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Effects of Injection Temperature and Pressure on Combustion in an Existing Otto Engine Using CNG Fuel

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ABSTRACT

Changes in temperature and pressure influence the operational conditions of motor vehicles using Compressed Natural Gas (CNG) fuel. Therefore, engine torque and exhaust emissions (CO, CO_2, NO_x and hydrocarbons) were tested to determine the effects of altering initial temperature and pressure of CNG prior to entering the combustion chamber of an Otto engine. It was found that variations in initial temperature and pressure do not affect torque. Increased gas temperature leads to decreased contents of CO, HC (hydrocarbons) and NO_x but increased CO_2 in exhaust gas. Meanwhile, increase in gas pressure is associated with decreased CO_2, HC and NO_x but increased CO in exhaust gas. Based on experimental results, it is clear that fuel gas temperature and pressure do not affect the engine torque but affect the exhaust gas composition.

Key words: CNG, emission, gas fuel, Otto engine

INTRODUCTION

Natural gas is widely used as vehicle fuel and has been gaining popularity in a number of countries over the last decade (Wadud, 2014) as it emit much less criteria air pollutants per mile of travel as compared to their petrol and diesel counterparts (Nijboer, 2010). The properties of natural gas have made it an essential commodity with huge markets. The distribution of natural gas requires specialized facilities such as pipelines, since it is transported in the form of CNG, LPG and LNG (Mahendra *et al*., 2013). CNG which is also known as natural gas for vehicles (NGV), is widely used. It is produced by compressing methane (CH_4) at pressures of up to ±200 bar. The goal of compression is to deliver greater gas volume compared to that achievable without compression (Handiko, 2012). CNG is stored and distributed in cylindrical pressure vessels. The general composition of CNG is approximately 90% methane, ethane and other hydrocarbons as well as some impurities but in Indonesia methane composition is much lower than the international standard that is above 70% of the total composition (Ministry of Energy and Mineral Resources, 2011). CNG is lighter than air (density of 0.55 to 0.80, compared with 1 for air) and will therefore evaporate to the atmosphere in the case of leakage. CNG has an octane number of approximately 120 and combustion heat of 9,000 to 11,000 kcal kg^{-1} or 38 to 47 MJ kg^{-1}. CNG affords several advantages such as low emissions, competitive price and low operation and maintenance costs (Arifin and Sukoco, 2009). Moreover, the need to address global warming motivates many countries to adopt CNG as a cleaner source of energy (Mahendra *et al*., 2014). CNG can be used as a fuel in Otto-and Diesel-type internal combustion engines (Richards *et al*., 2001).

Most existing compressed natural gas vehicles use petrol engines, modified by after-market retrofit conversions and retain bi-fuel capability. Bi-fuelled vehicle conversions generally suffer from a power loss and can encounter driveability problems, due to the design and/or installation of the retrofit packages (Semin and Bakar, 2008). The effectiveness of combustion within an engine cylinder is strongly influenced by temperature and pressure. However, the initial temperature and pressure can be varied by altering the temperature and injection pressure. Increased temperature promotes more efficient combustion, due to the increased kinetic motion of gas molecules. An increase in pressure at constant volume will result in higher mass density of the gas, thus increasing its heating value. The effectiveness of combustion is evaluated by the level of torque produced by the engine and by the chemical compositions of resulting exhaust gases. This study investigates the effects of injection temperature and pressure on torque and exhausts gas compositions in an existing Otto engine using CNG.

MATERIALS AND METHODS

Experimental setup: Schematic diagram of experimental setup is shown in Fig. 1. When combined with a gas converter, CNG is technically suitable for any Otto or Diesel engine. A retrofit gas conversion kit is required to use CNG in existing vehicles. A CNG converter kit as shown in Fig. 1, consists of a manual valve, automatic valve, filling valve, mixture valve, gasoline valve, high-pressure pipe, manometer, pressure regulator and switch. The use of CNG begins with feeding gas through a filling valve (1), vie the high-pressure pipe (3), into a tank (5), then supplying gas to the engine. A pressure regulator (8) reduces the pressure to approximately 2 bar and a mixture valve (13) mixes the gas with air. The mixture then flows into the combustion chamber. A diversion button (15) governs fuel adjustment in a vehicle fitted with a converter kit, by opening and closing the automatic valve for gas (2) or gasoline (6). A manometer (15) indicates the volume of gas stored in the tank.

