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Investigation of the effects of gasoline and CNG fuels on a dual sequential ignition engine at low and high load conditions

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ABSTRACT

In this study, a dual sequential spark ignition engine is separately tested either with gasoline or CNG at low and high loads. In addition, numerical engine analyses are performed by constructing a 1-D engine model in Ricardo-Wave software. Engine performance parameters in catalogue are generally given at full load conditions. However, during engine lifetime, vehicle engines rarely run at full load (wide open throttle) while engines work especially at the partial throttle openings.

Engine characteristics (engine performance and exhaust emissions) are strong functions of throttle opening level. For this reason, determining engine characteristics at partial throttle openings at which engine mostly runs provides valuable information. In this study, partial throttle openings of 25% and 75% defined as low and high load conditions are examined for gasoline and CNG, as well.

For this aim, the Honda L13A4 i-DSI (intelligent dual sequential ignition) engine was tested and engine characteristics were measured. This engine has unique features of dual sequential ignition with variable timing, asymmetrical combustion chamber, and diagonally positioned spark-plugs.

Tests and numerical analyses were performed at specified low and high load conditions for gasoline and CNG by varying the engine speed from 1500 rpm to 4000 rpm with an increment of 500 rpm without excepting 2800 rpm. Engine characteristics were determined for the investigated parameters.

Tests and 1-D model results are fairly matching each other. The average deviation between them is about 5.4%. Results show that the maximum torque for gasoline at 2800 rpm and 100% throttle opening reduced 12.6% and 26.3% for throttle openings of 75% and 25%, respectively. Compared to gasoline, CNG reduced the torque 15.6% and 19.6% for throttle openings of 75% and 25%, respectively. In general, CNG usage decreases all engine performance parameters (torque, power, volumetric efficiency, specific fuel consumption) and emissions (CO_2, HC), except NO_x formation.

1. Introduction

Ongoing works on internal combustion engines have especially focused on alternative fuel usage, increased engine performance and efficiency, and reduced exhaust emissions. The works have been carried out by using experimental and numerical methods. Numerical analyses are performed with modelling software at various levels before testing the design improvements. In parallel with the technological development of engine test capabilities such as in-cylinder combustion visualization, the capabilities of analysis software are also developing.

In addition, the number of CNG vehicles in the world has reached about 23.0 million; China (5.0 million), Iran (4.0 million), Pakistan (3.0 million), Argentina (2.3 million), India (1.8 million), and Brazil (1.8 million) [1]. CNG usage in engines has many benefits like lower knock tendency, higher compression ratio, uniform mixture formation, longer lubrication oil life, mitigated greenhouse gas emissions, reduced cold start problem and improved fuel economy [2]. CNG as an alternative fuel is applied to the gasoline engines without knowing and optimizing the engine conditions.

There are studies in the literature about measuring engine performance and exhaust emissions under effective parameters. One of the most important effective parameters is the throttle opening. Some studies on the effects of throttle opening for gasoline and CNG are summarized below.

At wide open throttle conditions, various engines have been tested with either gasoline or CNG [3–8]. Some tests included the concomitant injection of CNG [4,6,8]. Out of all these tests, the general observation is that when the gasoline engine is operated with CNG at wide open

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throttle; reduction in knock trend, fuel consumption, exhaust emissions, engine performance, volumetric efficiency are observed. When the concomitant injection of CNG is applied into gasoline at wide open throttle, it is reported that the thermal efficiency and the engine power improves up to a level while the emission values become worse. In addition to CNG, LPG and LNG are other alternative fuels worked on [6,9].

Partial throttle openings have also been tested by some researchers for gasoline and CNG fuel [10–12]. It is reported that, for CNG, the engine power is decreased, the exhaust gas temperature is increased, and the low emission values are obtained [10,11]. For CNG usage, at partial loads, combustion characteristics greatly improved with early and late injection at wide and partial throttle opening, respectively [12]. The test results are unique to tested engines.

Engine characteristics in engine catalogues have been especially determined at maximum torque and maximum power conditions. The number of publications for partial engine loads is limited while the engine mostly runs at partial load during its lifetime. This study covers the determination of engine characteristics at partial loads for both gasoline and CNG fuels by means of tests and numerical analyses. CNG usage has been increasing everyday due to emission regulations.

This study focuses on determination of a specific engine characteristics for CNG usage. Thus, when CNG as an alternative fuel is applied to the gasoline engines, the engine characteristics are known. In addition, as the importance of partial load operation is pointed out earlier, engine characteristics are determined for the partial throttle openings for both gasoline and CNG fuel. The partial throttle openings are selected as the two mostly practiced values of 25%, which is the low load position, and 75%, which is the high load position. Furthermore, the tested engine, which is the Honda L13A4 i-DSi engine, has unique features of dual sequential ignition with variable timing, asymmetrical combustion chamber, and diagonally positioned spark-plugs. In addition to engine testing, the study also includes the 1-D engine model built in the Ricardo-Wave software and numerical analyses of all tested conditions.

