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Gaseous fuel for lower emissions during the cold start and warming up of spark ignition engines

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Abstract: Gasoline engines during cold starting (cranking) and warming-up duration, particularly, at low environmental temperatures have negative impact on air pollutions, especially for sub-zero degrees. To achieve a stable engine operation at low environment temperatures, extra fuel has to be injected inside the combustion chamber and as a consequence more emissions particularly hydrocarbons are emitted. In this study, fuel consumption, emissions and engine-start conditions have been examined using different gaseous fuels during the period from the ignition time until the catalyst reaching its lighting off temperature at no load conditions. The results showed that gaseous fuels reduces fuel consumption and emissions due to achieving substantial reduction in the number of engine cranking in addition to the inherent low emission characteristics of gaseous fuel. Hydrogen, in particular, showed superior performance in comparison to other examined gaseous fuels. The significant number of engine-start using 200 g of gaseous fuel particularly hydrogen makes the gaseous fuel viable to be used together with conventional liquid gasoline fuel.

Keywords: gaseous fuel; gasoline engine; cold start; hydrogen fuel; engine cranking; cold start emissions; low temperature SIE emissions; engine warming up emissions; cranking time; engine emissions; engine cold start emissions; gaseous fuel in SIE; warm-up in SIE.

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Biographical notes: Ahmed Alashab is a PhD student. He has completed his Master in Mechanical Engineering 2003 from University of Technology, Baghdad-Iraq in 2003. His research interest is related to internal combustion engines. His PhD is focusing on cold start emissions in gasoline engines.

Hindawi Saleh has more than 40 years of practical and academic experience in the fields of fuels, combustion and internal combustion engines, air pollution control in transport and industry and energy efficiency. He received his PhD in the Effect of Fuel Type on CO and NO_x Formation from Cranfield University UK. After finishing his PhD, he was appointed for one year in the same university as a research officer. On October 1979, he returned back to Cairo University to work as a Lecturer, Associate Professor, Professor and Emeritus Professor till now except for the period 1991 to 1994 where he was on leave to work as an Associate Professor in Gar Younis University in Libya. He also was involved in many applied research projects with industry, governmental bodies and research institutes.

Essam Abo-Serie obtained his BSc with honours in 1989 and MSc in 1995 from Cairo University, Mechanical Power Engineering. He completed his PhD at Imperial College, Mechanical Engineering London in 2004. He was a Research Assistant in City University London 2002 to 2004 and contributed in a European project and industrial projects. He joined Engine Lab in KAIST, South Korea in 2004 to 2005 as a Postdoctoral Fellow. He also worked as a Postdoctoral Researcher at Loughborough University, UK, 2006 to 2007. Then, he was a Senior Lecturer at Coventry University, UK in 2007. He acted as the Director of the MSc programme ‘Engine Design and Development’ and involved in different researches and consultancy works. He joined Mevlana University in Turkey as an Associate Professor in 2012. He has wide range of research activities using optical techniques in measurements and control. He is a member of different prestige organisations.

Basem Rabee is an Assistant Professor in Mechanical Engineering Department, Faculty of Engineering, Al-Azhar University, Cairo – Egypt. His research interest is thermofluid systems particularly diesel engine combustion.

Mohsen Abdel Aal has been graduated on 1983 and completed his PhD on 1995. He is currently the Head of Mechanical, Engineering Department, Faculty of Engineering, Al-Azhar University, Cairo – Egypt. He established the combustion laboratory at Al-Azhar University. He supervised 11 PhD, and he accomplished several academic and industrial projects related to combustion and particularly internal combustion engine. He has over 40 publications in different topics related to fuel combustion systems. He is a member of different organisations nationally and internationally.

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1 Introduction

Transportation produces almost 30% of all US global warming emissions. 60% of US transportation emissions come from cars and light trucks. It is therefore crucial to minimise the environmental emissions from every possible source. Stricter emissions regulations are applied for registering new vehicles to be sold in different part of world. A new vehicle has to be tested under a specific driving cycle without exceeding the standard limits of CO, NO_x, un-burned hydrocarbon (UHC) and particular matter (PM). More recently, limits have been set to CO₂ emissions. The booklet published by Delphi Automotive PLC (2014) lists the different driving cycle and emission limits ~~are~~ set by different countries.

A major difficulty in meeting the rigorous emissions regulation during the driving cycle is the initial cold-start transient period and warming up. A large portion (60% to 80%) of the engine-out emissions occurs in the engine cold start during the first 300 s in the case of the new European driving cycle and the US federal test procedure (FTP) 75 cycles (Seokhwan and Choongsik, 2007). Substantial part of UHC emission (70% to 90%) during the vehicle test cycle takes place during cold start engine operation (Wang et al., 2011). The UHC is attributed mainly to engine misfiring, incomplete flame propagation, wall wetting and flame quenching. Other secondary factors are the crevice ~~that store~~ ^s of the fuel-air charge and release it at later stage, oil dilution with liquid and fuel vapour, poor post-flame oxidation and exhaust and inlet valves leakage (Henein and Tadomori, 1999).

Engines continue emitting harmful gases during the cold start and warm-up until the catalyst reaches its light off temperature 250–340°C (Chan and Hoang, 1999). Once the three way catalyst, TWC, is fully warmed up, engine-out emissions, CO, UHC, and NO_x, can be reduced by up to 95% (Hu et al., 2007; Cesur, 2011). Different techniques have been proposed to activate the catalytic converter fast in order to minimise the emissions during engine warm-up duration. Among the proposed techniques is the use of; electrically initiate chemically heated catalyst (Murphy et al., 1999), close-coupled catalyst system, exhaust gas ignition system (Cho et al., 2002), latent heat storage system (Korin et al., 1998), electrically heated pre-catalyst (Kirchner and Eigenberger, 1996) or thermal energy storage system (Gumus, 2009).

