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Evaluation of Fuel Consumption and Exhaust Emissions During Engine Warm-up

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Abstract: Engine exhaust emission and fuel consumption during warm-up period was experimentally investigated. Experiment was conducted on a four-stroke four-cylinder spark ignition engine alternatively equipped with CIS and EIS. Fuel consumption; and exhaust emissions included hydrocarbon, carbon monoxide and carbon dioxide were measured as a function of ambient temperature; i.e. 7, 25 and 40ºC. In order to simulate engine operation condition during warm - up period under various ambient temperatures axillaries cooling water and cooling air systems were designed and coupled to the engine being tested. Results show that as the ambient temperature increases the concentration of both hydrocarbon and carbon monoxide and fuel consumption decreases while the carbon dioxide increases. Also, the time required for the engine to fully warm-up is shortened. Moreover, operating the engine when equipped with EIS has a greater effect on HC, CO and fuel consumption reduction compared to when equipped with CIS at the same operation conditions.

Key word: Engine warm-up period, exhaust emission, fuel consumption, ignition systems, engine simulation

INTRODUCTION

Refined oil products used in Jordan is highly dependent on imported oil. Moreover, the Jordan fleet of gasoline and diesel-powered vehicles consume about 38% of the total Jordanian oil and contribute about 67% of the total Jordan pollutants emissions[1-4]. Therefore, improvement of the fuel efficiency can reduce both degree of the Nations dependence on imported oil and emissions production.

The primary factors affecting vehicle exhaust emissions and fuel consumption during engine warm-up period can be classified into three categories; which are vehicle technology-related factors, fuel quality-related factors and engine-related factors. These factors are discussed in further detail in the following sections.

Vehicle technology-related factors: All motor vehicles in Jordan are imported and their prices are very high mainly because of the heavy purchase tax. Therefore the old vehicles are expected to circulate for long before modern ones replace them. The old vehicles usually consumed more fuel and emit more pollutants than new ones as results of deterioration in engine efficiency and lack of proper maintenance. In addition, engine of old vehicles used conventional ignition system with mechanical breaker points. In practice operation of these system encountered the following faults: poor performance at high speed, inability to fire partially fouled spark plugs, relatively short life of the breaker points and spark plugs, poor starting and poor reproducibility of the secondary voltage rise to the maximum value. The effect of these factors combined led to increasing fuel consumption, hydrocarbon (HC) and carbon monoxide (CO) emissions. To overcome these faults in modern vehicle engines conventional ignition system have been replaced with coil ignition system (high energy electronic ignition systems). Electronic ignition systems (EIS) produce larger output voltage (35 kV) and longer spark duration. Therefore extending the engine operating conditions over which satisfactory ignition is achieved.

Fuel quality-related factors: Jordan National Petroleum Refinery currently produces two grades of gasoline, leaded (regular and premium) and unleaded. However, due to the high price of unleaded gasoline over leaded a few percent of automotive owners are using it. Also 75% of gasoline sold in Jordan is regular at 87 RON. It is therefore necessary to de-tuning the engines to enable them to operate satisfactory on lower quality fuel, thus more fuel is required and consequently more pollution. Moreover, most vehicles in use in Jordan are operated without catalytic emission system, due to the use of leaded gasoline; and its elimination by the automobile ownership.

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Engine-related factors: The increase in fuel consumption during engine warm-up can be attributed to several factors, such as: increased friction associated with cold lubricant, degradation of the lubricants by condensate and unburned fuel, less efficient combustion in a cold combustion chamber as a result of the heat transfer from the burning air-fuel mixture to the cold combustion chamber walls. Also, the cold combustion chamber walls lead to increase quenching of the flame front in the thermal boundary layers and the corresponding increase of the HC, CO emissions and fuel consumption. Moreover the induction system parts in contact with air-fuel mixture are cold and can't supply the heat needed to vaporize the sufficient quantity of fuel. Therefore to compensate the decrease in the fuel vaporization an excess fuel is supplied.

Several sources lead to hydrocarbon and carbon monoxide emissions during engine warm-up namely created by poor fuel vaporization and cold catalytic emission system. The catalytic emission system during warm-up is not fully operated prior to reaching its operating temperature (400ºC) and more fuel can be provided to get acceptable performance, thus the engine emits the highest HC and CO emissions. Further, during engine warm-up the friction and the heat losses are greater than once fully warmed and the time required to reach steady-state operating temperature is longer. These factors contribute to a longer period of relatively poor combustion and consequent need for more fuel enrichment (operation with more fuel than required for stoichiometry). The combination of these factors result in higher exhaust concentration of unburned fuel in the form of HC and CO.

