EXPERIMENTAL STUDY OF PERFORMANCE OF SPARK IGNITION ENGINE WITH GASOLINE AND NATURAL GAS

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Abstract The tests were carried out with the spark timing adjusted to the maximum brake torque timing in various equivalence ratios and engine speeds for gasoline and natural gas operations. In this work, the lower heating value of gasoline is about 13.6% higher than that of natural gas. Based on the experimental results, the natural gas operation causes an increase of about 6.2% brake special fuel consumption, 22% water temperature difference between outlet and inlet engine, 3% exhaust valve seat temperature, 2.3% brake thermal efficiency and a decrease of around 20.1% maximum brake torque, 6.8% exhaust gas temperature and 19% lubricating oil temperature when compared to gasoline operation. The results also revealed that, over the entire range of engine speed and equivalence ratio, the exhaust gas temperature and the lubricating oil temperature for gasoline operation is higher than that of natural gas operation while the exhaust valve seat temperature for natural gas operation is higher.

Keywords Engine performance, spark ignition engine, gasoline, natural gas, lower heating value

چکیده تغییرات نسبت هم‌ارزی و سرعت دورانی موتور به طور تجربی با تنظیم زمان جرقه به حداکثر گشتاور ماکزیمم در موقعیت کاملا باز دریچه گاز مورد آزمایش قرار گرفت. در این کار، ارزش حرارتی پایین سوخت بنزین در حدود ٪۱۳/۶ بالاتر از ارزش حرارتی پایین سوخت گازطبیعی است. نتایج آزمایش نشان داد که سوخت گاز طبیعی در موتور اشتعال جرقه‌ای در مقایسه با سوخت بنزین باعث افزایش ٪۶/۲ مصرف سوخت ویژه ترمزی، ٪۲۲ اختلاف بین دمای آب ورودی و خروجی موتور، ٪۳ دمای نشیمنگاه سوپاپ خروجی، ٪۲/۳ بازده حرارتی ترمزی و باعث کاهش ٪۲۰/۱ ماکزیمم گشتاور ترمزی، ٪۶/۸ دمای گاز خروجی و ٪۱۹ دمای روغن می‌گردد. همچنین نتایج آزمایشی نشان داد که در تمام محدوده سرعت موتور و نسبت‌هم‌ارزی، دمای گاز خروجی و دمای روغن در وضعیت بنزین‌سوز نسبت به وضعیت گازطبیعی‌سوز بالاتر است در حالیکه دمای نشیمنگاه سوپاپ خروجی در وضعیت گاز طبیعی بیشتر می‌باشد.

1. INTRODUCTION

The use of alternative fuels for engine is regarded as one of the major research areas for the age [1-3]. Gaseous fuels in general are promising alternative fuels due to their economical costs, high octane numbers and lower polluting exhaust emissions [4-5]. Natural gas is one of the major combustion fuels used throughout the country. The natural gas has different chemical and physical properties when compared to gasoline. Natural gas consists of a high percentage of methane and varying amounts of ethane, propane, butane, and inert (typically nitrogen, carbon dioxide, and helium). The composition of the natural gas used in this experiment are given in Table 1. Because of this composition, the lower heating value of gasoline is about 13.6% higher than that of natural gas in this work [6].

Many researchers have been directed their studies towards the effect of using natural gas and gasoline in internal combustion engines [7-11]. Evans et al. [7] determined the performance of gasoline and natural gas operations. The results showed that the brake power decreases by 11.3% with the natural gas operation compared to gasoline operation. The results also showed that the brake specific fuel consumption (BSFC) decreases with the natural gas operation. This is due to the higher heating value of natural gas fuel than that of gasoline fuel. Raine and Jones [8] measured the exhaust gas temperature, piston crown, spark plug body, exhaust valve and cylinder head temperature in natural gas and gasoline fuelled engine. The results showed that, at wide open throttle conditions and at stoichiometric fuel-air ratios, the temperature of combustion chamber for natural gas fuelling was lower than that for gasoline fuelling. The exhaust gas temperature was lower for natural gas operation than that for gasoline operation. The exhaust valve temperature with gasoline fuelling was higher than that with natural gas fuelling. Gupta et al. [9] investigated the performances and emissions of a spark ignited engine fuelled with gasoline and compressed natural gas. Results showed that for stoichiometric fueling, with a naturally aspirated engine, a power loss of 10 to 15 percent can be expected for natural gas over gasoline fueling. Higher brake thermal efficiencies can also be expected with natural gas fueling with maximum brake torque (MBT) timings over the range of equivalence ratios investigated in this work. Coefficient of variation data based on the indicated mean effective pressure demonstrated that the engine is much less sensitive to equivalence ratio leaning for natural gas fueling as compared to gasoline cases. Aslam et al. [10] investigated the performance and emission characteristics of natural gas in a spark ignition engine being operated in the lean fueling regime and compared the operation with gasoline fueling cases. These characteristics included the brake thermal efficiency (BTE), brake power, BSFC, equivalence ratio, carbon monoxide, unburned hydrocarbon and nitric oxide. Based on the experimental results, the authors found that compressed natural gas shows lower brake mean effective pressure, BSFC, BTE, higher efficiency and lower emissions of carbon monoxide, unburned hydrocarbon and carbon dioxide but more oxides of nitrogen compared to gasoline. Cho et al. [11] reviewed some of the characteristics of combustion and emission of natural gas engine. They mainly focused on carbon dioxide, particulate matter, nitrogen oxides, unburned hydrocarbons, temperature of piston and cylinder head, valve seat temperature, MBT timing and equivalence ratio. Results showed that the combustion duration, the coefficient of variation of the indicated mean effective pressure and engine-out emissions were dependent on the overall air fuel ratio, throttle positions and fuel injection timings.

