Energy Conversion and Management 98 (2015) 89–97

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Experimental investigation of the effects of direct water injection parameters on engine performance in a six-stroke engine

Emre Arabaci [a], Yakup İçingür [b], Hamit Solmaz [b], Ahmet Uyumaz [c,*], Emre Yilmaz [b]

[a] Mehmet Akif Ersoy University, Emin Gülmez High Vocational School of Technical Sciences, Department of Automotive Technology, Burdur, Turkey
[b] Gazi University, Faculty of Technology, Department of Automotive Engineering, Ankara, Turkey
[c] Mehmet Akif Ersoy University, High Vocational School of Technical Sciences, Department of Automotive Technology, Burdur, Turkey

ARTICLE INFO

Article history:
Received 17 December 2014
Accepted 12 March 2015
Available online 8 April 2015

Keywords:
Six-stroke engine
Exhaust heat recovery
Water injection
Engine performance

ABSTRACT

In this study, the effects of water injection quantity and injection timing were investigated on engine performance and exhaust emissions in a six-stroke engine. For this purpose, a single cylinder, four-stroke gasoline engine was converted to six-stroke engine modifying a new cam mechanism and adapting the water injection system. The experiments were conducted at stoichometric air/fuel ratio ($\lambda = 1$) between 2250 and 3500 rpm engine speed at full load with liquid petroleum gas. Water injection was performed at three different stages as before top dead center, top dead center and after top dead center at constant injection duration and four different injection pressure 25, 50, 75 and 100 bar. The test results showed that exhaust gas temperature and specific fuel consumption decreased by about 7% and 9% respectively. In contrast, fuel consumption and power output increased 2% and 10% respectively with water injection. Thermal efficiency increased by about 8.72% with water injection. CO and HC emissions decreased 21.97% and 18.23% until 3000 rpm respectively. NO emissions decreased with water injection as the temperature decreased at the end of cycle. As a result, it was seen that engine performance improved when suitable injection timing and injected water quantity were selected due to effect of exhaust heat recovery with water injection.

1. Introduction

Many investigations have been recently performed for high engine performance and lower fuel consumption in the internal combustion engines. It can be clearly said that small-volume and high efficiency engines can be easily produced with developing the technology especially after the computer control systems are developed [1].

Six-stroke engines are considered as an alternative engine instead of two and four-stroke engines in the reciprocating engines. Many patent studies have been performed on the six-stroke engines and a lot of six-stroke engines were produced [1–4]. Six-stroke cycle is based on the addition of steam stroke to the four-stroke cycle. Exhaust heat energy can be used in six-stroke engines [5]. Different engine cycles were applied to the internal combustion engines such as Miller and Atkinson unlike six-stroke engines. Miller and Atkinson cycles are the alternative cycle approaches in the internal combustion engines. However, power output losses occured with Miller and Atkinson cycles while thermal efficiency increased. For this reason, these engines have been used as hybrid. Similarly, power output decreases in six-stroke engines. On the contrary, thermal efficiency increases. It was also mentioned that specific fuel consumption decreased with the increase of thermal efficiency in six-stroke engines [5,6]. The first investigation was performed by Griffin [7] on six-stroke engines. In griffin's study two extra stroke was added to four stroke engines. Extra two stroke were performed as steam cycle. The operating principle of the most six stroke engines rely on the principle. Griffin [7] performed an experimental study in a single effect, sliding valve and six-stroke engine. In Griffin's study, extra air was delivered into the cylinder at the end of exhaust stroke. Second expansion stroke was obtained unlike four-stroke engine. A cycle was completed at 1080° crank angle degrees (CA). Schimanek [8] studied on the six-stroke engines. He proposed to increase the power output via increasing the volumetric efficiency. He also tried to add extra two strokes to four-stroke engines in his study. Liedtke [9] proposed to use the waste heat formed on cylinder walls and piston surface along the combustion by injection of steam. He also aimed to obtain the second expansion stroke. He emphasised the

* Corresponding author.
E-mail addresses: earabaci@mehmetakif.edu.tr (E. Arabaci), icingur@gazi.edu.tr (Y. İçingür), hsolmaz@gazi.edu.tr (H. Solmaz), auyumaz@mehmetakif.edu.tr (A. Uyumaz), emreylmz@gazi.edu.tr (E. Yilmaz).