In addition, the variations in mixture preparation can also affect engine fuel consumption and emissions. This effect can be explained as follows: in normal operation of the carbureted spark ignition engines fuel flow into cylinder is fuel vapor or small fuel droplets carried by the air stream, a fraction of the fuel flows onto the manifold and port walls and forms a liquid film. During cold starting liquid film established in the manifold and port evaporates more slowly than fuel carried by the air stream and introduces a lag between the air-fuel ratio produced at the carburetor and the air-fuel ratio delivered to the cylinder. Therefore, the subsequent poor control of the liquid film during warm-up, often leads to the combustion of rich air-fuel mixtures, with the consequent high fuel consumption and high emissions level.

Many studies were conducted to reduce the HC and CO emissions exhausted from the automotive engines. Caton *et al.* 1984 showed (by hydrocarbon oxidation in a spark ignition engine exhaust port) that for Stoichiometric and slightly rich conditions secondary air flow rate up to 30% of the exhaust flow increased the degree of burn up and consequently decreasing the HC and CO emissions. Russ et al., 1995 studied the effect of coolant temperature on HC emissions from a spark-ignition engine and found that by increasing coolant temperature the total HC emission decreases by 0.75% per one temperature degree. Tong, K.Q, et al., 2000, investigated the fuel volatility effects on mixture preparation and performance in a GDI engine during cold start and concluded that the direct injection of the fuel allows for the control of cycle-to-cycle fuel-air ratio and permits rapid initial firing of the gasoline, therefore reducing the HC emissions.

In addition many efforts are being made to eliminate the sources, which contribute to the formation of HC and CO emissions. These can be summarized as follows: optimizing the different injection design parameters (i.e. the degree of atomization, spray angle and targeting relative to the inlet valve seat) to reduce the cylinder wall wetting[5]; optimizing the intake system and ports design to reduce misfiring and incomplete flame propagation[6-9]; developing the after-treatment system to increase their effectiveness in reducing the emissions, light off temperature, thermal stability over extended period and mileage, increase in back pressure, system complexity packaging and durability[10-20].

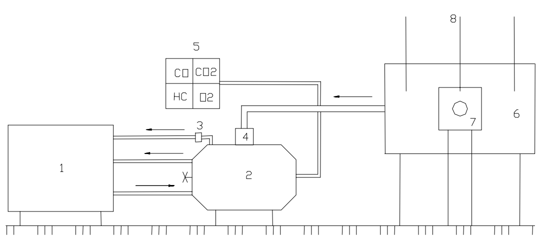
Air pollution in Jordan, especially in the Downtown of Amman has been studied. A study, which was conducted with objectives to monitor air quality, indicated that the concentration of some air pollutants exceeded the World Health Organization (WHO) standard, especially for CO, CO_2, NO_2 and SO_2, which are mainly emitted from motor vehicles[21]. Recently, the Jordan Ministry of Environment in other cities with the same objectives established measurement of the air pollutants. In all of these studies the technique used to evaluate the air quality were based on the analyses of the air samples obtained from the selected area.

No studies in Jordan were carried out in order to evaluate the vehicle fuel consumption and emissions during engine warm-up period. The objective of this study is to evaluate the engine fuel consumption and emissions related to the ambient temperature and engine technology during warm-up period. This provides a good representation of the trend in emission and fuel consumption control capability of vehicles used in Jordan.

MATERIALS AND METHODS

To study the effect of ignition system categories and ambient temperature on the engine fuel consumption and exhaust emissions [unburned hydrocarbons, carbon monoxide and carbon dioxide] under different ambient temperatures during engine warm-up period an apparatus was assembled.

The engine: The experiments were conducted utilizing four-stroke, 4-cylinder spark - ignition engine (type TOYOTA - 4K). The engine has a swept volume of 1290 cm^3 and a compression ratio of 9:1. The engine suitable to operate with both conventional and magnetic (type Denso 5K-U) ignition systems. The engine was equipped with a dual carburetor type AISAN with an electric automatic choke. In addition the thermostat located at the top of the cylinder head (for controlling the engine operation temperature) was used as an indicator to the end of the warm-up period. So, as the thermostat reached its operation temperature the experiment was stopped. This can be observed when the water flows from the cock valve mounted at the thermostat outlet. Figure 1 shows a schematic diagram of the engine and the instrumentation.