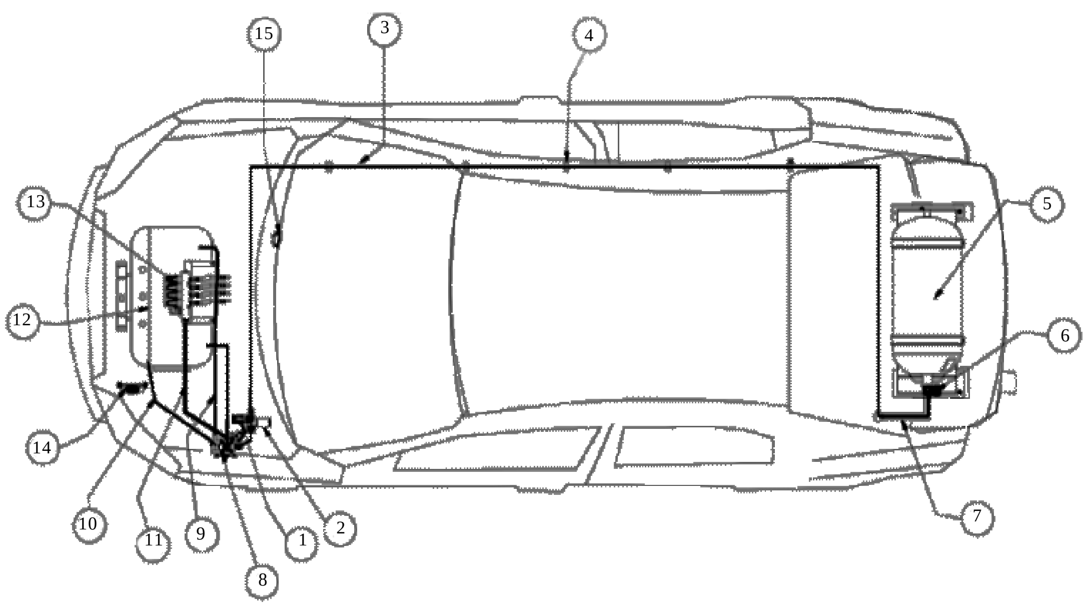

Fig. 1: Location of CNG converter components in a vehicle

Table 1: Specification of tested CNG

Characteristics	Tested CNG
C_1 (% volume)	80.1506
Particulate size (>10 μm)	–
Relative density	0.6379
Heat value (BTU/ft^3)	965.1882
Wobbe index (BTU/ft^3)	1068.7185

Table 2: Specification of test vehicle

Types	Values
Engine (G15A)	
Number of cylinders	4
Number of valves	16
Cylinder volume (cc)	1,493
Compression ratio	9.5:1
Bore×stroke (mm)	75.0×84.5
Maximum output (PS/rpm)	105/6,000
Maximum torque (N.m/rpm)	126/3,000
Type of fuel distribution system	Multipoint injection
Transmission (5-speed manual)	
Gear ratios	
1st	4.545
2nd	2.628
3rd	1.865
4th	1.241
5th	1
Reverse	4.431
Final	4.3

Experiments were conducted to determine internal combustion performance in an existing motor vehicle. As mentioned previously, CNG can be used for either Otto or Diesel engines. The experimental equipment consisted of CNG, a testing vehicle, preheating system, regulator and pressure gauge, regulator and flow meter, chassis dynamometers, a blower and emission testing equipment. The CNG used in this study was obtained from a commercial source in Jakarta. Table 1 presents the specifications of the CNG. The vehicle used in the experiment dates from 2013 and has an Otto engine fitted with an injection system and a tailored converter kit; the specifications of the vehicle are shown in Table 2.

