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35 Operation Of A Spark Ignition Engine With Superheated Fuel Vapor

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The quality of combustion in a spark ignition engine is improved by superheating the fuel using the energy of the exhaust gases. A double heat exchanger system is designed for this purpose. The engine automatically switches to superheated vapor operating mode at around 150 kPa (gage) and 250 C vapor pressure and temperature. The engine operates with an equivalence ratio of 0.7 without any power loss. The equivalence ratio can be less than 0.6 under partial load operation. At any fuel setting, the system allows for a wide variation in the throttle valve position. CO, HC and NOx emissions are reduced down to the levels of catalytic filter applied gasoline engines without using a catalytic filter.

Keywords : Engine, Fuel, Vaporized, Superheated , Exhaust Gas, Heat Exchanger

INTRODUCTION

There are many reasons why contemporary engines cannot work at the desired thermal efficiency and low emissions. Among these, the fuel is perhaps the most important reason. Conditions such as inferior properties of the fuel, non homogenized fuel distribution in the combustion chamber, inability to achieve full combustion of the fuel within the allocated time and many other similar deficiencies have a negative effect on the thermal efficiency and emissions of the engine. Engines are in general designed to operate under widely varying crankshaft speeds, loads and ambient conditions. The mixture in the combustion chambers of these engines does not fully burn and some unburnt fuel is expelled to the surroundings by the exhaust gases. In order to decrease the pumping work during the exhaust process the gases are expelled to the surroundings at pressures and temperatures which are considerably higher than that of the surroundings. This means that some of the useful enthalpy of the gases is expelled to the surroundings, thus lowering the thermal efficiency of the engine and increasing the emissions from the engine.

The fuel is generally introduced into the combustion chamber as small droplets mixed with air and vaporizes to form a combustible mixture in accordance with the conditions of the combustion chamber. There is a time lapse between the entrance of the fuel into the combustion chamber and the formation of a truly combustible mixture. Homogeneity is not achieved even though the activation energy and the required mixture ratio for combustion is achieved and consequently the fuel is not fully burned and the unburned fuel is exhausted to the surroundings. One of the best solutions for preventing this is to send a fully vaporized fuel into the combustion chamber, thus eliminating the time lapse for evaporating the fuel and achieving a more homogenized distribution of the fuel.

In spark ignition engines the air fuel mixture is ignited by a spark during which a flame nucleus is formed. The flame nucleus grows in a laminar manner as it interacts with its immediate surrounding gas through mass and mainly conduction heat transfer. Observations have shown that after reaching a threshold size the rate of growth of the flame nucleus accelerates as it grows in an increasingly turbulent manner. The flame velocity reaches a maximum as the frontal area of the flame is maximized. The flame then slows down as its frontal area decreases and a small amount of fuel in the boundary layers of the surfaces of the combustion chamber and in crevices continues to burn after the flame completes its travel. As the maximum mean flame velocity increases so does the rated speed of the engine. Observations have also shown that as the flame speed increases cycle to cycle variations decrease, knock tendency decreases, leaner mixtures can be used, relative effect of heat loss decreases. In general it can be stated that the quality of combustion increases as the mean flame speed increases. Design factors such as the shape of the combustion chamber, the position and number of the spark plugs, the motion of the gas during induction, compression and combustion affect mean flame speed. However, it is also evident that the physical condition and situation of the fuel molecules in air will affect the quality of the combustion process and thus the flame speed.

It is a known fact that the combustion reaction occurs at a molecular level and in engines using conventional fuel feed systems, although there are enough fuel molecules in the vicinity of the flame nucleus, there are also large clusters of fuel molecules which are still evaporating. In addition, if the kinetic energy of the fuel molecules in the combustion chamber is elevated through superheating then the positive effect of vaporizing the fuel on the quality of the combustion process will be evident. Elevating the kinetic energy of the fuel molecules will also affect the turbulent flame travel following flame nucleus formation. Consequently the use of highly lean mixtures will be possible. Also the amount of fuel in the boundary layer and crevices will decrease. As a result carbon monoxide emissions will decrease due to excess oxygen, hydrocarbon emissions will decrease due to higher combustion efficiency and due to less fuel trapped in the boundary layer and crevices and finally nitric oxide emissions will decrease mainly due to the cooling affect of excess nitrogen.