1.Cooling water unit 2.The engine 3.Observiation glass pipe 4.Carbureter 5.Gas analyzer 6.Air tank 7.Air condition 8.Thermometers

Fig. 1: The schematic diagram of the experimental test rig

Water-cooling system: The system is shown in Fig.1. The system mainly consists of hot and cold-water pumps, mixture tank, compressor and 7 valves. The function of this system is to raise or drop the engine water temperature to that temperature required to initiate the experiment. These temperatures are 7, 25 and 40°C. The outlet of the system was coupled to the inlet engine water pump, while the system inlet separately coupled to the primary circuit of the engine cooling water system and to thermostat outlet.

Air conditioning system: The main objective of this system is to cool or heat the air contained in the insolated cylindrical tank to the temperature corresponds to the engine water temperature established by the water-cooling system. The schematic diagram of the system is shown in Fig.1. The system consists of the Room Air Condition, Type, Toshiba, P-24 Btu. The operating temperature ranges from 5˚C to 45˚C. The air condition connects to the air cylindrical tank and the tank output connects directly to the engine carburetor input. The system was operated continuously until the engine thermostat opened, whereby signaling the end of the warm-up period.

Temperature measurement: Four thermometers are used for temperature measurement. Three of them are distributed along the cylindrical tank in order to measure the air temperature inside the tank and the fourth is used to measure the water temperature in the mixture tank.

Fuel consumption and exhaust emissions measurements: The fuel consumption was measured by using a calibrated burette and a stopwatch with accuracy of 0.2 sec. The concentrations of exhaust emissions (CO, CO_2 and HC) were measured using a "Sun Gas Analyzer" SMP 2000. The analyzer has non-depressive infrared (NDIR) module for CO, CO_2 and HC. The sample line tube is fitted to the tailpipe 300 mm away from the exhaust port in order to allow sufficient mixing of exhaust gases. The Gas Analyzer upon star-up requires 15 minutes warm-up period and automatically sets into auto-calibration. The concentration of each gas is measured (printed) continuously and digitally every 15 second.

Procedure: The engine cold-start was designed to simulate the vehicle cold-starting; e.g. starting the vehicle for the first time after a cold evening.

Before beginning the experiments the engine equipped with conventional ignition system was started and allowed to warm up for a period of 20 minutes. Then the engine was adjusted to yield minimum CO and HC exhaust emissions (as recommended by the engine manufacturer) at ambient temperature of 25°C and at idling engine speed of 800-rpm with both carburetor choke and throttle being closed. The experimental procedure followed in testing the engine consists of two steps: first, the engine was equipped with conventional ignition system (CIS), while in the second it was equipped with electronic ignition system (EIS). The testing temperatures are 7, 25 and 40˚C. Procedures for both steps are similar, which include: 1) Starting the cooling water system and air conditioning units until the experiment temperature is reached. When the temperature stabilized at the desired level, the test was ready to begin; 2) Starting the engine and recording (printed) the HC, CO and CO_2 emissions value every 15 second until the thermostat of the engine cooling system opens. This meant that the engine operation temperature reached (80-82°C); 3) The test was concluded by stopping the stopwatch and recording the fuel consumed; 4) The previous steps were repeated for the other testing conditions.

For each experiment the airflow into the engine cylinders was assumed to be constant since the air was supplied at constant temperature and pressure with the engine operating at a constant speed (800 rpm). Also, for each experiment three runs were carried out to obtain an average value of the experimental data.