TABLE 1. Natural gas composition

Component	Chemical formula	Volumetric %
Methane	CH_4	83.5
Ethane	C_2H_6	3.6
Propane	C_3H_8	0.7
N-Butane	C_4H_{10}	0.2
Pentane	C_5H_{12}	0.1
Nitrogen	N_2	10.8
Carbon Dioxide	CO_2	1.1

It can be seen from the literature survey given above that the heating value of natural gas used for the experimental is higher than that of gasoline. Therefore, in this work, the comparison of engine performance between gasoline operation and natural gas operation is investigated when the heating value of natural gas is lower than that of gasoline. BTE, BSFC and MBT are selected for study. Reviewing the literature also showed that the lubricating oil temperature and the water temperature difference between outlet and inlet engine have not been investigated before. In addition, there is no sufficient information about the exhaust gas temperature and the exhaust valve seat temperature. Hence, the present work also investigates and compares these temperatures for natural gas and gasoline operations. However, this study extends the understanding of spark ignition engine for gasoline and natural gas operations.

2. EXPERIMENTAL ANALYSIS

Fig. 1 shows a schematic diagram of the experimental setup. In the experimental study, a four cylinder spark ignition engine was modified to operate with natural gas and gasoline whose specifications are shown in table 2. The engine was operated on a test bench which had been previously installed and instrumented in an engine hall for typical dynamometer experiments. The gasoline and natural gas fuels at various engine speeds and equivalence ratios were used in the present work. This engine was equipped with an electronically controlled injection system that allowed a full control of the injection parameters for gasoline operation. According to natural gas operation, a few additional components were incorporated into the existing system to operate the engine on natural gas fuel. Natural gas fuel is supplied to engine intake port through gas mixer, and the amount of fuel is controlled by a mass flow controller. A wide band lambda meter was installed for the measurement of relative air/fuel ratio. The inlet airflow rate was measured with a laminar flow meter. At five various points, temperatures were measured using a temperature measuring device which was attached to a board. Temperature measuring points were: outlet exhaust gases from manifold, inlet water to engine, outlet water from engine, outlet oil from pump oil, valve seat surface. The engine speed was measured by a tachometer on the engine crankshaft.