There have been various studies on the affect of vaporized fuel on combustion in spark ignition engines. Some of these studies [1,2,4,6] used the coolant water to vaporize the fuel, either as it entered or in a tank prior to feeding it into the inlet manifold. Vaporization was also achieved by electrical means [3,4,5] as supplemental to coolant water or independent systems. Exhaust gas was used to vaporize the fuel at low pressures [7,8] for feeding directly into the inlet manifold as a supplement to the fuel fed through the carburetor. Coolant water vaporization was supplemented by exhaust gas superheating [9]. The fuel/air mixture was heated by the exhaust gas before entering the inlet manifold [10,11,12,13]. All of the studies acknowledged the increase in the quality of the combustion process, resulting in fuel economy. However, these studies did not include capacitive facilities that would enable adequate fuel flow rate during transient modes of operation. The systems include heating the fuel/air mixture, in the carburetor, inlet manifold or externally and heating the fuel alone. Some of these systems are efficient enough and some of them are not sufficiently practical. Some of these systems have resulted in backfiring and explosions in the carburetor. Others seem to be exceedingly complicated systems. Although some of these systems have attained the required efficiencies, they are not practical or they are applicable to limited engine operating conditions. At present the emission standards are met by using unleaded fuel and three way catalytic converters. The equivalence ratio of around the stoichiometric ratio is dictated by oxygen sensors and on board diagnostic systems. Some of the proposed systems which vaporize the fuel in the carburetor or the inlet manifold require modifications on the engine. Some systems have aimed at vaporizing the fuel and the mixing it with the air. However, in spite the complicated control, the success has been limited. Also some systems require extra energy. Some systems have been successful under partial load. However, they have suffered losses at full power and prolonged operation. As a result, there is still a search for practical and applicable systems that will decrease the specific fuel consumption, lower the exhaust emissions of spark and compression ignition engines. The purpose of this study is to achieve the operation of internal combustion engines by using superheated fuel.

EXPERIMENTAL SETUP

The vaporization system consists mainly of two heat exchangers (Figure 1) through which controlled amounts of hot exhaust gases pass. The system is connected to the exhaust pipe of a 1600 cc, 8 valves, four cylinders, in-line, eight valve, single point injection spark ignition engine. The engine is coupled to a hydraulic dynamometer in a test cell. The operation of the engine and the vaporization system is controlled by a data acquisition (DAQ) card. Four stepper motors are used to turn three throttle valves and a needle valve for controlling the exhaust gas flow through the two heat exchangers and the bypass pipe and the superheated vapor fuel flow. Solenoid valves are used for controlling the flow of liquid and vapor fuel flow. The liquid fuel level in the shell and tube heat exchanger is controlled by a level switch. The liquid fuel pump of the engine is also used for filling the shell and tube heat exchanger. Both of the heat exchangers are insulated.

OPERATION OF THE VAPORIZATION SYSTEM

The system will be explained with respect to the component numbers in Figure 2. When the ignition switch is turned on the solenoid valve 22 is open and either solenoid valve 23 or 24 is open depending on the signal from the level switch 15. The engine is initially operated with liquid fuel from the fuel pump 16 as all other solenoid valves remain closed. If initially the shell and tube heat exchanger 13 is not half full then after a few minutes of operation the liquid level rises to the desired value and the solenoid valve 24 closes as 23 opens. During the warm-up period the throttle valves 7 and 8 are fully closed and 6 is fully open. All of the exhaust gas goes through the tubes in 13 and the liquid fuel starts to evaporate and boil. The saturated fuel vapor pressure is monitored by a strain gage pressure transducer 10 and when the pressure reaches 100 kPa gage pressure throttle valve 7 fully opens and when it reaches 150 kPa the solenoid valve 21 starts opening intermittently while the needle valve 19 is set to a 10 degree turn opening. At this point the fuel pipe from the shell and coil heat exchanger 14 to the solenoid valve 21 contains a mixture of liquid and vapor fuel. The pipe is purged by the superheated vapor emitting from the shell