RESULTS AND DISCUSSION

Hydrocarbon emission: The influence of ambient temperature on engine hydrocarbon emission is shown in Fig. 2. As shown from the figure, an inverse relation between the HC levels and the ambient temperature is evident. So, as the ambient temperature increases the hydrocarbon emission decreases for both ignition system categories. The higher levels of HC emission are recorded during the first 30-second engine warm-up period. Lower levels are recorded at the time when the engine thermostat is about to open; i.e., at the end of the engine warm-up period. These trends can be attributed to the variation in the mixture preparation as follows. At the beginning of the engine warm-up period (after engine start) the air-fuel ratio of the mixture entered to the engine cylinder is lower than that being burnt due to the liquid film formation on the intake manifold walls by an initially rich mixture. This leads to the combustion of enriched mixture and consequently high HC emission. This process continues up to 30-second at which time the HC emission levels reach its maximum value. After that time, due to the increase in engine intake manifold and cylinder walls temperature which raises the amount of fuel vaporized and reduces the quenching effect, the amount of unburned hydrocarbon oxidization increases and the HC emission decrease until the engine reaches its warm-up operating temperature. However, the decreasing rate accelerates at the engine warm-up time; 150,120 and 90-seconds for the operation temperature of 7, 25 and 40ºC, respectively, due to the opening of the carburetor choke. At the end of the warm-up period, the mixture enrichment is reduced and the HC levels stabilized at a significantly lower concentration. Also from the Fig. 1 can observe that the HC emission levels, when the engine equipped with conventional ignition system are higher than that with electronic ignition system for all testing temperatures. This is due to the larger of both arc duration and output voltage of the EIS over the CIS. The increased output voltage increases the activity of fuel-air mixture and creates larger flame kernels and consequently increases the burn rate and decrease HC levels. The maximum and the minimum values of HC emissions for both ignition system categories occur at temperatures of 7°C and 40 °C, respectively.

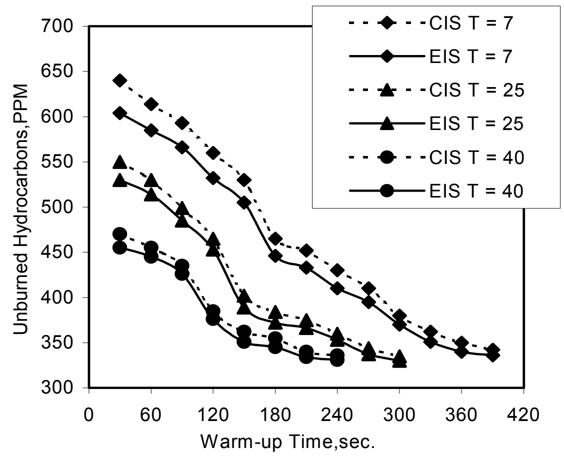


Fig. 2: Variation of the hydrocarbon emission levels as a function of the engine warm-up time at different ambient temperature

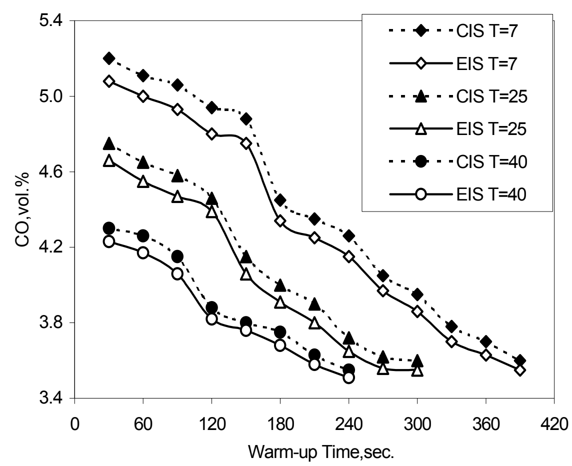


Fig. 3: Variation of the carbon monoxide emission levels as a function of the engine warm-up time at different ambient temperature

Carbon monoxide emission: Results of the ambient temperature on the formation of CO during the engine warm-up operating condition are good wishes to the HC emissions. The increased in the amounts of hydrocarbons oxidization leads to the decrease in the CO levels; i.e. when decreases in the HC are produced the CO emissions are reduced as shown in Fig. 3.

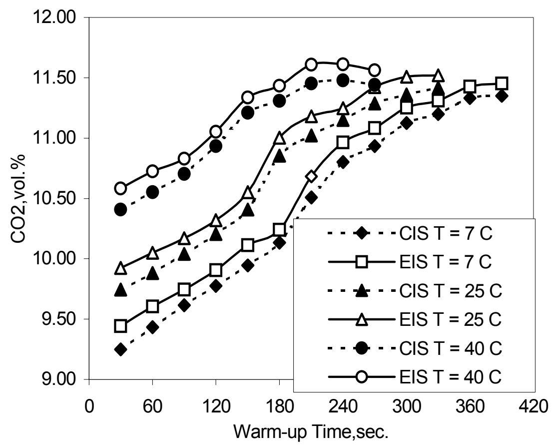


Fig. 4: Variation of the carbon dioxide emission levels as a function of the engine warm-up time at different ambient temperature