http://dx.doi.org/10.1016/j.enconman.2015.03.045
0196-8904/

importance of the usage of waste exhaust heat in the cylinder. Dyer [10] discussed the operation of six-stroke engines in a more detail. He mentioned that engine efficiency increased due to usage of the waste heat. It was also implied that exhaust system was improved and cooling system was simplified with six-stroke engine. Thus, water is compressed by a water pump. Moreover, it was noticed that cylinder pressure increased with the water injection into the hot exhaust gases. At this point, water was vaporized. Singh [11] developed the water injection system and controlled with computer in the six stroke engine. He performed a detailed study on six-stroke engine. In his work, sensors were mounted on the spark ignition engine and signals delivered by the sensors were processed in the computer. So, the water was injected using sensors and computer. The water was compressed by a high pressure water pump. In addition, the water was injected into the cylinder using high pressure direct injector. Injected water was warmed up by transferred heat from the engine to the coolant. Crower [12] claimed that waste heat could be used via injection of the water into the cylinder after combustion. He also said that NO_x (nitrogen oxides) emissions decreased due to cooler operation of the engine. He showed that the water was vaporized with the injection of water and the second expansion stroke was obtained. Furthermore, the requirement of the cooling system is expected to be reduced. The required cooling capacity will be also reduced in the engine. Kelem [13] explained the method and studied on six-stroke engine including extra two strokes. Exhaust valve do not close and fresh air is delivered to the cylinder after intake, compression, expansion and exhaust stroke unlike four-stroke engines. So, fifth stroke occurs. The exhaust gases are expelled from the cylinder as piston moves toward to top dead center (TDC) at second exhaust stroke. Szybist [14] conducted a theoretical study on high efficiency six stroke engine. He proposed to increase the thermal efficiency of six-stroke engine. Whole exhaust gases did not expel from the cylinder. Some exhaust gases were trapped in the cylinder. The water was vaporized injecting the water into the burnt hot gases with usage of the waste heat energy of water. It was seen a slight increase on cylinder pressure but cylinder temperature when the water was suddenly vaporized. Water droplets were suddenly vaporized via injection the water on warmer surface. This is called Liedenfrost effect [15–20]. So, a second expansion stroke was obtained. There are many theoretical studies or patents on six stroke engines in the literature [15–36]. Mears [37] investigated the usage of the waste exhaust heat in water distillation. He showed that water injection could be used in the internal combustion engines. Domingues et al. [38] studied the usage of R123 and R245 in Rankine cycle. It was found that thermal efficiency increased by about 1.4–3.52%, 10.16–15.95% for mechanical efficiency. Fu et al. [39] also studied on the usage of exhaust heat recovery with steam turbocharge. Fu et al. [40,41] also studied on exhaust heat recovery with steam ve steam-assisted turbocharging. It is expected that engine brake torque increased by % 25. Yu et al. [42], performed an investigation on utilization of waste exhaust heat using thermoelectric generator. Wang et al. [43], studied on Rankine cycle based exhaust energy recovery system for heavy duty diesel ve light duty gasoline engine. Gasimi et al. [17], Kiran [44] and Manglik [45], have performed theoretical studies regarding the conversion of four stroke engines to six stroke engines. Karmalkar et al. [46] analyzed the usage of six stroke engines in hybrid vehicles. It was not seen experimental study on six stroke engines in the literature. All researches about the six stroke engines are theoretical.

The main objective of this study is to investigate the effects of exhaust heat recovery with direct water injection on engine performance and exhaust emissions in a six stroke engine fueled with LPG. In this study, a single cylinder, four-stroke, spark ignition engine was converted to the six-stroke engine and the conversion was performed using the knowledges in Dyer's and Szybist's study. The cam shaft of the test engine was modified and remanufactured. High pressure direct injector was mounted in the cylinder head in order to inject the water to the cylinder. A simple electronic control unit was developed and used in order to vary the water injection quantity and injection timing. The experiments were conducted at stoichometric condition and full load using LPG as test fuel. The effects of water injection quantity and injection timing were investigated on engine performance and exhaust emissions in six stroke engine.

2. Material and method

A single cylinder, four stroke, spark ignition Honda GX 270 model test engine was used in the experiments. The technical specifications of the test engine are given in Table 1.

It is hoped that the thermal efficiency of six-stroke engines is higher than four stroke engine due to extra expansion stroke with water injection. More energy can be converted to the useful work via the extra expansion stroke [13–15]. Cam shaft should be redesigned and the water injection system should be mounted in the engine in order to convert four-stroke engine to the six-stroke engine. The structural differences are seen between four- and six-stroke engines in Fig. 1.

Cam-crank gear ratio was changed in the test engine. For this purpose, new cam profiles were determined and designed at original valve timing of the test engine. Partial exhaust process was added to the valve timing diagram of the test engine as exhaust valve opened twice in a cycle. The view of the modified six-stroke engine is seen in Fig. 2.

2.1. Water injection system

Injector drive circuit was used in order to operate the water injector. Moreover, high pressure system was also used in order to compress the water. A electronic control unit was utilized in order to control the injector. For this purpose, a rotary encoder was mounted in the cam shaft of the test engine in order to determine the camshaft angle. High pressure (160 bar) water pump was used in order to compress the water. 70 W power is needed to operate high pressure water pump [47]. Pressure limiting valve was used for keeping constant the water pump pressure. The water injection system operation is seen in Fig. 3.

Before the electronic control unit was designed a simple water injection system was developed in order to determine the injector characteristics. Injector delay time and water injection quantity were determined. According to obtained values, electronic control unit was programmed in order to provide desirable values. The technical properties of the injector are given in Table 2. Bosch HDEV 5.2 model high performance injector was used in the experiments.

Water injection advance can be controlled via the control unit. The water injection quantity depends on the water pressure and

Table 1
The technical specifications of the test engine.

Model	Honda GX 270
Valve system	OHV
Number of cylinder	1
Diameter/stroke (mm)	77/58
Swept volume (cm^3)	270
Compression ratio	8.2:1
Ignition timing (°CA, before TDC)	20
Cooling system	Air cooled