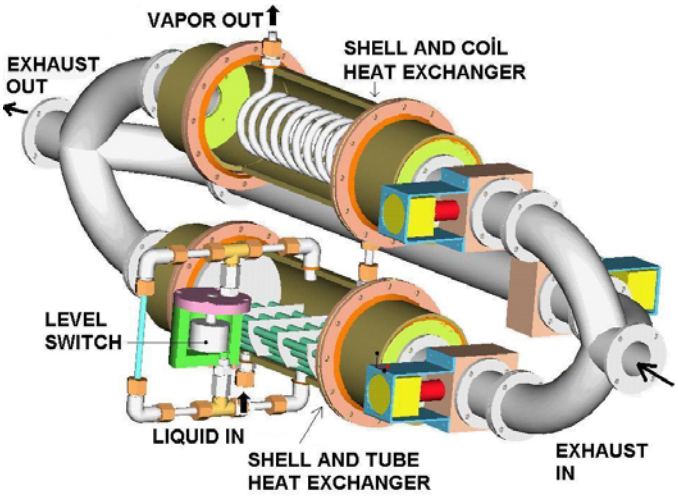

Figure 1 Heat exchangers

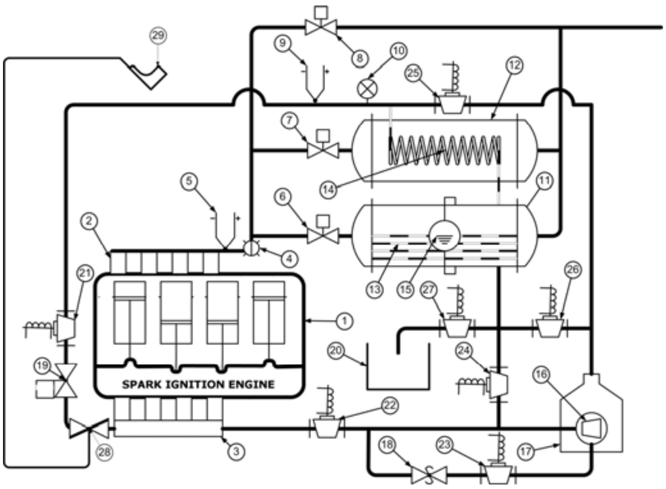

Figure 2 Superheated fuel vaporization system

and coil heat exchanger 14 in less than 30 seconds while the temperature recorded by the thermocouple 9 rapidly rises to the superheated vapor temperature. When the temperature recorded by the thermocouple 9 reaches 150 C the intermittent operation of the solenoid valve 21 is converted to a continuously open position while the needle valve 19 turns open a preset number of turns with respect to the throttle valve 28 position, the engine speed, the torque on the engine shaft and the mass flow rate of air into the engine and the pressure and temperature of the vaporized fuel. At the same instant the solenoid valve 22 is closed. During this transition from liquid to superheated vapor operating mode the throttle valve 6,7 and 8 are continuously adjusted with respect to the pressure and temperature of the vaporized fuel such that a steady state superheated fuel vapor production is achieved at 150 kPa and 250 C in less than one minute after shutting down the liquid fuel flow. Later on as the engine is accelerated or decelerated and the dynamometer load is varied the pressure of the vaporized fuel changes less than 5 percent and the temperature changes less than 10 %. However these changes are gradual and the performance of the engine is not affected since the density of the vapor is continuously calculated through measured data. During normal operation the liquid fuel level in the shell and tube heat exchanger 13 will decrease. When a signal is issued from the level switch 15 the solenoid valve 24 opens as 23 closes. Therefore a fuel pump with an outlet pressure of 200 kPa or above will quickly fill the heat exchanger until a preset time elapses after a signal is issued from the level switch at which point the solenoid valve 23 opens and 24 closes.