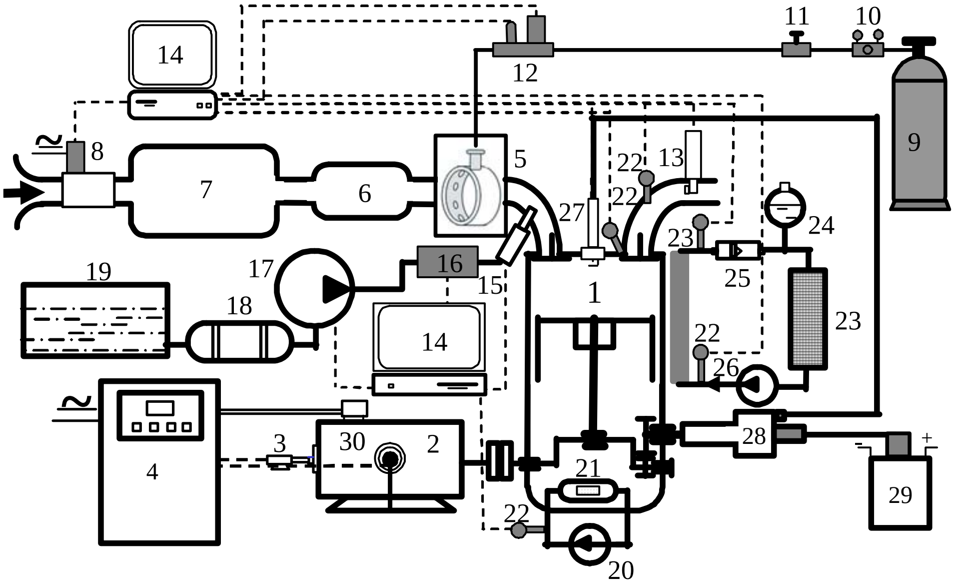

Figure 1. Schematic view of the experimental setup. 1. Engine 2. Dynamometer 3. Speed counter 4. Control unit 5. Gas carburetor 6. First-plenum chamber 7. Second-plenum chamber 8. Air flow meter 9. Natural gas cylinder 10. Regulator 11. Manual valve 12. Mass flow meter and mass flow controller 13. Oxygen sensor 14.Computer 15.Gasoline injector 16.Gasoline flow meter 17. Injection pump 18. Fuel filter 19. Gasoline fuel 20. Oil pump 21. Oil filter 22. Thermocouple 23. Radiator 24. Water tank 25.Water flow meter 26.Water pump 27- Spark plug 28. Coil driver 29. Coil 30. Load cell

TABLE 2. Specifications of test engine

Cylinder bore	76mm
Piston stroke	87mm
Length of connecting rod	148mm
Compression ratio	9.6

The torque was measured using a lever arm force balance with a load cell. For each operating condition, the MBT spark advance was determined and the engine was normally run at the MBT spark timings. The air/fuel ratio was varied from lean to rich sides of the stoichiometric condition. Variations in the air/fuel ratio were accomplished by manual adjustment of the fuel flow rate. The engine was allowed to reach a stable condition before recording any data after any parameter changes. During the tests, the steady state data acquisition system was used for monitoring and recording engine speed, torque, air flow rate and intake temperature, natural gas and gasoline flow rate, exhaust temperature, inlet and outlet coolant temperatures and exhaust valve seat temperatures. To insure the repeatability and comparability of the measurements for different fuels and operating conditions, experimental data were averaged over consecutive 100 cycles. The measuring accuracy of each instrument is shown in Table 3. Further detailed description of the experimental apparatuses has also been reported in Ref. [6].

TABLE 3. Accuracies of the measurements

Parameter	Accuracy
Dynamo torque	±0.5 N m
Engine speed	±0.1 rpm
Fuel consumption	±0.01 Kg/h
Exhaust gas temperature	±1°C
Exhaust valve seat temperature	±1°C
Water temperature	±1°C

3. RESULTS AND DISCUSSION

In the current study, all experiments were carried out with the spark timing being manually adjusted to the MBT timing in a wide open throttle (WOT) position with various equivalence ratios and engine speeds. It should be noted that the heating value of gasoline, in this work, is higher than that of natural gas.

3.1. Maximum brake torque (MBT) Fig. 2 illustrates the variation of MBT versus engine speed at different equivalence ratios for gasoline and natural gas operations with WOT condition. The figure shows that the MBT improves with increasing engine speed up to about 3000 rpm in both fuels for throughout the equivalence ratio range where it reaches its peak value then starts to decline as the engine speed increases. The lower MBT at low engine speeds are primarily due to lower volumetric efficiency [12]. The decline of MBT at high engine speed can be explained with reduced engine volumetric efficiency and increased friction forces. Furthermore from this figure it can be seen that there is a significant improvement in MBT with increasing equivalence ratio from 0.8 to around 1.1 for both fuels. Further increase of equivalence ratio leads to the decline of MBT. Rich mixture regions decrease MBT due to increasing time required to finish the combustion which causes an increase in incomplete combustion. Lean mixture regions decrease MBT due to a reduction in the volumetric lower heating value of the intake mixture, despite increasing combustion efficiency [13]. At rich mixture regions, it can be concluded that the MBT of natural gas operation drops more quickly than that of gasoline operation when equivalence ratio increased. This result is consistent with reference [8]. This is due to the fact that, at rich mixture regions, the decreasing of the flame temperature and burning rate in the natural gas fuel is higher than that in the gasoline fuel [8]. Referring to Fig. 2, it can also be observed that the trend of MBT is the same for different equivalence ratios at both fuels. It can be observed that MBT of natural gas operation is always lower than that of natural gas operation over the entire range of engine speed and equivalence ratio. The result is consistent with reference [10]. Considering that the heating value of gasoline is lower than that of natural gas in reference [10], it can be concluded that there is no significant relationship between the MBT and the heating value of natural gas. Consequently, it may be concluded that the MBT depends on the combustion duration rather than the heating value of fuel. Thus, the decrease in MBT can be related both to lower burning velocity of gas natural which causes natural gas burns away from the top dead centre and lower heating value per volume unit of the natural gas with air mixture. In addition, MBT is proportional to volumetric efficiency, and as natural gas causes a lower volumetric efficiency, its MBT also decreases [14]. The significance of this decrease in MBT for natural gas operation varies with the engine speed and the equivalence ratio. It is worth noting that the optimum spark timing of natural gas engine is different from gasoline engine, it affects the phase of combustion duration and slow burning speed of natural gas also influences the MBT. The maximum value of MBT is 106.2 N-m at an equivalence ratio of 1.1 for gasoline operation and is 89.1 N-m at an equivalence ratio of 1.06 for natural gas operation. However, on average, the MBT of natural gas operation is around 20.1% (16.2 N-m) lower than that of gasoline operation. Referring to Fig. 2, it can be seen that the peak MBT for natural gas operation is relatively flat as compared to gasoline operation. It can also be seen that the rate of increase in MBT for gasoline operation increases with increasing equivalence ratio while that for natural gas operation decreases.

