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An experimental investigation of effect on diesel engine performance and exhaust emissions of addition at dual fuel mode of hydrogen

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ABSTRACT

Internal combustion engines are an indispensable part of our daily life, especially in transportation and agriculture sectors. However, the reduction of petroleum resources and environmental problems are leading to an increasing trend towards alternative energy sources. In this regard, hydrogen usage is expected to be a solution for previously mentioned problems as one of the renewable energy resources. In this concept, effects of hydrogen as an additional fuel used in a compression ignition engine performance and exhaust emissions parameters different engine speeds were investigated at full load. For this purpose, a compression ignition engine (CI) with 17/1 compression ratio, four cylinders, four stroke, turbocharger and 3.908 liters engine volume was used. While diesel fuel was injected directly to combustion chamber, hydrogen was added to inlet manifold at rates of 2.5%, 5% and 7.5% as volume.

As a result, an increase in engine torque, power, thermal efficiency, nitrogen oxides (NO_x) and exhaust gasses temperatures were acquired at every hydrogen addition ratio while a decrease in hydrocarbons (HC), carbon monoxide (CO) and oxygen (O_2) emissions were attained. While engine torque exhibited an increase at a rate of 8.3% comparing with standard diesel operation at 1250 min^{-1} and 7.5% hydrogen addition ratio, engine power increased 17% at 2250 min^{-1} engine speed and 7.5% hydrogen addition ratio. Brake thermal efficiency of 2.5% was obtained as 40.4% comparing with 33% value of SDI at 1750 min^{-1}. The lowest CO, CO_2, HC and NO_x emission values were obtained at 2250 min^{-1} engine speed and 2.5% hydrogen addition ratio as 0.013; 2500 min^{-1} engine speed and 7.5% hydrogen addition ratio as 7.4%; 1250 min^{-1} engine speed and 2.5% hydrogen addition ratio as 10 ppm and 1000 min^{-1} engine speed and 7.5% hydrogen addition ratio as 1092 ppm respectively comparing with standard diesel operation.

1. Introduction

For more than a century, hydrocarbon fuels have played a leading role in the transportation and agricultural sectors. However, increase in stringent emission regulations and envisaged depletion of worldwide petroleum reserves in future provide a strong encouragement to carry out research on alternate fuels. In this context, over the past two decades the topic has been studied by a considerable number of research groups to develop and various transportation fuels have been considered as substitutes for hydrocarbon-based fuel [1–3]. Alternative fuels that aspire to replace petroleum-based fuels include alcohols, liquefied petroleum gas (LPG), compressed natural gas (CNG), hydrogen, vegetable oils, bio-gas, producer gas and liquefied natural gas (LNG). Among these alternative fuels, hydrogen is the most promising one. Its clean burning characteristics and better performance derive more interest compared to other fossil fuels. In addition to, hydrogen is a long term renewable, recyclable and non-polluting fuel [4,5]. Due to these features, many researchers have conducted experiments using hydrogen in compression ignition (CI) engine. While using hydrogen in a compression ignition (CI) engine, the compression temperature is not enough to initiate the combustion due to its higher self-ignition temperature. Hence a CI engine requires an ignition source for using hydrogen. However, hydrogen can be used in a CI engine in the dual fuel mode with diesel fuel [2–17]. In this method a large quantity of hydrogen cannot be used, since the hydrogen will replace the air, thereby reducing the air available for diesel combustion. Therefore many techniques have been studied and tested to inject or induct the hydrogen in air manifold or air intake passage. Carburetion, timing manifold/port injection (TMI), direct hydrogen injection (DHI) and continuous manifold induction (CMI) are the techniques mostly used. In the case of external mixing method, where hydrogen is mixed with air inside the intake port, the system structure and the operation control is straightforward. And, mixture formation can be also easily conducted by this method. However, because of abnormal combustion such as knock, pre- ignition and backfire, the maximum engine output power should be kept significantly low. The problems associated with inlet manifold injection, such as back fire and power decreasing will not occur when using direct injection. But DHI requires injector to resist higher

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combustion temperature as well as to prevent injector from corrosion due to exhaust gases. Further, lubrication between the injector moving parts also makes the design of DHI and TMI more complicated. [21–24]. The most serious problem with CMI is the high possibility of pre-ignition and backfire, especially with rich mixtures [25].

Some researchers tested diesel engines; it was very difficult to operate a diesel engine with hydrogen just by increasing the compression ratio, due to its high self-ignition temperature. Das et al. [13] have carried out experiments on continuous carburetion, continuous manifold injection, timed manifold injection and low pressure direct cylinder injection. The maximum brake thermal efficiency of 31.32% was obtained at 2200 rpm with 13 Nm torque. Hydrogen used in the dual fuel mode with diesel and exhaust gas recirculation by Bose and Maji [8] showed the brake thermal efficiency increases by 12.9% without EGR with the supply of 0.15 kg/h of hydrogen. Bari and Esmaeil [14] studied the performance enhancement of a conventional diesel engine through the addition of H_2/O_2 mixture, generated through water electrolysis. The introduction of 6.1% total diesel equivalent H_2/O_2 mixture into diesel, the brake thermal efficiency increased by 2.6% at 19 kW, 2.9% at 22 kW, and 1.6% at 28 kW. The brake specific fuel consumption of the engine reduced by 7.3%, 8.1%, and 4.8% at 19 kW, 22 kW, and 28 kW, respectively. Altunes et al. [15] have carried out an experimental setup for the testing of a diesel engine in direct injection hydrogen-fuelled mode. A significant efficiency advantage was found when using hydrogen as opposed to diesel fuel, with the hydrogen-fuelled engine achieving a fuel efficiency of approximately 43% compared to 28% in conventional, diesel-fuelled mode.