Further control and safety measures

In order to speed up the transition to operation with superheated fuel vapor the throttle valve 6 is left fully open until the operating pressure is achieved. As a result of the thermal inertia of the tubes in the shell and tube heat exchanger 13 the pressure of the vaporized fuel continues to rise during the initial stage of superheated fuel vapor operation. When the pressure reaches 170 kPa the solenoid valve 25 which connects the vapor fuel line to the fuel tank automatically opens and the pressure is reduced as some vaporized fuel escapes through a coiled copper pipe in which the vapor condenses. The vapor escape sequence is repeated for two or three times with decreasing escape periods and the vapor pressure settles down to 150 kPa.
In case the pressure of the vaporized fuel continues to increase as a result of malfunctioning exhaust gas throttle valve(s) or any other unforeseen reason the solenoid valve 26 also opens at a preset pressure. A warning signal is issued and the system returns to liquid fuel operation. The solenoid valves 22, 23 are open and also the solenoid valves 25 and 26 are kept open until the pressure of the vaporized fuel falls below 50 kPa. All other solenoid valves are closed. The exhaust bypass throttle valve 8 is fully open and the other exhaust throttle valves 6 and 7 are fully closed. The system has to be reset in order to resume superheated vapor operation. There is also provision for draining the heat exchanges through the solenoid valve 27.

MEASUREMENT OF TEST PARAMETERS

The DAQ card could accept 16 single input analog and 16 digital signals and output 16 digital signals. The engine speed, the force on the arm of the dynamometer, the pressure and temperature of the superheated fuel vapor, the temperature of the exhaust gas before it entered the heat exchangers, the inlet and outlet engine cooling water temperatures, the ambient temperature, pressure and relative humidity, the position of the air throttle valve on the SPI unit, the inlet manifold air temperature, the air volume flow rate, the superheated fuel vapor volume flow rate are all measured as analog voltage signals coming from various transducers

ELECTRONIC CONTROL OF THE SYSTEM

The vaporization system and the throttle valve in the SPI unit are controlled by the DAQ card. A visual interface program (Figure 6) is prepared using the Delphi 4 environment. It is possible to set various working and limiting parameters such as superheated fuel vapor temperatures and pressures, lapse time during switch over between liquid and vapor fuel operation, equivalence ratio, initial opening of the needle valve during the purging of the vapor fuel line of saturated and condensed fuel and the time lapse after the level switch indicates that the required level is reached during the filling of the shell and tube heat exchanger.

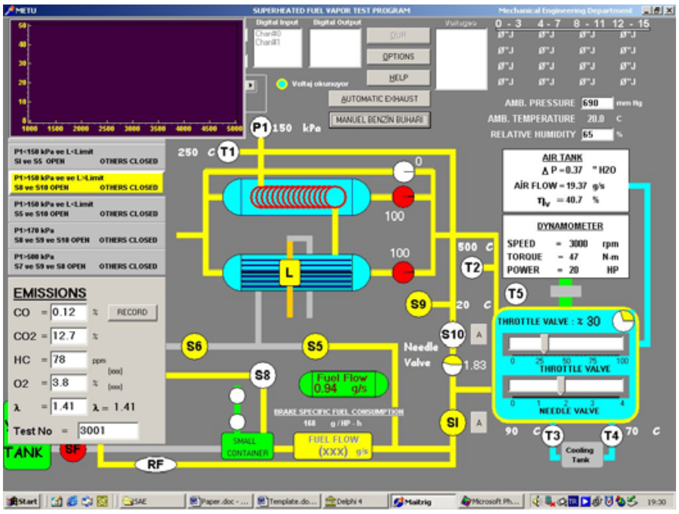

Figure 3 Visual interface program

The solenoid valves and the dc motor which is used to actuate the air throttle valve are activated by relays. An interface circuit is designed and manufactured for connecting the DAQ card. Each digital input channel has a dip switch selectable pull-up resistor connected to a 5 volt dc supply. The digital input signals are from the level switch, the liquid fuel flow meter.