A preheating system is used to increase the temperature of gas before entering the combustion chamber. The preheating system is powered by vehicle batteries and comprises electric heaters, sensor and control thermocouples, pressure gauge and inlet/outlet valves as shown in Fig. 2. A pressure regulator was used to control injection pressure which was measured by two pressure transmitters and one pressure gauge. An analog flow meter (maximum capacity 2.5 m^3 h^{-1}) was used for measuring and controlling inlet gas flow rate. A chassis dynamometer was used to measure maximum engine torque. This tool was equipped with a mounting base with a roller for one axle. During the test, the vehicle was secured tightly by means of steel wires on either side of the chassis dynamometer to prevent unpredictable movements if the wheels detached from the roller. This experiment collected data on engine torque and gearbox

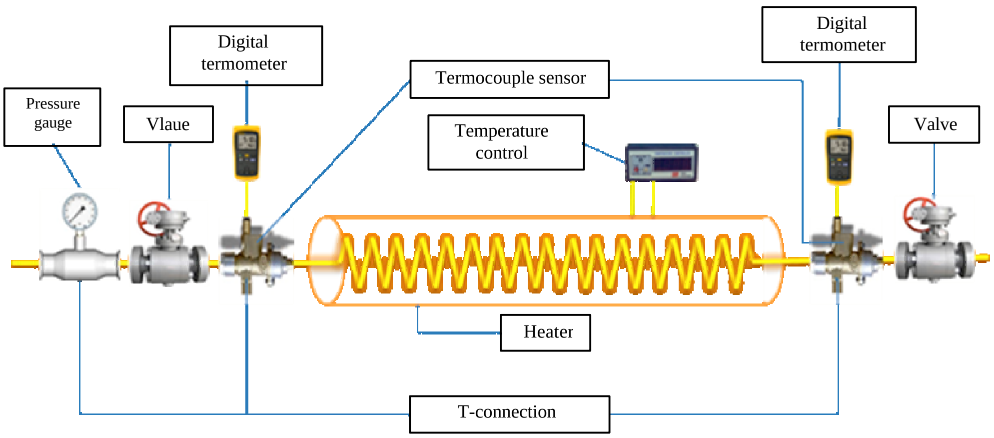

Fig. 2: Schematic of CNG preheating system

Table 3: Effect of temperature and pressure variation on the performance of Otto engine

Symbol	Values
Temperature (°C)	
T22 (without preheating/normal)	22
T30	30
T40	40
T50	50
Pressure (bar)	
P1.9	1.9
P2.0	2.0
P2.1 (without setting)	2.1
P2.2	2.2
P2.5	2.5
P2.7	2.7
P2.9	2.9

speed. The variations in gas temperature and pressure were also conducted and in the same range of conditions. The blower is used to maintain engine temperature during the test. Emission test equipment was attached to a gas outlet to analyze the carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC) and nitrogen oxide (No_x) contents of exhaust gases.

Data collection: The main aspect of the analysis was to identify the influence of fuel gas temperature and pressure on engine parameters such torque and exhaust gas composition. To analyze the effects of initial temperature and gas pressure on the performance of the Otto engine, the temperature and pressure were varied as shown in Table 3. In the temperature experiments, pressure and flow rate were kept constant at 2.1 bar and 0.4 SCFH (standard cubic feet per hour), respectively. In the gas pressure experiments, gas temperature and flow rate were kept constant at 22°C and 0.1 SCFH, respectively.

RESULTS AND DISCUSSION

Figure 3a shows the effect of temperature on torque at various engine speeds (rpm). The results show that increased preheating temperature does not significantly affect torque as the combustion chamber temperature is far higher than the variation in preheating temperature. The adiabatic flame temperature of CH_4 is between 1,000 and 5,000°C. Combustion chamber temperature is much higher than the injection temperature, due to the heating effect of the combustion reaction.

Pressure does not significantly affect torque, mainly because temperature and pressure parameters are predetermined within the combustion chamber. When the injection pressure was varied from 1-2 bar, the pressure in the combustion chamber into a vacuum since fuel injection occurs on the intake stroke of the engine cycle. The variations in CNG injection pressure have very little effect on the pressure in the combustion chamber, because the gas is rapidly expanding and the wall of the combustion cylinder is already at high temperature due to the heat of the previous fuel combustion cycle. As a result, the variation in initial CNG pressure will not affect the torque generated as shown in Fig. 3b.