In addition to the emitted harmful gases rich air/fuel mixture is required during the cold and warm-up time duration to compensate for the liquid fuel fraction, which is not easily vaporised for mixture preparation. This is attributed to the low temperature of the intake system and cylinder. As the environment temperature reduces as more fuel needed to start the engine. Previous research showed that when the ambient temperature was 22°C, 57% of the injected gasoline could be vaporised to support the combustion. Nevertheless, when the temperature further dropped to 0°C, only 30% of the gasoline fuel was vaporised to form the combustion mixture (Wang et al., 2011). A study on a single-cylinder engine indicated that the supply equivalence ratio needed for starting with gasoline varied from 5.6 at –29°C to 1.1 at 21°C (Quader, 1992). Similar finding is reported from experiments on a multi-cylinder production engine (Sampson and Heywood, 1995).

Different strategies are currently applied to limits the engine emissions during the cold start and until the three-way catalyst reaches its light off temperature. Retarded spark timing, split homogenous-stratified injections (Fan and Li, 2013), high fuel pressure,

retarded exhaust valve timing and stratified cranking are among the applied techniques. An optimum combination of the different mentioned strategies have been applied in the engine management system in the current modern engines (Amini et al., 2014). Although the current strategies with the complex engine control system can meet the current emission regulations, it may struggle to meet the future more strict regulation.

Using gaseous fuels such as CNG, LPG or hydrogen as a replacement to gasoline fuel during cold start and warm up is an attractive option. Gaseous fuel has low boiling point and therefore it will enter into the cylinder in form of gas even at low environmental temperature, i.e., there is no absorbed energy for evaporation such as gasoline. Early study using a single cylinder engine showed that by using propane, the supply equivalence ratio for engine starting was nearly constant at all temperature up to -29°C (Quader, 1992). The LPG was used to play a part as a start-aid in the LPG/methanol engine (Gong et al., 2011). Using additional LPG injection into the inlet port, results in a reliable firing of the LPG/methanol engine at low ambient temperature during cold start. However, when ambient temperature drops, the mass ratio of injected LPG/methanol for the reliable firing of the LPG/methanol engine during cold start has to be increased significantly.

Compressed natural gas (CNG) is another convenient fuel to replace gasoline and other conventional fuels. Using CNG extends engines lean limit and leads to higher engine efficiency due the high specific heat ratio ($k = C_p / C_v$) in addition to inherent low emissions as a gaseous fuel. However, it has low combustion speed and needs more ignition energy to start the combustion. One of the proposed methods for decreasing negative effects of CNG is blending CNG with hydrogen due to nature properties of hydrogen of having lower ignition energy and faster flame speed than CNG (Hu et al., 2009). Further study (Afkhami et al., 2012) on the effect of low environment temperature for both CNG and hydrogen-CNG mixture, it was observed that engine maximum speed decreases, but when hydrogen added to CNG engine, maximum speed increases in comparison to pure CNG. It was also observed when adding hydrogen to CNG some instantaneous rising and falling occurred in rotational speed exactly after cranking duration, which was attributed to the conversion of highly reactive OH into less reactive HO_2 and H_2O_2 during low-temperature oxidation.

This study investigates the influence of using gaseous fuel instead of the gasoline liquid fuel only during cold cranking and engine warming up. A comparative study has been carried out for different gaseous fuels (LPG, natural gas, or hydrogen) relative to the liquid gasoline fuel at different engine environmental temperatures from 10 to -10°C . It is worth mentioning that this study provides comparison since the absolute values of the emitted gas can be different if the engine is optimised with direct injection system or the engine has different setup.

2 Experimental set-up and operating conditions

The present study has been conducted on Ricardo E6 variable compression ratio single cylinder research engine. The engine is equipped to operate with gaseous fuels as well as gasoline liquid fuel for port injection. The technical specifications of the Ricardo E6 engine and its operating parameters are given in Table 1. The engine is coupled with A DC dynamometer which has been used for cranking the engine. All the tests have been carried out during this study was under no load conditions.

Table 1 Research engine Ricardo E6 technical details

Bore, mm	76.2	Gasoline carburettor, mm	26
Stroke, mm	111	Gas mixer choke size, mm	27
Capacity, cc	507	Inlet valve opens, BTDC	7 deg.
Max. cylinder pressure, bar	150	Inlet valve closes, ABDC	37 deg.
Motoring speed, rpm	300	Exhaust valve opens, BBDC	42 deg.
Maximum speed, rpm	3,000	Exhaust valve closes, ATDC	10.5 deg.

The engine is connected to different gaseous fuel supply systems. Natural gas is supplied through high-pressure (200 bar) commercial CNG bottles; typical to those used in vehicular applications. The bottles are connected to a common header where a pressure gauge is installed to indicate the CNG pressure. A normally-closed solenoid valve is mounted on the line to prevent/permit the gas flow. Three-stage pressure regulator is used to reduce the CNG pressure to sub atmospheric level suitable for engine suction. The LPG used in this study contains 1 butane and propane 70%:30%. The LPG gaseous fuel circuit consists of eight gas bottles, main header with eight inlet ports and single outlet port, followed by an on/off valve, gas pressure regulating device to maintain the feeding gas pressure constant for accurate and stable operation through over the test. The hydrogen was supplied from a 120 bar bottle. For supplying the liquid gasoline fuel a 1 litter tank, the fuel feed pump, filter and relief valve are used. The fuel supply system is equipped with a set of valves to allow easily the change from one fuel to another.

