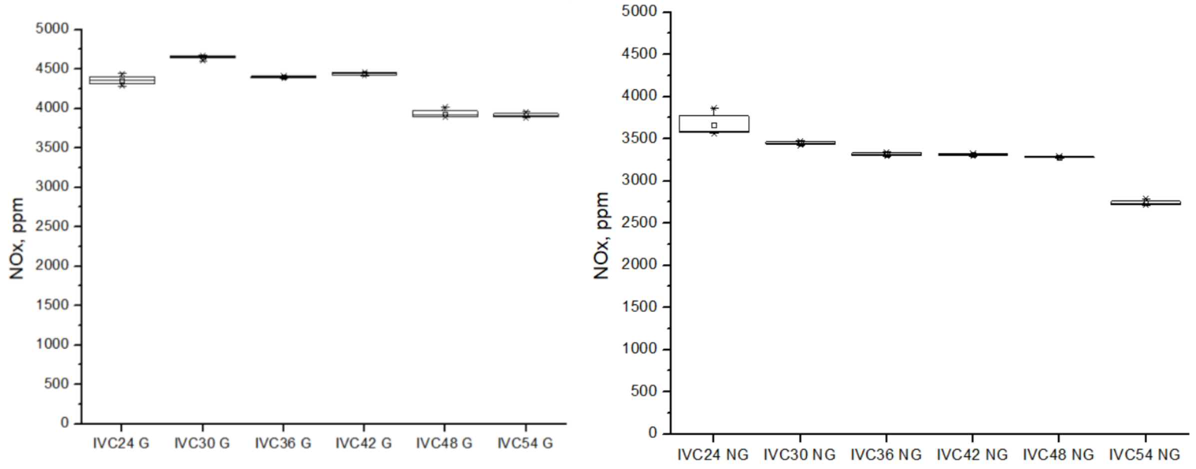


Fig. 7. The concentration of nitrous oxides in the exhaust gas when the engine is running on Gasoline (G) or natural gas (NG) when the IVC timing is adjusted

When delaying the IVC timing from 24 CAD aBDC to 42 CAD aBDC, the NOx concentration changes little in the case of Gasoline and NG (Fig 7). By delaying the IVC timing more (up to 54 CAD aBDC), the NOx concentration decreases by 12 ... 20% in the case of gasoline, and by 25 ... 50% in the case of NG. This is due to the reduced combustion temperature due to the reduced real compression ratio. In the case of NG, the NOx concentration decreases more due to the likely decrease in the amount of air in the cylinder, since in the analyzed mode the engine speed was not high (*n* = 2500 rpm) and the air flow did not develop enough inertia to give a positive effect at late IVC timing. NG requires ~17% more air (Table 2).

4. CONCLUSSIONS

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

1. NG CO_2 concentration is ~25% lower than G, due to lower C/H ratio. Engine load and IVC timing have no significant effect.
2. The O_2 concentration changes little, 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, but late IVC timing at low engine speed (n = 2500 rpm) reduces volumetric efficiency.
3. CO concentration in G and NG cases does not differ significantly. It is noticed that with higher load and delay in IVC timing CO increases (especially in case of NG), as the real compression ratio decreases and the combustion temperature decreases. A reduced 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 8 ... 10 times higher, but the concentration of methane hydrocarbons (CH_4) is 7 ... 8 times lower compared to NG. IVC timing does not significantly affect the concentration of unburned hydrocarbons.
5. Changing G to NG reduces the NOx concentration by 22 ... 32%, because the combustion process is slower. As the load increases, the NOx concentration increases, but as the IVC timing is delayed more (48 … 54 CAD aBDC), NOx G decreases by 12 … 20% due to a decrease in the real compression ratio. In the case of NG, it decreases by 25 ... 50%, because the additional influence is caused by a slight decrease in the amount of oxygen.

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