Figure 4a shows the effect of preheating temperature on CO contents of the exhaust gas. Higher preheating temperature tends to lower CO content of exhaust gas. Rising temperatures caused the temperature of the injection gas mixture in the combustion chamber to increase.

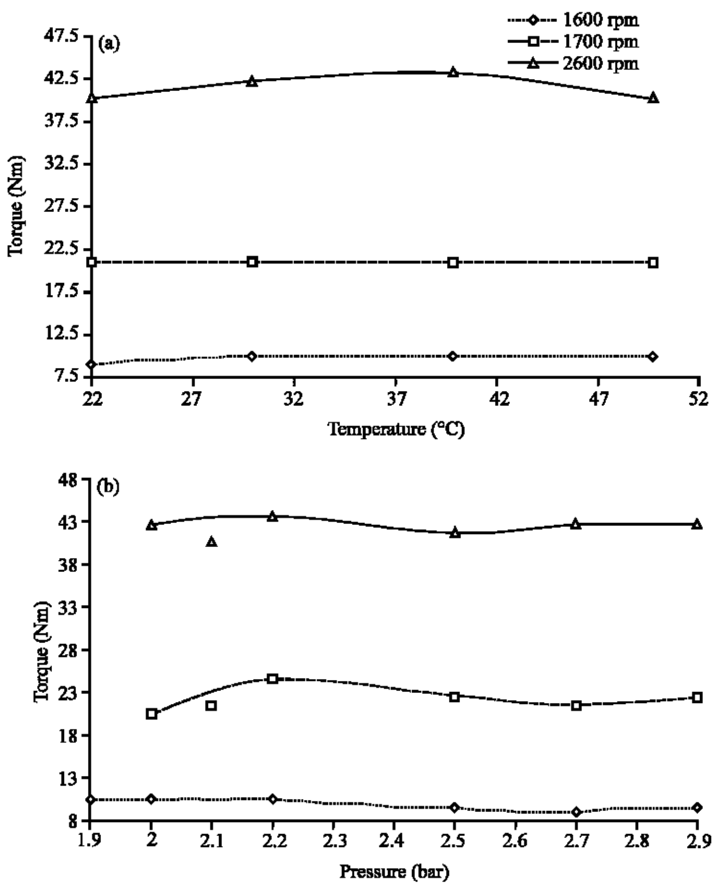

Fig. 3(a-b): Effects of (a) Temperature and (b) Pressure on torque

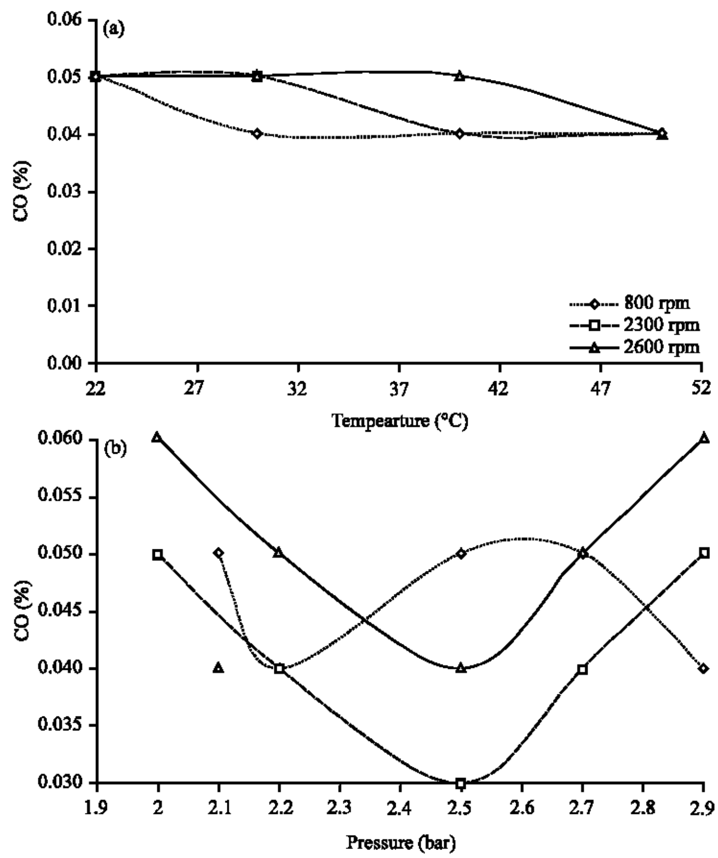

Fig. 4(a-b): Effects of (a) Temperature and (b) Pressure on carbon monoxide contents in exhaust

However, this increase is very small, since the temperature of the combustion chamber wall is very high due to heating by previous the previous combustion cycles. The increase in temperature is therefore very small but, nevertheless, still influences the CO emissions. Higher temperature increases the kinetic energy, resulting in more collisions between molecules of CO and O_2 gas, thereby promoting the oxidation of CO to CO_2. Figure 4b shows that the CO contents were fluctuated with pressure. The higher pressure leads to higher CO content of exhaust gas as there is less time for CO to react further with oxygen, especially