The engine was installed inside a freezing room with dimensions ($2.4 \times 2.0 \times 2.2$ m) with its all related facilities, i.e., dynamometer, air intake system, exhaust system and measurements sensors. The room walls are well insulated with thermal insulation material to reduce the heat loss. The refrigeration unit has a rated power of 3.75 tons of refrigeration. A photo of the cold room with the engine test rig is shown in Figure 1.

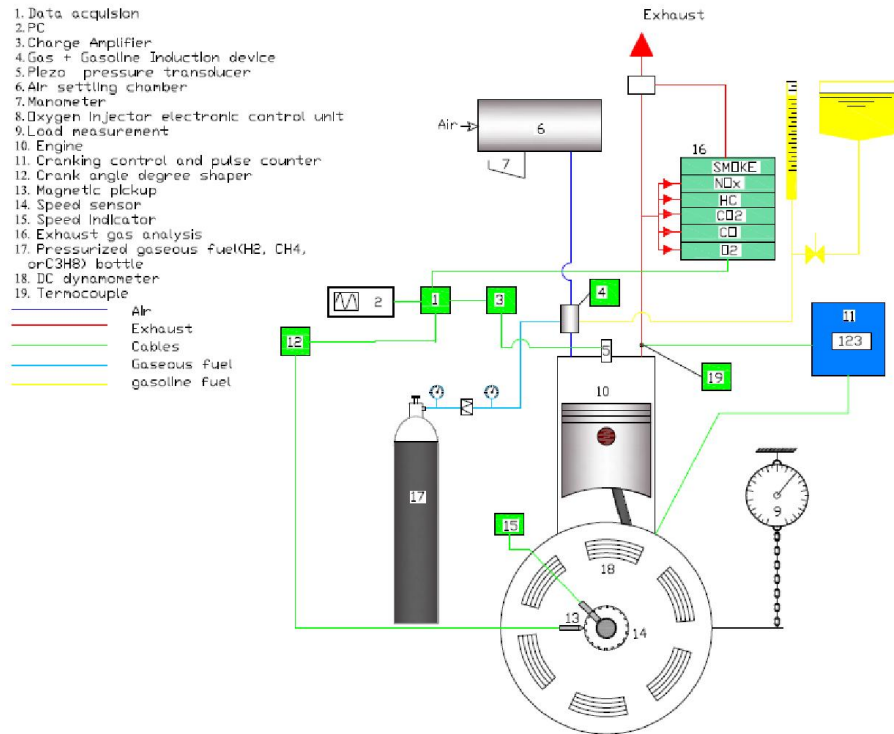
The engine is equipped with different sensors and devices to measure the operating conditions and control the engine operation as shown in Figure 2. Engine speed, monitoring cooling water temperature, oil pressure and temperature, exhaust gas temperature and engine temperature are among the parameters that are monitored by the engine control unit. A PCB Piezotronics engine combustion piezoelectric transducer, model 112B11, was used to measure the cylinder pressure. A PCB dual mode charge amplifier, model F464A, was used to amplify the signal from the transducer. The crank angle degree was recorded by a magnetic pickup sensor and the generated wave was treated by an electronic degree marker shaper.

Measuring gas fuel flow received special attention due to the nature of the internal combustion engines in fuel is admitted only during the suction stroke while the other three strokes no fuel is admitted to the engine. Moreover, there is a cycle-to-cycle variations. A small box to damp the fuel flow fluctuation has been connected between the engine and fuel supply system. A pitot tube is mounted on an inline fitted pipe for identifying the gas flow rate by measuring the pressure drop between the static and total pressure. The pressure drop was measured using a fine differential pressure transducer, which was pre-calibrated for the gas flow rate. The ADC infrared multi-gas analyser, model MGA3000 was employed for measuring the concentrations of NO, CO, CO₂ from the engine tail pipe.

Figure 1 A photograph of the engine inside the freezing room (see online version for colours)



Figure 2 Schematic diagram of the test facility (see online version for colours)



The engine control panel was employed to monitor and control the different engine operating parameters such as water temperatures, oil temperature, oil pressure, and engine speed. A fast data acquisition system of 1.25 MHz was employed to acquire the output signals of the pressure transducer together with crank angle degree marker. The gas fuel differential pressure, exhaust temperature and catalyst temperature are also recorded. The data acquisition system continues to acquire data during from the start of ignition until the catalyst reaches a temperature of 250°C. An especially designed electronic control circuit equipped with pulse counter storage was used. This circuit is used for ~~making~~ ^{recording and} controlling the cyclic cranking until the engine start-up ~~while recording the number of cycles from the start until the engine start firing.~~ It also allow ^S recording the number of cycle until the catalytic converter reaches a temperature of 250°C. After the test is carried out, the engine has to be stopped for at least 6 hours to reach the cold room temperature before carrying out another test.

3 Results and discussions

In the following subsections, the effect of low ambient temperature when using different types of fuels on the number of cycles before the engine start and also before the catalyst reaching its light off temperature will be examined. The temperature effect on engine speed build up and emissions will also be discussed. Finally, the practical implementation of gaseous fuel during for engine starting and warming up will be investigated. All the results are for no load conditions.

3.1 The number of cranking cycles

This test started after the room and engine reach the steady state temperature. The automatic cranking circuit operates the starting motor and identifies the number of crank rotations before the engine start firing. The engine firing was detected by the sudden change in exhaust temperature which is detected with the fast response K type thermocouple (approximately reaches 100°C). Figure 3 shows the significant reduction in the number of cranks for starting the engine when using gaseous fuel instead of gasoline liquid fuel at lower environmental temperature (−6°C and −10°C). At higher temperature, the difference is not significant. In general, gaseous fuels do not need energy to evaporate and therefore they are ready to burn if the ignition energy is enough to start the flame kernel. However, this not the case with gasoline liquid fuel which needs heat to evaporate enough amount of fuel to produce a combustible mixture and hence more cranking is needed.