3.2. Brake Thermal Efficiency (BTE) Fig. 3 illustrates BTE with engine speed for different equivalence ratios at MBT timing with WOT condition for both the tested fuels. The figure shows that BTE increases as the engine speed is increased in the low engine speed range and decreases in the high engine speed range for the both fuels. The lower BTE at low engine speed is primarily due to the great heat loss to the combustion chamber walls. The high engine speed causes a decrease in the combustion duration with respect to time and hence required time require for complete combustion is reduced. This result demonstrates the incomplete combustion at high speed engine that causes the decrease in the MBT. It can also be seen that there is an improvement in BTE when the equivalence ratio increased from 0.8 to around 1.0 for gasoline operations and from 0.8 to around 0.9 for natural gas operation. With further increase in equivalence ratio, the BTE decreases significantly. This is due to the fact that, in case of lean mixture regions, specific heat ratio values are lower than stoichiometric equivalence ratio value and in case of rich mixture regions combustion is not complete [14]. The highest BTE, 31.2% at equivalence ratio 1.0 for gasoline operation and 31.7% at equivalence ratio 0.9 for gas natural operation, is reached at engine speed near about 3000 rpm for both fuels. It is also observed that natural gas operation shows higher BTE throughout the engine speed and equivalence ratio ranges when compared to gasoline operation. This result is consistent with references [7]. Considering that the heating value of gasoline is lower than that of natural gas in reference [7], it can be concluded that there is no significant relationship between BTE and the heating value of natural gas and gasoline. Based on the above reason, the improvement in BTE associated with the natural gas is due to the more advanced MBT timing and better mixing of natural gas with air as compared to gasoline [15]. This leads to increase in the proportion of energy captured from natural gas fuel in comparison with gasoline fuel. In other words, the high thermal efficiency means that a larger portion of combustion heat has been converted into work. However, on average, the BTE of natural gas operation is around 0.67% higher than that of gasoline operation.

3.3. Brake specific fuel consumption (BSFC)

Fig. 4 illustrates BSFC with engine speed for different equivalence ratios at MBT timing with WOT condition for natural gas and gasoline operations. It can be observed that BSFC drops down as the engine speed increase up to about 3000 rpm and then it increases when the engine speed exceeds 3000 rpm for both fuels. Higher BSFC at low engine speed is the result of great heat loss to the combustion chamber walls. At high speed, the rate of increase of friction power with engine speed is more than that of indicated power in this condition which results less brake power and hence more BSFC [10]. It can also be seen that there is a decrease in BSFC with the increment of equivalence ratio from 0.8 to around 1 for gasoline operation and from 0.8 to around 0.9 for natural gas operation. But further increase of equivalence ratio leads to the significant increasing of BSFC due to a reduction in combustion efficiency. Referring to Fig. 4, it can also be observed that BSFC of gasoline operation was always less than that of natural gas operation over the entire range of engine speed and equivalence ratio. This is due to higher heating value of gasoline than that of natural gas in this research. It should be noted that if heating value of natural gas could be more than that of gasoline, BSFC for natural gas operation would be lower than that for gasoline operation, reported by the authors in 2 and 3. The lowest BSFC is 258.6 g/kWh for gasoline and 282.46 g/kWh for natural gas. Furthermore, BSFC of natural gas is on average 18.9 g/kWh (6.2%) higher than that of gasoline. Additionally as can be seen from Figs. 2 and 3, the equivalence ratio of maximum MBT is higher than the equivalence ratio of maximum BTE for both fuels.