TEST PROCEDURE

The performance tests are first made with conventional liquid fuel in order to establish a baseline for comparison. After these tests are over the engine is operated with superheated fuel vapor. In vapor fuel operating mode the air throttle valve and the vapor needle valve are varied independently.

The tests with superheated fuel vapor begin with the position of the air throttle valve corresponding to the position with liquid fuel. The engine is started and the dynamometer is adjusted in order to achieve a preset engine speed. Under these conditions the heating of the fuel in the heat exchangers continues for 5 to 10 minutes. Initially, only the pressure rise of the vapor is sensed. The thermocouple at the exit of the shell and coil heat exchanger does not sense the rise in the vapor temperature until the vapor starts flowing from the heat exchangers to the engine. The flow of vapor is initially restricted by the small opening of the needle valve. This flow is also intermittent due to the periodic opening and closing of the solenoid valve at the entrance of the inlet manifold in order to avoid flooding the combustion chambers with condensed liquid fuel in the pipe which connects the shell and coil heat exchanger to the adapter at the entrance of the inlet manifold. Under these conditions the temperature recorded by the thermocouple rapidly increases in less than a minute to 150 C. At this point the solenoid valve on the liquid fuel path from the pump is closed and the engine automatically switches to superheated fuel vapor operation by opening the solenoid valve continuously and by opening the needle valve such that the excess air coefficient is approximately 1.05. After a few oscillations the temperature and pressure of the superheated fuel vapor settle down to 250 C and 150 kPa. The engine is allowed to operate for 15 minutes and the data is recorded. Then as the needle valve position is kept constant the air throttle valve is opened such that the excess air coefficient rises to approximately 1.4 and after 10 minutes of operation the data is recorded. Keeping the needle valve position fixed, the throttle valve is finally opened until the excess air coefficient rises to approximately 1.7. The test is repeated for different initial torque values with the initial position of the air throttle valve remaining fixed at the corresponding value in the tests with liquid fuel. For each test the initial setting of the needle valve is for an excess air coefficient of approximately 1.05 which corresponds to the excess air coefficient value set by the ECU of the engine during liquid fuel operation.

TEST RESULTS

The vaporization system was tested at approximately half throttle. The engine speed was set at 3000 rpm and the torque was set at 55 N-m and the engine was operated with single point fuel injection and vaporized fuel as described above. The fuel consumption decreased from

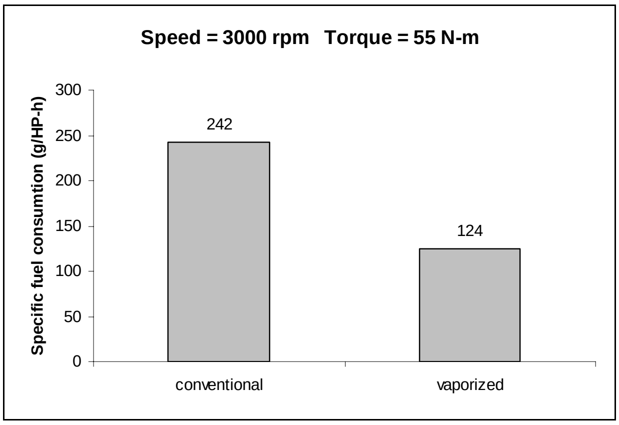

Figure 1 Fuel saved by vaporization

1.58 g/s to 0.81 g/s resulting in a decrease of 48.8 % in the specific fuel consumption of the engine (Figure 1).