in the range pressure of 2.2-2.7 bar and 2.5-2.9 bar for engine speed of 800 and 2300 and 2600 rpm, respectively. The increase in pressure affects the chemical reactions that involve a third body. In a reaction that is constrained by a third body, the reactants gain energy through collisions with the third body. The result is that both pressure and the overall rate of reaction increase. The similar results were also found in Hagos *et al.* (2014), where the CO emission in Otto Engine were increase for fuel gas pressure from around 3.6-3.9 Bar for engine speed 1500 and 2100 rpm. However, the results were in contrast if the pressure is in the range of 0.8-1.6 MPa for engine speed 1320 rpm (Liu *et al.*, 2013).

The effect of preheating temperature on the CO_2 content of exhaust gas is shown in Fig. 5a. The emissions tests show that carbon dioxide content increases with temperature in the range of 22-30°C. This is due to reaction of methane which is strike by hydrogen, hydrogen oxide and

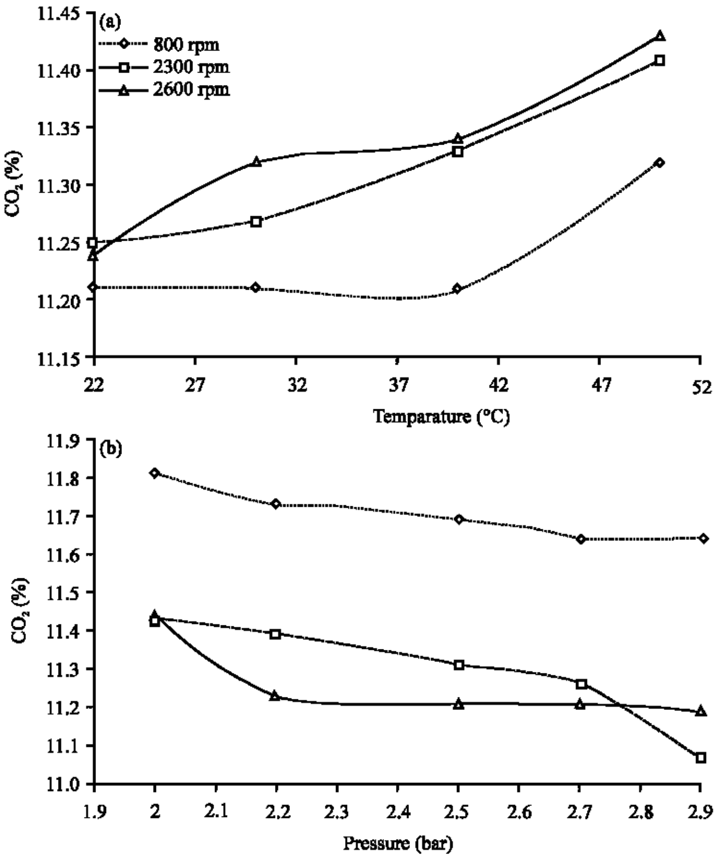

Fig. 5(a-b): Effects of (a) Temperature and (b) Pressure on carbon dioxide contents in exhaust gas