3.4. Water temperature difference between outlet and inlet engine Fig. 5 shows the effect of engine speed on the water temperature difference between outlet and inlet engine with the different equivalence ratios at MBT timing with WOT condition for both natural gas and gasoline operations. From this figure, it seems that the water temperature difference between outlet and inlet engine decreases with the increase of engine speed. The figure also shows that the variation in water temperature difference between outlet and inlet engine for gasoline operation is lower than that for natural gas operation over the entire range of engine speed and equivalence ratio. As can be seen from Figs. 5 and 2, the water temperature difference between outlet and inlet engine for gasoline operation is lower than that for natural gas operation, but the MBT of gasoline operation is higher than that of natural gas operation. This means that the water temperature difference between outlet and inlet engine is independent of the MBT produced by the fuel. In other words, it depends on combustion characteristics of fuel. The water temperature difference between outlet and inlet engine for natural gas is on average 22% (1.3°C) higher than that for gasoline operation. It means that the heat transfer loss to the cylinder walls for natural gas operation is higher than that for gasoline operation. This can be attributed to the fact that the combustion duration for natural gas is higher than that for gasoline operation. It is worth noting that the engine coolant flow rate primarily depends to the engine speed, because typical water pumps are directly connected with crankshaft in this research.

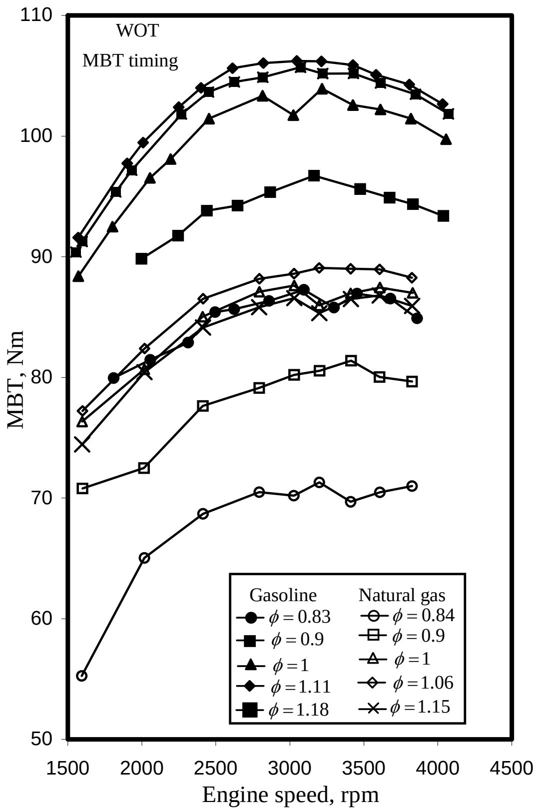

Figure 2. MBT values versus engine speed at different equivalence ratios

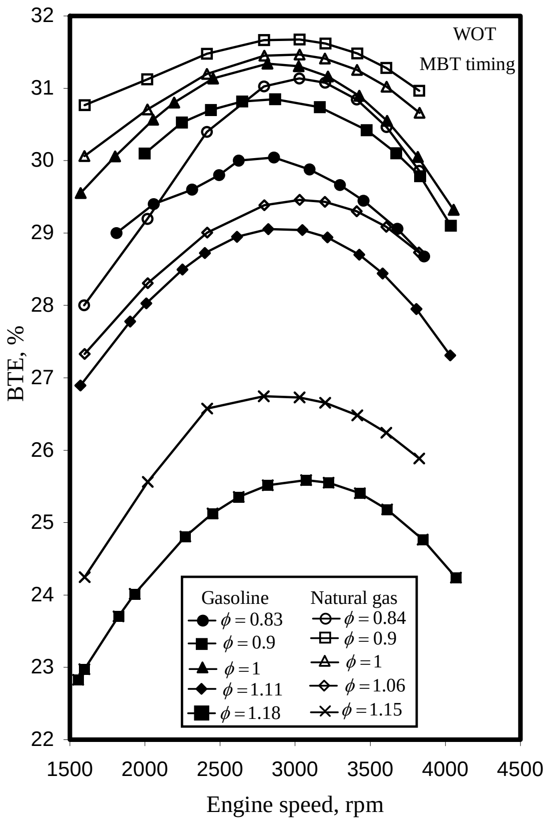

Figure. 3. BTE values versus engine speed at different equivalence ratios

3.5. Exhaust gas temperature Fig. 6 exhibits the exhaust gas temperature versus engine speed with different equivalence ratios at MBT timing under WOT condition for gasoline and natural gas operations. The exhaust gas temperature increases with increasing engine speed, which may be due to the increase in combustion temperature. The figure shows that the rate of increase in exhaust gas temperature with engine speed for gasoline operation is higher than for natural gas operation. Also, it can be concluded that the maximum exhaust gas temperature appears at equivalence ratio around 1.0 for both fuels. This indicates that the flame temperature during combustion and the prevailing gas temperature at the end of the expansion process are higher in the case of stoichiometric than in lean or rich mixtures [16]. Referring to Fig. 6, it can also be observed that the