The CNG in particular, showed slightly longer cranking relative to other fuels due to its higher ignition energy requirements relative to other fuels (Afkhami et al., 2012). In addition, the CNG consists mostly of methane which is very critical to ignite due to its narrow flammability equivalence ratio as shown in Figure 4 and it has also low flame speed. The CNG also has relatively lower density (0.69 kg/m³) and therefore occupies a large volume of the inlet manifold, and restricting the amount of air entering the cylinder and consequently, the mixture sometimes became outside the flammability range. However, it is noticed that the CNG cranking duration was reduced with the decrease in

ambient temperature. This reduction in cranking can be attributed to the increase of CNG and air densities as well as the water vapour concentration in the air.

Figure 3 The number of cranking cycles versus temperature for different fuels (see online version for colours)

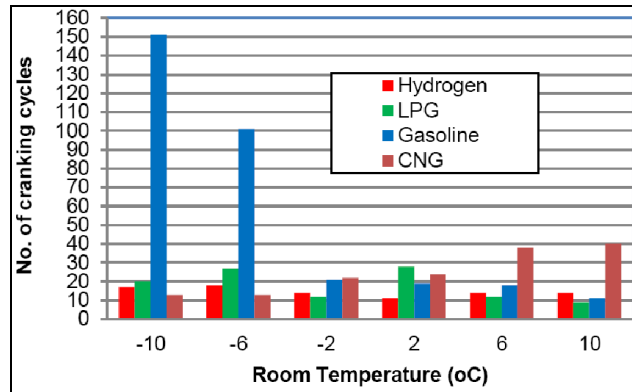
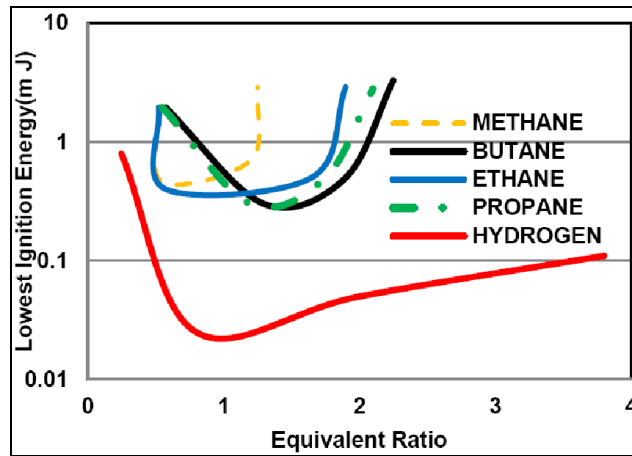


Figure 4 Minimum ignition energy versus equivalent ratio for different gas-air mixture (see online version for colours)



Source: Cesur (2011)

Results showed that LPG is better than CNG at relatively higher ambient temperatures since it is easier to ignite and relatively wider flammability limit. The hydrogen can be considered the best fuel to start the engine as it has the lowest ignition energy, widest flammability range, and higher flame speed (Hu et al., 2009). The number of cranking cycles does not much affected by the ambient temperature, as shown in Figure 3.

3.2 Engine speed

Figure 5 shows the engine speed variation from the start of cranking until it reaches its maximum steady value under no load conditions, for the different types of fuel at 10°C. Figures 6 and 7 are similar but for ambient temperatures -2°C and -10°C , respectively. Figure 5 shows that the engine speed increases till it reaches a steady speed condition for all types of fuel. However, the maximum speed at steady conditions is different for each fuel. Gasoline fuel reaches the highest steady speed conditions followed first by LPG, and then the CNG and the lowest steady speed was for the hydrogen. Having different maximum engine speeds is attributed to the different fuel densities and therefore the mass of fuel admitted to the cylinder volume is not the same. As the fuel density, increases more fuel and air are admitted to the same cylinder volume and hence, more heat is produced and ~~this~~ more power is generated, assuming all the fuel is used in the combustion process.

Figure 5 Engine speed versus cranking time at temperature of 10°C (see online version for colours)

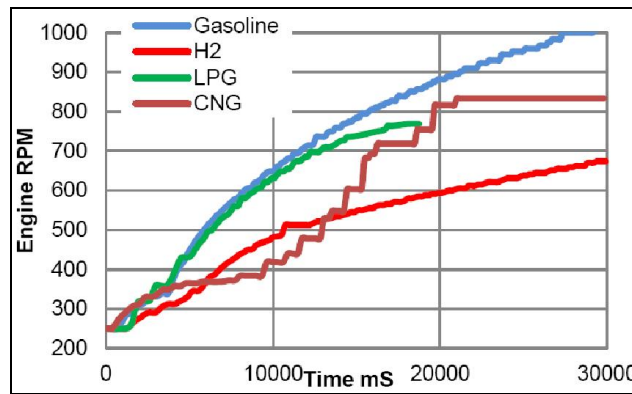


Figure 6 Engine speed versus cranking time at temperature of -2°C (see online version for colours)