In this work, four cylinder direct injection diesel engine was modified to work in the dual fuel mode with hydrogen and continuous induction of hydrogen in the air inlet manifold with mixer and diesel injected in the conventional manner. Experiments were conducted at a different engine speed of, full load conditions and the amount of hydrogen were varied. Comparison has been made with results obtained while using diesel.

2. Combustion characteristics of hydrogen

Combustion of hydrogen is fundamentally different from the combustion of hydrocarbon fuel. Hydrogen has wider flammability limits of 4–75% by volume in air compared to diesel fuel which is 0.7–5% by volume. The burning velocity is so high that very rapid combustion can be achieved. The limit of flammability of hydrogen varies from an equivalence ratio of 0.1 to 7.1, hence the engine can be operated with a wide range of air/fuel ratio [4]. The minimum energy required for ignition of hydrogen–air mixture is only 0.02 mJ. This enables hydrogen engine to run well on lean mixtures and ensures prompt ignition. Other properties of hydrogen are given in Table 1.

Table 1
Properties of hydrogen in comparison with diesel and gasoline.

Properties	Diesel	Gasoline	Hydrogen
Chemical composition	$C_n H_{1.8n}$ (C_8-C_{20})	$C_n H_{1.8n}$ (C_4-C_{12})	H_2
Auto-ignition temperature (K)	530	533–733	858
Minimum ignition energy (mJ)	–	0.24	0.02
Flammability limits (volume % in air)	0.7–5	1.4–7.6	4–75
Stoich. Air/fuel ratio on mass basis	14.5	14.6	34.3
Density 16 °C and 1 bar (kg/m^3)	833–881	721–785	0.0838
Net heating valve (MJ/kg)	42.5	43.9	119.93
Flame velocity (cm/s)	30	37–43	265–325
Diffusivity in air (cm^2/s)	–	0.08	0.63
Cetane number	40–55	–	–
Octane number	–	92–98	130

3. Experimental setup

The engine used for the investigation is a "4DT 39T/185B-217299" modeled turbocharged diesel engine of TUMOSAN (Konya, TURKEY). The engine used in the study has four-stroke water cooled, four cylinder, direct injection swept volume of 3.908 liters, direct injection compression ratio of 17:1. The general specifications of the engine are given in Table 2. Ratio turbocharger with 1.3 compression located on the engine was replaced with 1.7 compression ratio turbocharger which has more stable operation than the previous one. The shaft of the engine is coupled to the rotor of a hydraulic dynamometer type BT-190 which is used to load engine to measure the engine output torque and calculate power. A load sensor type TEDEA 3410 was employed to determine the load of dynamometer. The general specifications of the hydraulic dynamometer and load sensor are given in Table 3. The engine speed was measured by rotation sensor installed on the dynamometer. The mass flow of hydrogen was measured using a digital mass flow meter type Smart-Trak C100L. The specifications of the digital mass flow meter are given in Table 4. The inlet manifold of the engine was modified to allow for hydrogen flow. A mixer similar to LPG mixer was designed and placed allow good mixing of hydrogen and air. The engine intake port was connected to controller hydrogen cylinder which was used to supply high-pressure hydrogen gas. A calibrated burette and a stopwatch were employed to measure the volumetric flow rate of fuel. A inclined tube manometer is used to quantity the head difference of air flow to the engine, while allowing the intake air to pass through an orifice meter. The schematic view of the test equipment is show in Fig. 1 and a photograph of the setup in Fig. 2. Exhaust emissions (CO_2, CO, HC and NO_x) were measured with a Bosch BEA 350 exhaust emission device. The analyzer was calibrated with standard gases and zero gas before each experiment. Exhaust emission temperature was measured with K-type thermocouple. The general specifications of the emissions device and thermocouple are given in Table 5.

The fuels used in this study were euro-diesel and hydrogen fuels. Before the test process, standard diesel engine (SDI) test were carried out according to Turkish Standards 1231 (TS-1231). Euro diesel was purchased from OPET (İstanbul, Turkey). Hydrogen, with a purity of 99.99% was purchased from The Linde Group (Ankara, Turkey).

4. Experimental procedure

The research engine was coupled to the rotor of the hydraulic dynamometer. Then, the engine was run at steady-state condition using diesel at full load. So, the engine technical properties changed and maximum engine torque value occurred at 1250 min^{-1} was measured as 318 Nm. Maximum engine power value at 2250 min^{-1} was determined as 58 kW. In addition, the average of volumetric efficiency value increased 13%.

Pressure of hydrogen stored in a high-pressure storage tank at 250 bar was reduced to 1–4 bar by using a pressure regulator. Hydrogen

Table 2
Technical specifications of the test engine.

Tumosan engine 185 B	Technical specification
Cylinder number	4
Cylinder bore	104 mm
Stroke	115 mm
Total cylinder volume	3908 ml
Compression ratio	17:1
Maximum torque	318 Nm (at 1250 min^{-1})
Maximum power	58 kW (at 2250 min^{-1})
Maximum speed	2700 min^{-1}
Cooling system	Water cooling
Injection advance	18 (crank shaft angle)
Injection pressure	230 bar