The induced mixture became leaner and the oxygen concentration in the exhaust gas increased from 0.42 % to 7.28 % as the excess air coefficient increased from 1.02 to 1.45. The carbon monoxide emission decreased 89.7 % from 1.16 % to 0.12 %. The carbon dioxide emission also decreased by 27% (Figure 2).

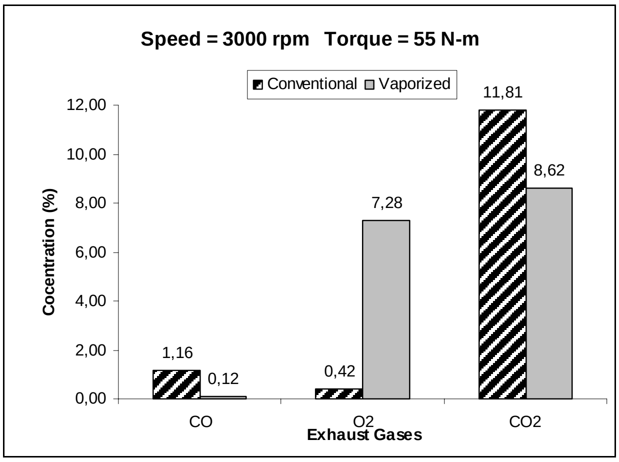

Figure 2 CO, O2 and CO2 emissions

The unburned hydrocarbon concentration in the exhaust gas decreased by 71.8 % from 411 ppm to 116 ppm and the total nitric oxide emission decreased by 58.3 % from 2085 ppm to 720 ppm (Figure 3). There was no significant change in the air consumption of the engine.

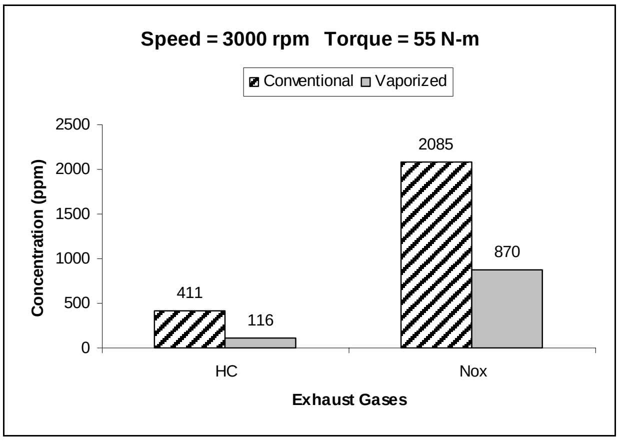

Figure 3 HC and NOx emissions

The test was repeated for 2000 rpm engine speed by keeping the throttle position fixed and increasing the load applied by the dynamometer. The vaporized fuel flow rate was adjusted to maintain the same torque level as with single point fuel injection. The air flow rate decreased with engine speed. The excess air coefficient decreased to 0.92 for single point fuel injection and 1.29 for vaporized fuel. The specific fuel consumption was still 39.2 % less for vaporized fuel operation (Figure 4).
The oxygen concentration in the exhaust gas was still more than 5 % The carbon monoxide emission decreased 96.4 % from 7.26 % to 0.26 %. (Figure 5).

The unburned hydrocarbon concentration in the exhaust gas decreased by 78 % and the total nitric oxide emission decreased by 58.6 % (Figure 6).