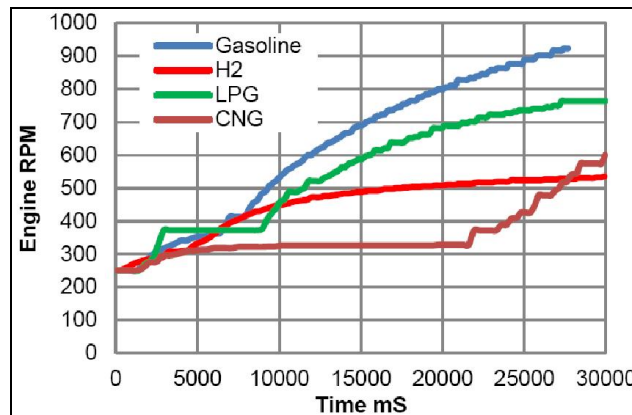
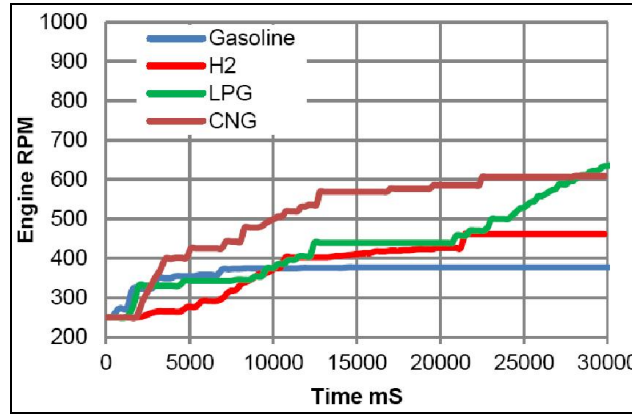


Figure 7 Engine speed versus cranking time at temperature of -10°C (see online version for colours)

All fuels shows gradual increase in engine speed except CNG, which shows erratic engine operation due to misfires or incomplete combustion. This is clear in Figures 5 and 6 where the rpm of CNG fuel experiences step changes instead of smooth increase in engine rpm. The high ignition energy and the limited flammability limits can be responsible for erratic behaviour (Hu et al., 2009).

By comparing Figures 5, 6 and 7, it can be seen that as the environment temperature goes down, the steady engine speed decreases due to a change in the physical conditions and parameters of the engine. As the ambient temperature drops, the density of the fuel increases and therefore, the mass of gaseous fuel admitted to the engine increases resulting in an increase in the maximum engine speed at no load conditions. However, this is only true if the power increase due to the additional fuel exceeds the engine friction power and without a change in the combustion process. Nevertheless, this is not what has been observed in the results and the reason can be attributed to the rise up in lubrication oil viscosity in addition to the decrease in the engine clearance and therefore more friction power. Moreover, the reaction rates and flame propagation speed become slower with lower temperatures and thus combustion process takes longer time and leads to lower engine speed. The heat loss to the engine body is also increasing with the drop in the ambient temperature.

Figure 7 (at temperature = -10°C) was plotted only for 30 s to be similar to Figures 5 and 6. However, at -10°C the engine started after 120 seconds when using gasoline as a fuel. During the 30 s shown in Figure 8, the engine speed, when using gasoline fuel, was slightly above the motoring speed due to some engine misfires. Hence, the ~~same~~ trend is found to be identical for all fuels but over different time durations; (120 s) for gasoline. This time duration is relatively long when compared to recent port injection engine or direct injection engines (Fan and Li, 2013), which has better atomisation and therefore faster evaporation. Nevertheless, the overall drawn conclusions will not change.

3.3 Warm up emissions analysis

The engine tail pipe emissions time history during the engine warm-up period have been examined in this section. The emitted gases named, nitric oxide (NO), oxygen (O₂), carbon dioxide (CO₂), carbon monoxide (CO) and hydrocarbons (HC), during 120 seconds have been measured using the gas analyser. The exhaust gas is admitted to the gas analyser through a control valve after the engine cranking period and when the engine starts and its rpm starts to increase. Measurements have been carried out for the different types of fuel and at the predetermined room temperature (10°C, 0.0°C or -10.0°C).

Figure 8 The time history of CO₂ concentration in the engine exhaust for different fuels during the warm-up period at a room temperature of 10°C (see online version for colours)

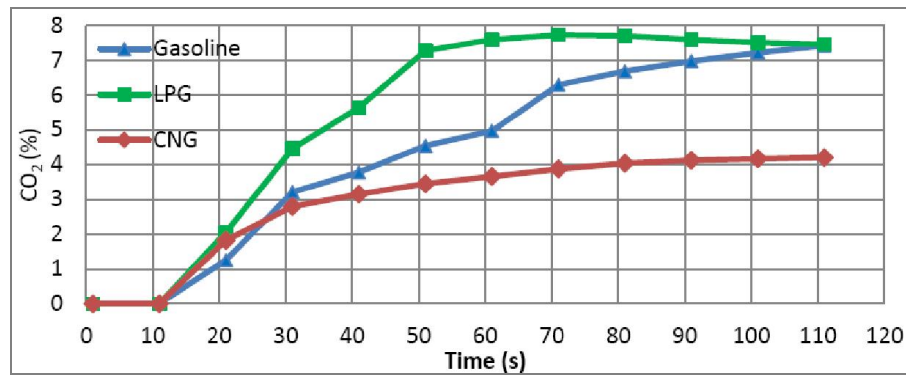


Figure 9 The time history of CO₂ concentration in the engine exhaust for different fuels during the warm-up period at a room temperature of 0°C (see online version for colours)