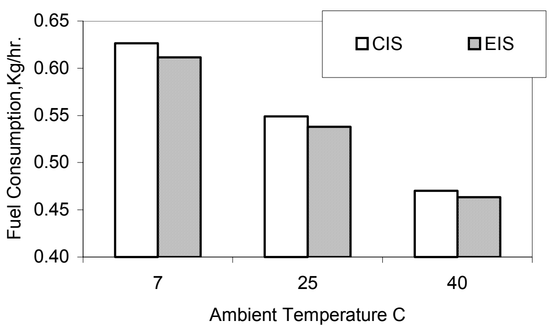


Fig. 5: The effect of the ambient temperature on engine fuel consumption

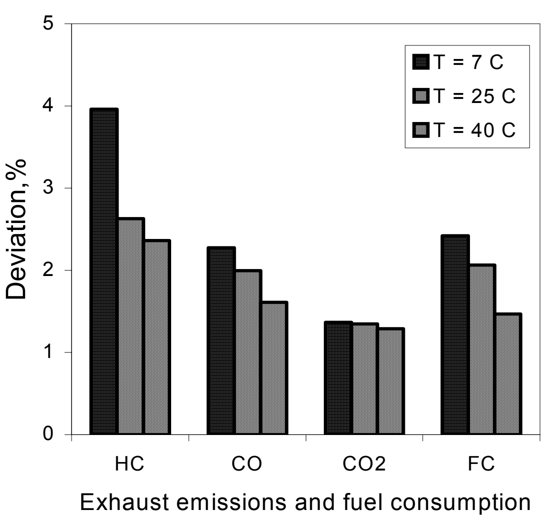


Fig. 6: Deviation of the exhaust emission levels and fuel consumption of an engine equipped with CIS from that with EIS at different ambient temperature

The warm-up peak in the CO occurs at the same time as the peak in the HC; i.e., occurring with the first 30 seconds. Comparing the CO results between the EIS and CIS (Fig.3) one concludes that the EIS affects the quality of combustion more than with CIS.

Carbon dioxide emission: The influence of ambient temperature variation on carbon dioxide emissions is shown in Fig. 4. As shown from the figure, the carbon dioxide increases as the ambient temperature increases for both types of ignition systems. These results confirm the CO results. As the CO concentration in the exhaust emission gases decreases the CO_2 concentration increases and vice-versa. Comparing the CO_2 emissions data for the testing engine when equipped with EIS and CIS the EIS demonstrates a clear superiority to improved combustion equality and the corresponding higher CO_2 emissions over the CIS. The maximum values of the CO_2 emissions were conducted at the temperature 40 ^oC, while the minimum value at the temperature 7 ^oC.

Fuel consumption: The fuel consumption is estimated by measuring the volume of fuel consumed per unit time and the fuel mass flow rate was calculated using the following equation:

$m_f = [Q_f * 10^{-3} * 3.6/t] * \rho_f$,

Where m_f is the fuel mass flow rate, kg/hr, Q_f is the volumetric fuel consumption, cm3, t is the time spent until the engine reached its operation temperature, seconds and ρ_f is the fuel density, kg/m^3.

The effect of the ambient temperatures on the fuel consumption of an engine equipped with EIS and CIS categories during warm-up is shown in Fig. 5. As shown from the figure, the fuel consumption decreases as the temperature increases for both ignition systems. This behavior can be explained as follows. At a lower operation temperature the fuel distribution and vaporization are exacerbated and the time required for the engine to reach fully warmed operation temperature is longer compared with a higher operation temperature. These factors contribute to a longer period of relatively poor combustion and the consequent need for more fuel enrichment. The combination of increased fuel enrichment and poorer combustion results in higher fuel consumption. Also it was observed that the fuel consumption when the engine operates with EIS is lower than that with CIS for all operation temperatures.

In summary, the average deviation of the HC, CO, CO_2, emissions; and fuel consumption of an engine equipped with CIS from that with EIS is illustrated in Fig. 6. The deviations are calculated for each warm-up time period at 7, 25 and 40ºC engine operation temperatures. Also the figure shows that as the temperature increases the deviations decrease.

CONCLUSION

This study focuses on measurement of the engine exhaust emission and fuel consumption during engine warm-up period. Based on the experimental results, the following conclusions can be deduced:

* Replacing engine CIS with EIS can reduce HC, CO emissions and fuel consumption.
* Increasing ambient temperature decreases the levels of HC and CO emissions; and decreases the fuel consumption.
* Increasing the ambient temperature reduces the time required for the engine to become fully warmed-up.
* The deviations of the exhaust emission levels and the fuel consumption of an engine operating with CIS from that with EIS decreases as the operation temperature increases.

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