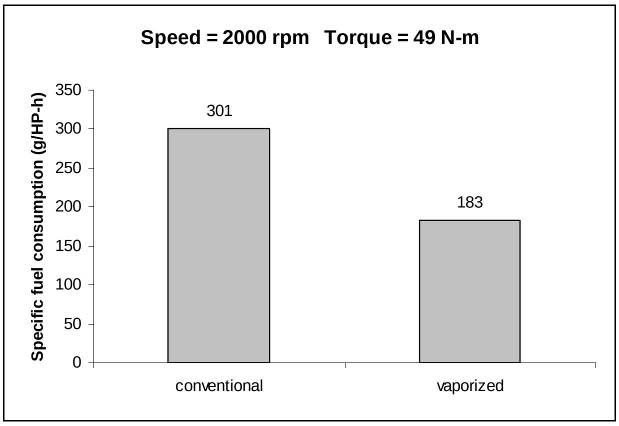

Figure 4 Fuel saved by vaporization

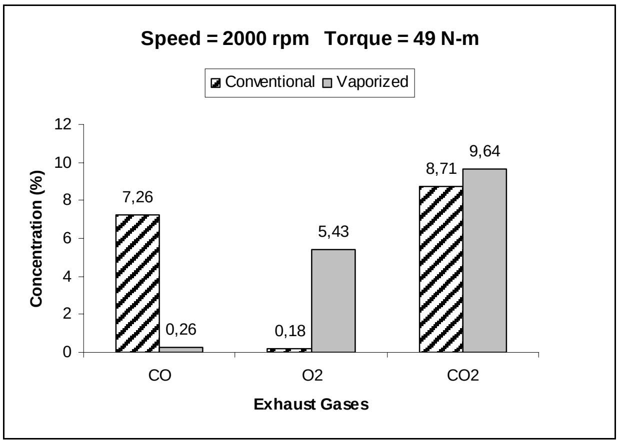

Figure 5 CO, O2 and CO2 emissions

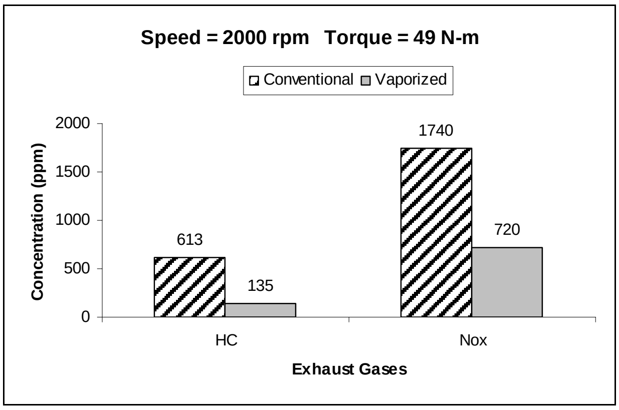

Figure 6 HC and NOx emissions

DISCUSSION

The strategy of the tests was to compare the performance of the spark ignition engine for equal flow conditions of the working gas and the results show a significant decrease in fuel consumption and improved exhaust emissions. However it is also possible to vary the throttle valve and achieve the same speed and torque performance at even leaner mixtures. Superheating commercial gasoline to approximately 250 C and 1.5 bar may have altered the chemical composition of the fuel and this may have also affected the combustion efficiency in a favorable manner. The performance of the heat exchangers was not affected by decreasing the flow rate of the exhaust gas as this was accompanied by an increase in the exhaust gas temperature. The capacitive effect of the saturated gas generating heat exchanger made it possible to rapidly change the flow rate of the vaporized fuel. Although the tests were done at steady engine speed and torque the system was capable of handling transient operation of the engine.

CONCLUSIONS

The double exhaust gas heat exchange system used of obtaining vaporized fuel for a spark ignition engine returns a significant amount of the enthalpy of the exhaust gases to the combustion process and also improves the combustion efficiency. However, the system in its present state is oversized for a practical application on a vehicle. It might be possible to reduce the size by using micro heat exchanger. However, a capacitive volume will be necessary for the saturated vapor. A similar study is continuing on vaporization of diesel engine fuels. The primary aim of this study will be to reduce the particulate emissions. Finding an appropriate place for the system will be easier on trucks and buses.

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