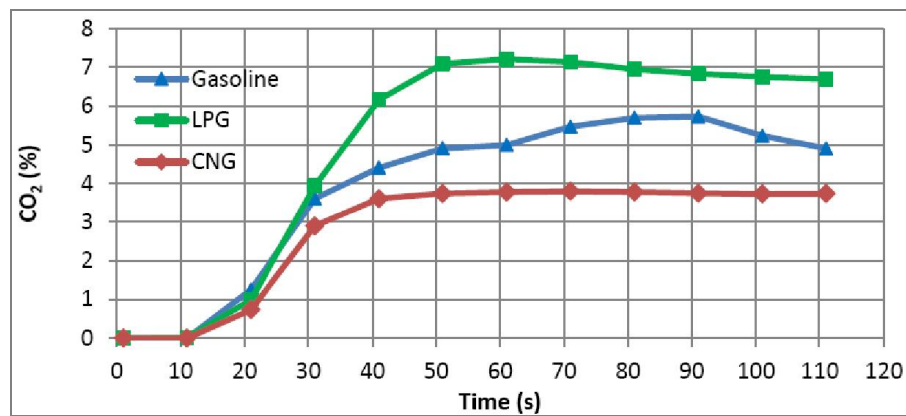


Figure 8 shows the time history of the emitted CO₂ concentrations for the different fuels at a room temperature of 10°C. The delay time, which is approximately 11 second is the time required for the exhaust gas to reach the gas analyser. After this delay time, the CO₂ concentration smoothly increase until it reaches almost a constant value. Figures 9 and 10

are similar to Figure 8 but for room temperature 0 and -10°C respectively. By examining the three figures, it is noticeable that the CO_2 reaches its maximum concentration after approximately 40 seconds from the start of the engine and it is independent of room temperature or fuel type. In some cases, liquid gasoline can deviate and takes longer as in Figure 8 due to some reasons, which are difficult to examine in this study. However, the liquid fuel metering and evaporation can be among that reasons.

Figure 10 The time history of CO_2 concentration in the engine exhaust for different fuels during the warm-up period at a room temperature of -10°C (see online version for colours)

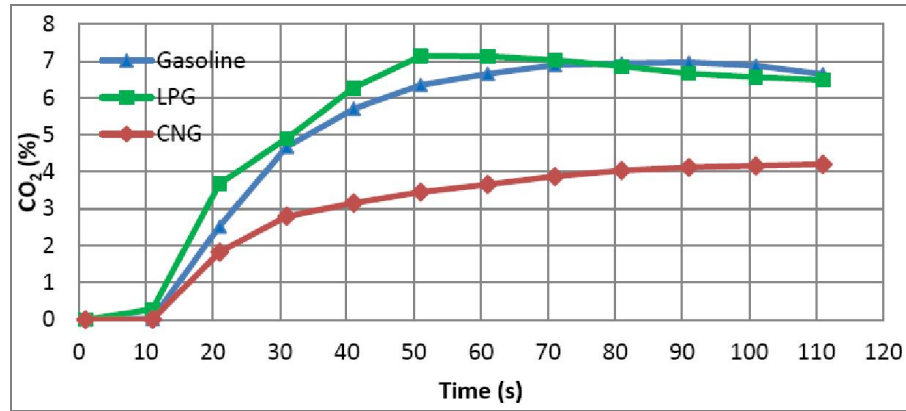
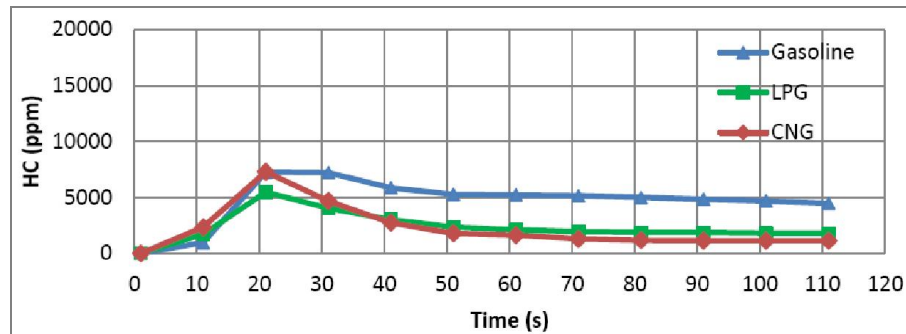


Figure 11 The time history of HC concentration in the engine exhaust for different fuels during the warm-up period at a room temperature of 10°C (see online version for colours)



The maximum concentration of CO_2 is not the same for all fuels. Figures 8 and 9 show that the highest concentration value is for the LPG followed by gasoline and the last one is the CNG. The difference between the LPG and CNG can be attributed to the density difference since the density of LPG is more than three times the density of CNG. Thus, the amount of LPG fuel entering the cylinder is more than that of CNG. However, the reason of having CO_2 concentration lower for gasoline than LPG can be attributed to the efficiency of the atomisation, evaporation and mixing process before combustion process. This process may lead to lower amount of fuel actually participates in the combustion process. The lower amount of fuel participating in the combustion process can be

there processes

confirmed with the high percentage of HC concentration in the exhaust relative to that emitted from the gaseous fuels as shown in Figures 12, 13 and 14.

Figure 12 The time history of HC concentration in the engine exhaust for different fuels during the warm-up period at a room temperature of 0°C (see online version for colours)