oxygen free radicals. Increasing temperature will enhance CO reaction with oxygen, the result of which is detected as CO_2. Increasing gas temperature will promote complete combustion. Carbon dioxide also increases as engine speed increases. However, carbon dioxide content decreases with temperature in the range of 30-50°C. This could be attributed to an incomplete combustion due to a richer mixture at and near stoichiometric conditions (Hagos *et al.*, 2014). In contrast with temperature, increasing gas pressure will reduce the CO_2 content as shown in Fig. 5b, due to shortened time for carbon monoxide to react with oxygen, especially at engine speed of 800 and 2300 rpm. Higher temperature translates to greater kinetic energy among the reactants which will also tend to increase the rate of oxidation of CO to CO_2, resulting in lower CO and higher CO_2 concentrations, respectively.

Figure 6a shows the relationship between gas temperature and the NO_x content of exhaust gas. Based on the experimental results, higher temperature promotes kinetic activity in the combustion chamber, resulting in lower NO_x content in exhaust gas. As described in the previous section, higher temperature increases kinetic activity among the reactants, promoting reactions that lead to the formation of CO_2. This result in lower oxygen concentration in the combustion chamber, ultimately inhibiting the formation of NO_x compounds. Similar results were found for the pressure experiments: Increasing pressure is associated with lower nitrogen oxide content of exhaust gas as shown in Fig. 6b, due to shorter dwell time. The similar results were also found in (Hagos *et al.*,

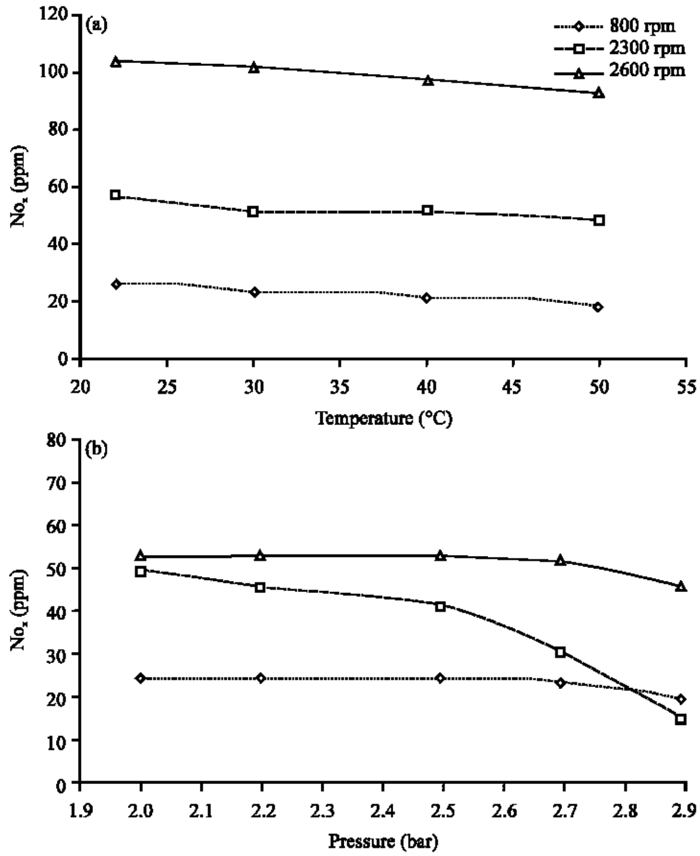

Fig. 6(a-b): Effects of (a) Temperature and (b) Pressure on NO_x contents in exhaust gas

2014; Liu *et al.*, 2013), where NO_x contents in exhaust gas for Otto Engine increase for pressure from around 3.3-3.9 bar and 2.4-2.9 bar for engine speed of 1500 and 2100 rpm, respectively (Hagos *et al.*, 2014) and from around 0.8-1.6 MPa for engine speed of 1320 and 1627 rpm (Liu *et al.*, 2013).