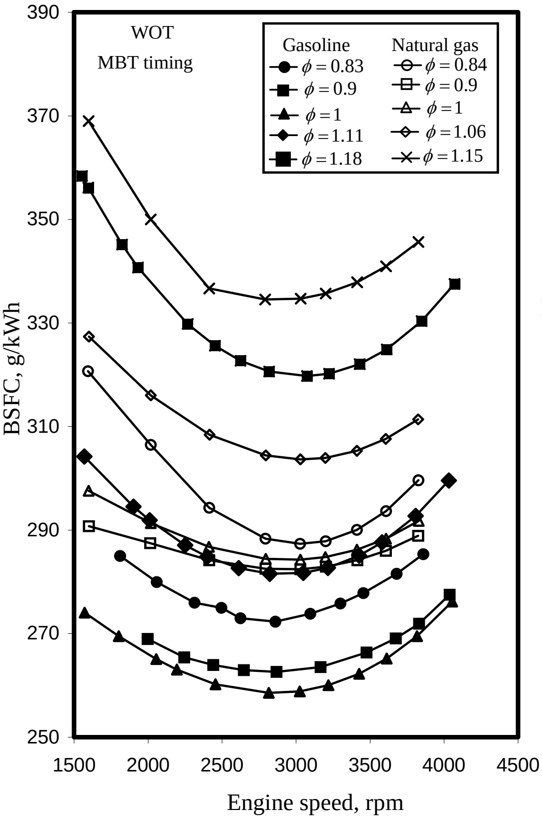

Figure. 4. BSFC values versus engine speed at different equivalence ratios

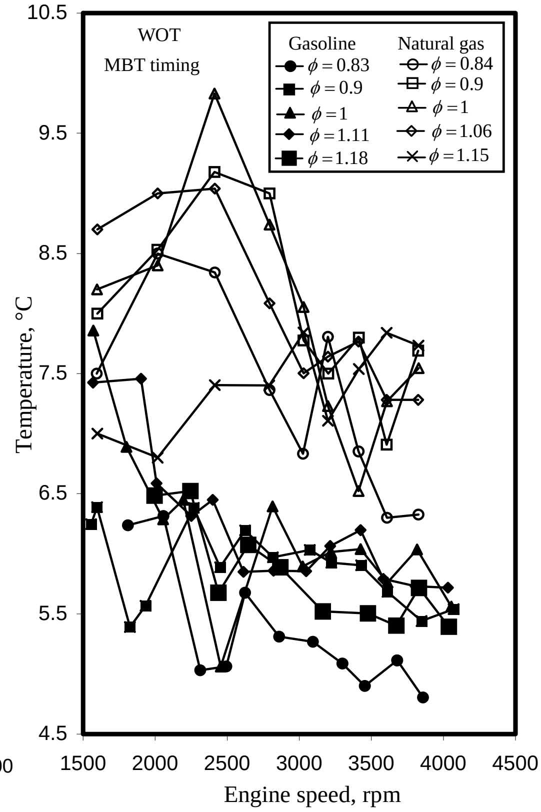

Figure. 5. Variation of water temperature difference between outlet and inlet engine versus engine speed at different equivalence ratios

natural gas operation has lower exhaust gas temperature than the gasoline operation throughout the engine speed and equivalence ratio ranges. This is because of the improvement in combustion efficiency and the reduction in combustion temperature for natural gas operation as compared to gasoline operation. Also it can be attributed to the higher combustion duration in the natural gas operation which causes an increase in the heat transfer loss to the cylinder walls. This result is consistent with reference [11]. It should be noted that the lower exhaust temperatures (below 750 K) at natural gas operation increase the difficulties in methane oxidation and result in low THC (total hydrocarbon) conversion efficiency [11]. The figure also shows that the exhaust gas temperature difference between gasoline and natural gas operations increases with the increase in the engine speed. However, on average, the exhaust gas temperature of natural gas operation is 48.64°C (6.8%) lower than that of gasoline operation.