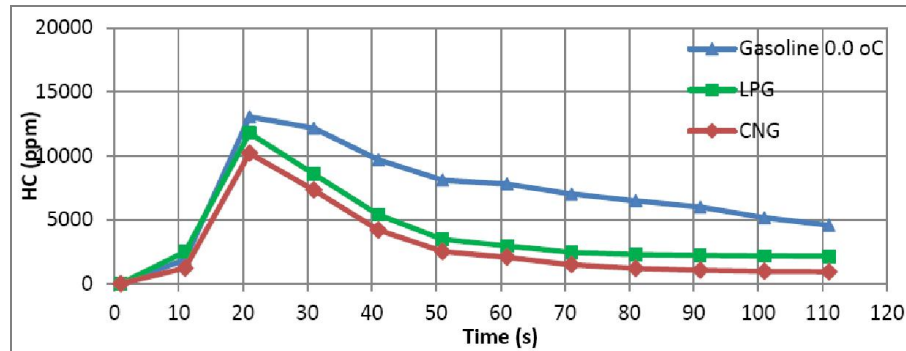
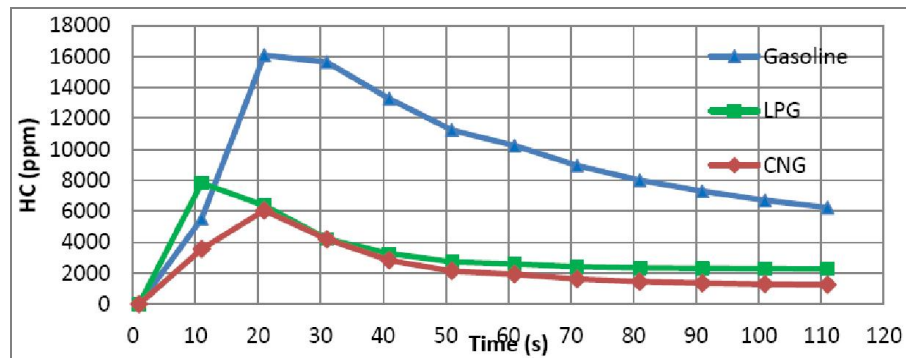


Figure 13 The time history of HC concentration in the engine exhaust for different fuels during the warm-up period at a room temperature of -10°C (see online version for colours)



The effect of temperature can only be noticed at low temperature at 0°C and -10°C as shown in Figures 10 and 11. During the first 20 seconds after the delay time the rate of increase of CO₂ formation for the case of -10°C is higher than that of 0.0°C. The higher concentration of CO₂ at -10°C can be attributed to the lower percentage of water vapour in the air. As the room temperature goes beyond the freezing temperature of water, the water vapour contents in air decrease. The percentage of water vapour contents in air is inversely proportionally to the combustion rates. This may explain having better combustion at -10°C than that of 0.0°C (Lindhjem et al., 2004; Manos et al., 1972).

Figures 11, 12 and 13 show the effect of using different fuels on the time history of hydrocarbon emissions during the warming up time period at different room temperatures (10.0°C, 0.0°C, -10.0°C), respectively. Similar to Figures 8, 9 and 10 there is approximately 11 seconds for the gas to reach the gas analyser, however the hydrocarbon concentration is not zero as CO₂ at 11 seconds. The reason is the unburned fuel, which was injected in the previous cycles and has not been burnt. After the engine starts, its

speed and temperature increase until it reaches the steady conditions at no load. During this transient period, the amount of HC is high due to the low efficiency of combustion. The low water and oil temperatures and the low engine speed are all factors affecting the combustion process during this transient period. As the engine approaching the steady conditions the HC concentration starts to goes down till reaching its minimum value at steady state condition. This trend was the same for all the tested room temperatures (10.0°C , 0.0°C , -10.0°C). At steady state engine conditions, the gasoline fuel is clearly showing much higher HC emissions particularly at low temperature -10°C . The high HC concentration at low temperature is due to the higher chance of fuel condensation at the intake wall and because of the low compression temperature. The low compression temperature results in a lower flame propagation speed and therefore, combustion takes longer and consequently, some fuel may exit the engine without burning.

Figure 14 The time history of CO concentration in the engine exhaust for different fuels during the warm-up period at a room temperature of 10°C (see online version for colours)

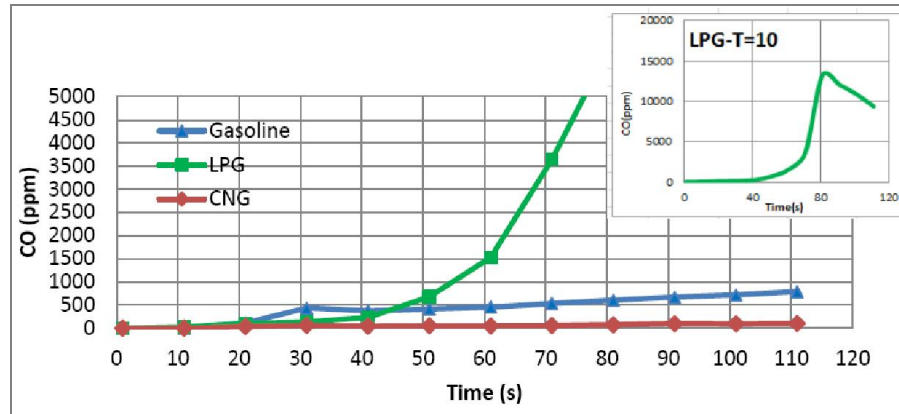


Figure 15 The time history of HC concentration in the engine exhaust for different fuels during the warm-up period at a room temperature of 0°C (see online version for colours)