The tests and analyses were performed at specified low and high load conditions for gasoline and CNG by varying the engine speed from 1500 rpm to 4000 rpm with an increment of 500 rpm without excepting 2800 rpm. Engine performance (torque, power, volumetric efficiency, specific fuel consumption), emissions (CO_2, HC, NO_x), and the exhaust gas temperature were determined. The results obtained from tests and analyses were compared.

2. Engine test process

The engine used in the investigation is the Honda L13A4 i-DSI engine which is a dual-spark ignition engine. The photograph and schematic of the engine test rig is shown in Fig. 1. The test rig mainly consists of four components; engine, eddy-current dynamometer, emission measurement unit, and instrumentation-control unit. The engine test rig is controlled by a computer.

The technical specifications of the Honda L13A4 i-DSI engine are listed in Table 1. The engine is an engine with different features within its class and has played an important role in the development of technologies such as VTEC and VVT [13,14]. The engine is originally designed for gasoline. In the engine, there are two spark plugs located diagonally in different zones on each cylinder. As presented in a technical review [14], the engine has four cylinders with an intake valve and an exhaust valve in each cylinder. Engine's intake port is designed for high swirl ratio (1.10–1.36) and tumble ratio (1.30–1.58), thus, turbulence at the compression time increases and the flame propagation is fast. Fuel is injected into the intake port behind the intake valve, thus, fuel-air mixture is fed into the cylinders. Unlike usual engines, the engine has two spark plugs per cylinder. The dual spark plugs located diagonally on each cylinder. One spark plug is closer to the intake valve while the other is at the exhaust valve side. This feature enhances flame formation and propagation into entire cylinder, and yields increased combustion efficiency, decreased HC emission. The dual spark plugs ignite at the same time at the idle state and above 4000 rpm. At other engine speeds, the spark plugs ignite at different times. The ignition time difference for spark plugs is determined by the electronic control unit (ECU) of the engine between 2 and 5 CAD depending on the engine speed. Another unique feature of the engine is that the combustion chamber is such asymmetrically shaped that it produces more turbulence/swirl/tumble resulting in more homogeneous air-fuel mixture and better combustion. The engine has higher compression ratio arising from both reduced angle between the intake and the exhaust valves, complex shape of the combustion chamber and pent-roof head. The combined effect of these design features is that the premixed flame passes the exhaust valve and propagates into combustion chamber without forming auto ignition [14].

The eddy-current type dynamometer used in the engine test rig can measure up to 100 kW of power and 500 Nm of torque, and generate 3000 Nm of braking torque. The system can operate in manual and automatic modes. The test rig is equipped with necessary instrumentations, sensors, actuators, and data transmitters. In addition to measurement instrumentation, there are many temperature and pressure sensors for safe operation of the test rig. The control unit keeps the engine speed constant for a prescribed throttle opening by adjusting the dynamometer load. The test data is collected on a data acquisition card. During the tests, the throttle opening and the engine speed are adjusted to the desired values. Once the system stabilizes at steady conditions, the measurements are recorded every 0.5 s for 5 min. Thus, test data for each point is evaluated by averaging 600 data that normalizes the instant changes during the test.

The general properties of gasoline and CNG fuels used in this study are given in Table 2.

Tests are carried out for gasoline and CNG over the speed range of 1500–4000 rpm with an increment of 500 rpm. The speed of 2800 rpm is also tested for comparison purposes since this speed is given as the maximum torque speed in the engine catalog. The partial throttle openings are specified as 25% and 75% for low and high load conditions, respectively.

The engine test is carried out by measuring physical parameters (torque, power, fuel consumption, intake air flow rate, temperatures, etc.) in a time interval of 0.5 s for 5 min. Meantime, exhaust emissions (CO, CO_2, O_2, HC, NO_x and lambda) are also measured and recorded. Thus, under low and high loading conditions, the effects of engine speed on engine performance parameters and exhaust emissions have been measured. Table 3 summarizes the all investigated parameters in this study.

The test engine rig including the engine is also modeled in the Ricardo-Wave software. In the 1-D engine model entire engine test conditions are analyzed and results are presented. The 1-D engine model is explained in the following section.

3. 1-D engine model

The tested commercial engine is also simulated by using the Ricardo-Wave software. In the engine simulation model, a 1-D model is built for the entire test rig including the Honda L13A4 i-DSI engine from the beginning of the intake line to the end of the exhaust line. The 1-D engine model is plotted in Fig. 2.

At the beginning of the engine modelling phase, dimensions of related engine parts are measured with a CMM device. Then, each engine components (pistons, cylinders, valves, ports, engine blocks, intake and exhaust manifolds, fuel line, exhaust line and throttle) are separately formed by defining their properties in Ricardo-Wave software. After that, they are connected to each other by defining the relevant relations and boundary conditions.

In the 1-D model, in order define port injection, injection timing and ignition timing, a MATLAB code is written. This code is transferred to signal processing and control elements in Ricardo-Wave software. As