3.6. Exhaust valve seat temperature Fig. 7 illustrates the effects of equivalence ratio and engine speed on the exhaust valve seat temperature at MBT timing with WOT condition for natural gas and gasoline operations. The figure shows that the exhaust valve seat temperature increases slowly with engine speed at both fuels. On average, the exhaust valve seat temperature with the engine speed is linear with R2 values of 0.955 and 0.976 for natural gas and gasoline operations, respectively. It can be also seen that there is a little improvement in the exhaust valve seat temperature with the increase of equivalence ratio from 0.8 to 1.0 for both fuels. With further increase in equivalence ratio, the exhaust valve seat temperature decreases for both fuels. Also from this figure, it can be seen that the exhaust valve seat temperature of natural gas operation is higher than that of gasoline operation throughout the engine speed and equivalence ratio ranges. This conclusion is coincident with that of reference [6]. Referring to Fig. 7, it can be observed that the exhaust valve seat temperature difference between natural gas and gasoline operations increases slowly with increasing engine speed. As can be seen from Figs. 7 and 6, the exhaust gas.

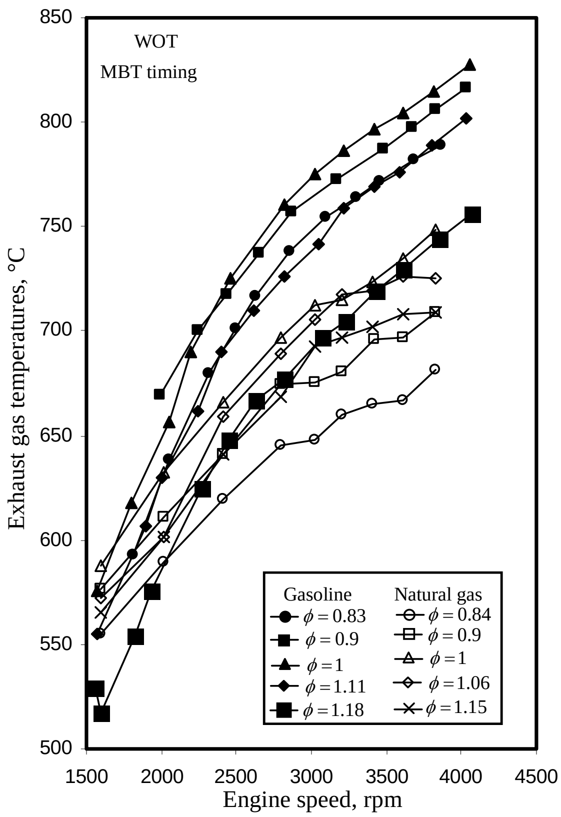

Figure. 6. Variation of exhaust gas temperature versus engine speed at different equivalence ratios

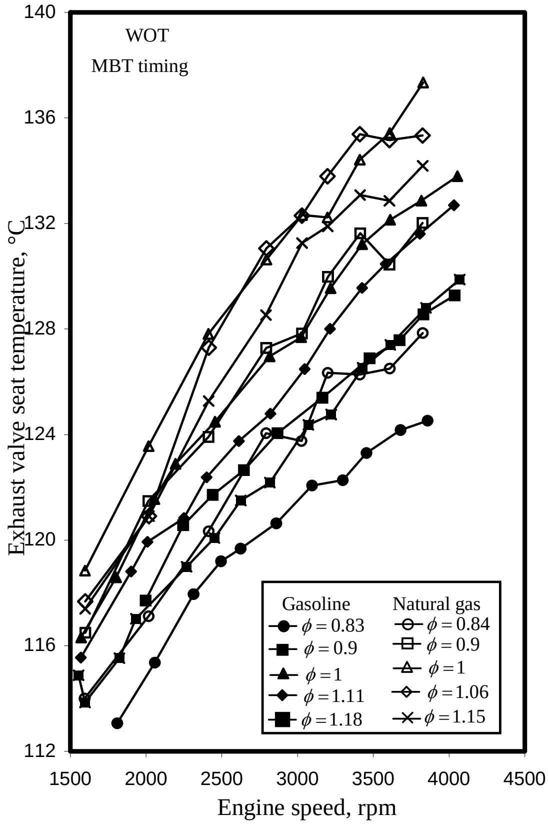

Figure. 7. Variation of exhaust valve seat temperature versus engine speed at different equivalence ratios

temperature for gasoline operation is higher than that of natural gas operation, while the exhaust valve seat temperature of natural gas operation is higher. It should be noted that the exhaust valve seat temperature of natural gas operation is higher than that of gasoline operation, although the MBT and exhaust gas temperature of gasoline operation is higher than that of natural gas operation, as can be seen from Figs. 2, 6 and 7. However, on average, the exhaust valve seat temperature of gasoline operation is around 3% (4°C) lower than that of natural gas operation.