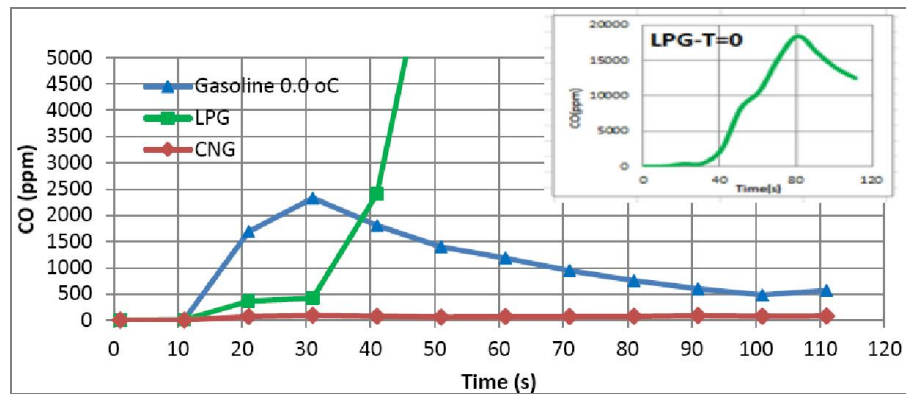
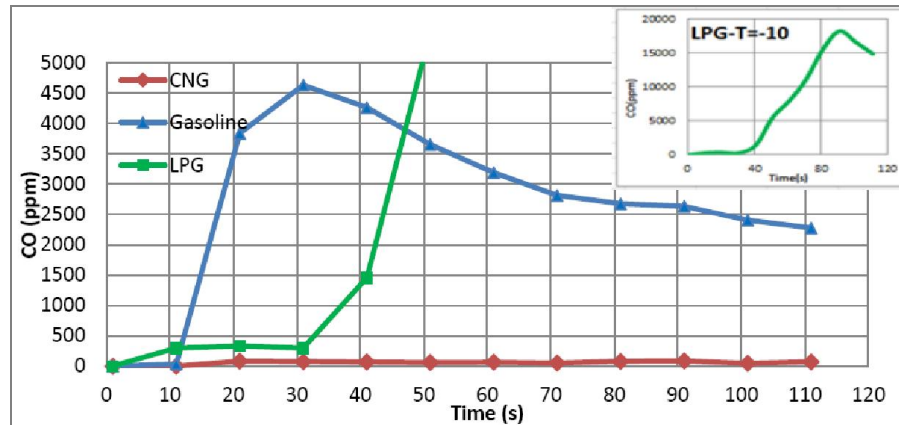


Figure 16 The time history of HC concentration in the engine exhaust for different fuels during the warm-up period at a room temperature of -10°C (see online version for colours)



Figures 14, 15 and 16 show the effect of using different fuels on the time history of carbon monoxide CO emissions during the warming up time period at different room temperatures (10.0°C , 0.0°C , -10.0°C), respectively. The CO concentration during the warm-up period can be divided into three distinct stages. During the early first stage, there is no or very little combustion reactions and therefore the amount of CO concentrations is almost zero. During the second stage, a low temperature combustion reaction occurs. As the temperature increases more CO is produced and also CO_2 and HC. This is due to partial reactions but not complete combustion since the temperature still did not reach its maximum value. The final is the higher temperature stage and during this stage the temperature inside the cylinder is high and the flame speed increases which resulting more depilation of CO formation. However, dissociation reactions are still allowing CO to appear in the exhaust. This is clearly shown in the case of LPG which produces the highest values of CO due to its fast flame relative to liquid fuel. The CNG has much lower density and therefore the amount of heat and energy produced is much lower for the same engine size as discussed in the first part during the discussions in CO_2 emissions (Glover, 1999).

3.4 Implementation of the gas starting system

Recent gasoline engine became more and more complicated and exhibit complex control system, which leaves no room to add more equipment or devices. It was therefore necessary to investigate the additional volume needed if the engine to be equipped with a gas fuel for engine-start-up and warming up before switching into gasoline liquid fuel. Investigation was carried out to evaluate the number of times to consume a 200 g of gaseous fuel in start-up the engine and continue feeding the engine until the catalyst reaches a specific temperature. The number of times was calculated using the fuel flow rate measurement data for the different gaseous fuels. Table 2 lists the results of these calculations for the different types of gaseous fuels and to achieve different catalyst temperatures 100, 150 and 250°C . The table shows that the 200 g hydrogen bottle can be used for 27 times to start the engine and continuously feeding the engine until the

catalytic converter reaches 250°C at environment temperature -10°C . This small bottle may be implemented in the engine and can only be used when the ambient temperature drops and can leads to better engine start and low emissions.

Table 2 The number of engine cycles to start-up the engine and warming up the engine located at ambient temperature of -10°C using a gas bottle of 200 gm with different gaseous fuel

<i>Catalyser temp. ($^{\circ}\text{C}$)</i>	<i>Number of cycles (#)</i>		
	<i>CNG</i>	<i>LPG</i>	<i>H₂</i>
100	15	22	132
150	10	15	50
250	4	10	27

4 Conclusions

line alignment for the conclusion part

The current study investigates experimentally the use of gaseous fuel CNG, LPG and H₂ for starting the gasoline engine and during the warming-up period at no load conditions before switching back to the gasoline liquid fuel. The following conclusions have been drawn up from the experimental results.

- 1 Gaseous fuels can treat the physical drawbacks of liquid fuel at the low temperatures and showed much shorter time duration for starting the engine, as there is no evaporation process, which is affected much by the environment temperature.
- 2 The design of a system for engine cold start process using gaseous fuel instead of liquid fuel during cranking can lead to a significant reducing in the HC emissions particularly at lower environmental temperature. Moreover, extending the use of gaseous fuel until the catalyst reaches its light off temperature can help meeting the future strict emission regulations.
- 3 The idling speed of the engine varies for different fuels if the throttle position is kept constant due to the difference in fuel densities. The idling speed was also found to be varied with the environment temperature.
- 4 Although LPG shows significant reductions in the number of cycles needed to have the engine started at low temperature, the CO emitted during the engine warm-up can be high until the catalyst reaches its lighting off temperature.
- 5 Hydrogen has many superior properties, fast flame speed, lower ignition energy, and wider range of flammability; these properties enhance engine start-up irrelative to the environmental temperature. It proved experimentally to be the best gaseous fuel for engine start-up and warming up particularly at low environment temperature in addition, it has zero emission.
- 6 A 200 g of hydrogen can be used to start the engine (500 cc) at ambient temperature of -10°C for up to 132 times or to start and warm up the catalyst to 250°C for up to 27 times. The gas injection system can be used for limited number of times and therefore can be viable when the environment temperature significantly low.

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