As shown in Fig. 7a, increasing temperature has the effect of lowering the HC content of exhaust gas as the higher kinetic energy of the reactant molecules in turn increases their rates of reaction. Most reactants in the combustion chamber are HCs, therefore higher temperature will lead to decreased HC emissions. In contrast with temperature, the opposite results are observed for pressure as shown in Fig. 7b. At increased pressure, the reaction rate decreases, leading to higher concentration of the reactants. Most reactants within the combustion chamber are HCs, therefore higher pressure results in higher concentration of HCs in exhaust emissions which could be attributed to a weak mixture calorific value (Hagos *et al.*, 2014) or high content of heavy hydrocarbons (Liu *et al.*, 2013). The similar results were also shown in (Hagos *et al.*, 2014) where higher concentration of HCs in exhaust emissions occurred in the range pressure around of 3.0-3.9 bar for engine speed of 1500 rpm (Hagos *et al.*, 2014). The results were in contrast with Liu *et al.* (2013) where lower concentration of HCs in exhaust emissions occurred in the range pressure around 0.8-1.6 MPa for engine speed 1320, 1627 and 1933 rpm (Liu *et al.*, 2013).

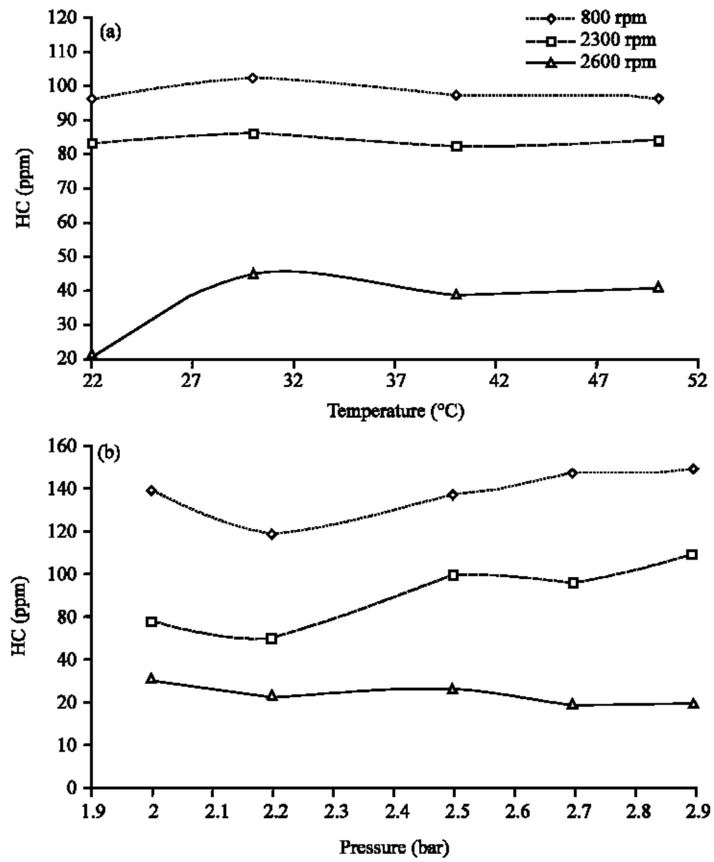

Fig. 7(a-b): Effects of (a) Temperature and (b) Pressure on HC contents in exhaust gas

CONCLUSION

Experiments were conducted to determine the effects of gas temperature and pressure on torque produced by an Otto engine powered by compressed natural gas and on the contents of carbon monoxide, carbon dioxide, nitrogen oxide and hydrocarbon in the resulting exhaust emissions. Torque was relatively unaffected by the temperature and pressure of fuel gas. Increased gas temperature was associated with decreased contents of carbon monoxide, hydrocarbon and nitrogen oxide gas but increased carbon dioxide content in exhaust gas. Meanwhile, increased gas pressure was associated with decreased contents of carbon dioxide, hydrocarbon and nitrogen oxide but increased carbon monoxide content in exhaust gas.

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