3.7. Lubricating oil temperature Fig. 8 shows the trends of the oil temperature as a function of engine speed for the gasoline and natural gas operations at MBT timing with WOT condition. It is clear from the figure that the lubricating oil temperature increases with the increase of engine speed for both fuels. The lubricating oil temperature of gasoline operation is more sensitive to the variation of engine speed and equivalence ratio as compared to natural gas operation. The lubricating oil temperature with the engine speed is linear with R2 values of 0.978 and 0.986 for natural gas and gasoline operations, respectively. Additionally as can be seen from Figs. 8 and 6, the oil temperature and the exhaust gas temperature for gasoline operation are higher than for natural gas operation. Based on these results, it can be concluded that the higher temperature blow-by (combustion gases blowing past the piston ring) causes higher oil temperature for gasoline operation when compared to natural gas operation. It should be noted that the short combustion duration for gasoline operation causes an increase in the cylinder pressure when compared to natural gas operation. Hence, the blow-by products in natural gas operation is lower than that in gasoline operation. It should be also noted that the higher temperature combustion causes higher temperature of blow-by for gasoline operation when compared to natural gas operation.
Additionally as can be seen from Figs. 8 and 2, the lubricating oil temperature of gasoline operation is higher than that of natural gas, although the MBT of gasoline operation is lower than that of natural gas operation. It means that the lubricating oil temperature is independent of MBT produced by the fuel. On average, the lubricating oil temperature for natural gas operation is around 17.3°C (19%) lower than that for gasoline operation.

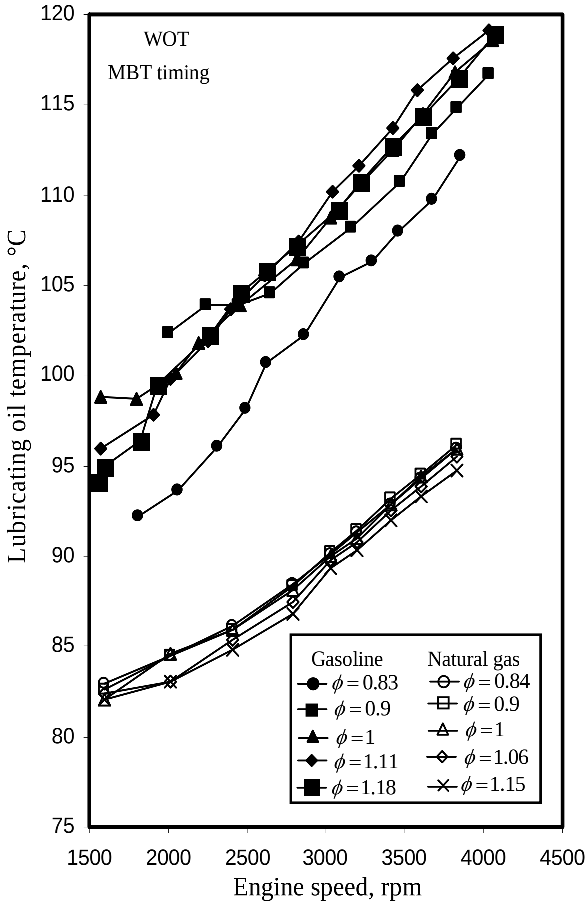

Fig. 8. Variation of lubricating oil temperature versus engine speed at different equivalence ratios

4. CONCLUSIONS

The objective of this study was to observe the effects of natural gas fuel on the engine performance by comparing it to gasoline fuel. In this work, the tests were carried out with the spark timing adjusted to MBT timing with WOT condition at different engine speeds and equivalence ratios for gasoline and natural gas operations. The following conclusions were drawn from the experimental results:

- On average the results showed that natural gas operation causes an increase of about 6.2% in BSFC, 22% in water temperature difference between outlet and inlet engine, 3% in exhaust valve seat temperature, 2.3% in BTE and a decrease of around 20.1% in MBT, 6.8% in exhaust gas temperature and 19% in lubricating oil temperature when compared to gasoline operation .

- The maximum of MBT, BTE, exhaust gas temperature and the minimum of BSFC at gasoline operation are found around equivalence ratio 1.11, 1.0, 1.0 and 1.0, respectively and are found around equivalence ratio 1.06, 0.9, 1.0 and 0.9 for natural gas operation, respectively .
- It can be concluded that the equivalence ratio of maximum MBT is higher than equivalence ratio of maximum BTE for natural gas and gasoline operations.
- The BSFC depends on the heating value of the fuel rather than the MBT and BTE.
- The exhaust gas temperature of gasoline operation is higher than that of natural gas operation, while the exhaust valve seat temperature of natural gas operation is higher .
- Over the entire range of engine speed and equivalence ratio, the exhaust gas temperature and the lubricating oil temperature for gasoline operation are higher than those for natural gas operation while the exhaust valve seat temperature for natural gas operation is higher.
- The exhaust valve seat temperature and the lubricating oil temperature are almost linear with the engine speed for natural gas and gasoline operations.

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