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An investigation on effect of in-cylinder swirl flow on performance, combustion and cyclic variations in hydrogen fuelled spark ignition engine

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This study investigates how engine performance, cyclic variations and combustion parameters are affected by swirling flow in hydrogen spark ignition (SI) engine. Swirling flow was produced in the cylinder during the induction stroke by intake port having entry angles of 0°, 10°, 20° and 30°. In addition, tumble angle of 8° was positioned for given entry angles. The engine was operated under lean mixture ($\phi = 0.6$) conditions and engine speeds of 1400, 1600 and 1800 rpm. As a result, it was found that swirling flow enhances performance of hydrogen SI engine around 3% when operating engine with entry angle of 20°. The combustion duration and the cyclic variation in hydrogen SI engine can be reduced with optimum swirling flow. The stability of combustion in hydrogen SI engine is mainly dependent on cyclic variations in the flame initiation period and the cyclic variations in this period can be reduced with controlled swirling flow.

1. Introduction

Recent drastic increase in the price of petroleum, rapid increase in emission of green house gases and very strict environmental legislations are major motivating factors for usage of hydrogen in fuel cells and internal combustion engines [1]. Hydrogen has unique combustion characteristics that are different from hydrocarbon fuels. High flame speed and wide flammability limit of hydrogen–air mixture allows running engine on wide-open throttle while controlling load with changing equivalence ratio. This would improve engine efficiency due to minimization of pumping losses [2]. Hydrogen induction techniques play crucial role in determining the performance characteristics of the hydrogen fuelled internal combustion engine [3]. The majority of internal combustion engine research using hydrogen fuel has focused on pre-mixed charge, spark ignition engines [4]. External mixture formation by means of port fuel injection has been unveiled to result in higher engine efficiencies, extended operation at lean mixture, lower cyclic variation and lower NO_x emission [5,6]. Hydrogen gas is characterized by a rapid combustion speed, wide combustible limit and low minimum ignition energy. Such characteristics play a role to decrease engine cycle variation for the safety of combustion [7,8]. Cycle variation in an SI engine is produced by the change in the mean effective pressure caused by combustion variation [9]. The initial stages of combustion play an important role on the later flame development [10], thus small differences at the kernel formation may produce significant in-cylinder pressure variations. The disappearance of cycle-to-cycle variations can lead to a fuel economy up to 6% [11]. Even under constant conditions, consecutive cycles are not exactly the same; combustion process does not progress in the same way, resulting a different in-cylinder pressure curve. The reasons of these cyclic variations are the differences of turbulence within the cylinder from cycle to cycle, the non-homogeneous air/fuel mixture, and the bad mixture of the exhaust gas residuals with the unburned charge, especially in the vicinity of the spark plug [12]. The in-cylinder flow is a decisive factor for combustion in the engine, which in turn provides significant effects on the engine performance. There are three main kinds of turbulence that can influence the flow in the cylinder: the swirl, the tumble and the squish [13]. Swirling combustion is one of the most effective ways to enhance the combustion process in engines. Swirl can have remarkable effects on combustion processes in various

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aspects, e.g. on ignition, flame propagation, and combustion duration. Swirl can generate turbulence, which in turn increases the global burning rate and the heat release rate from the chemical reaction [14]. Arcoumanis et al. found that a 24% of turbulence enhancement can be achieved under a combined tumbling/swirling vortical flow particularly generated [15]. The flammable range of the pre-mixed combustible gases is broadened when the turbulence intensity of the in-cylinder flow increases. Accordingly, the fuel–air mixture becomes easier to be ignited such that the flame propagation speed is increased and the cyclic variability is significantly reduced. Shortening in the combustion duration will make the engine to possess the potential to be operated at higher speeds and to develop higher engine outputs [16].

This study presents the effects of the swirl flow generated by entry angle of intake port, together with the air breathing capacity for hydrogen fuelled SI engine. The swirl flow generated with entry angle of the intake port on the cylinder head was compared in terms of effect on combustion, cyclic variation and engine performance. The paper concludes by providing insights on the correlation between swirl flow produced by entry angle and combustion characteristics in hydrogen fuelled SI engine.

2. Experimental setup and method

A single cylinder, L-head type SI engine was modified to be fuelled with hydrogen injected into the intake port. The experimental research was conducted with this modified engine having compression ratio of 7.6 and displacement volume of 476.5 cc. Hydrogen was injected into the intake manifold at a pressure of about 5 bar. The engine was operated at the wide-open throttle (WOT) and under lean mixture ($\phi = 0.6$) conditions. The ignition timing was set to a minimum advance for best torque (MBT) for all engine operating conditions. The experiments were conducted at engine speeds of 1400, 1600 and 1800 rpm. Fig. 1 shows the schematic diagram of the experimental setup.

The crank angle and TDC positions were determined via a Kistler 2618B type shaft encoder producing 1800 pulses per revolution. The cylinder pressure was measured using Kistler 6052C type piezoelectric pressure sensor. A Motec M4 engine control unit was used to control spark timing and H_2 injection process. Hydrogen and air flow rates were measured using Aalborg GFC67 and GFM77 types thermal mass flow metres. Hydrogen was stored in a gas cylinder at a pressure of around 200 bar. A pressure regulator was used to feed the injector with hydrogen at a pressure of 5 bar. For manifold injection of hydrogen, Bosch NGI2 type gas injector was used. Hydrogen was injected into the manifold after the start of the intake stroke (300° CA before top dead centre). To stop flame travelling up the fuel line, a Wittgas RF53 type flashback arrestor was connected to the fuel supply line. Stainless-steel pipes and leak proof fusion joints were used in the fuel supply line. The air inlet temperature was kept at a constant value of 30 °C using an 800 W electric heater and a PIC temperature controller. The exhaust gas temperature and engine oil temperature were measured via K-type thermocouples. The engine was coupled to a hydraulic dynamometer for loading. Measurement Computing USB-1616HS-4 type data acquisition system was used to acquire and process crank angle sensor and pressure transducer signals. The in-cylinder pressure data was recorded by a PC controlled data acquisition system along with crank angles for 50 consecutive cycles. The data captured was then used to calculate "real time" engine performance and combustion parameters such as indicated mean effective pressure (*imep*), indicated thermal efficiency (ITE), indicated power, indicated specific fuel consumption (ISFC), mass fraction burned (*mfb*). The equations used for the calculations are given below.

Rassweiler and Withrow [17] used a method for estimating the mass fraction burned profile from in-cylinder pressure and volume data. In this method, the *mfb* is given by;

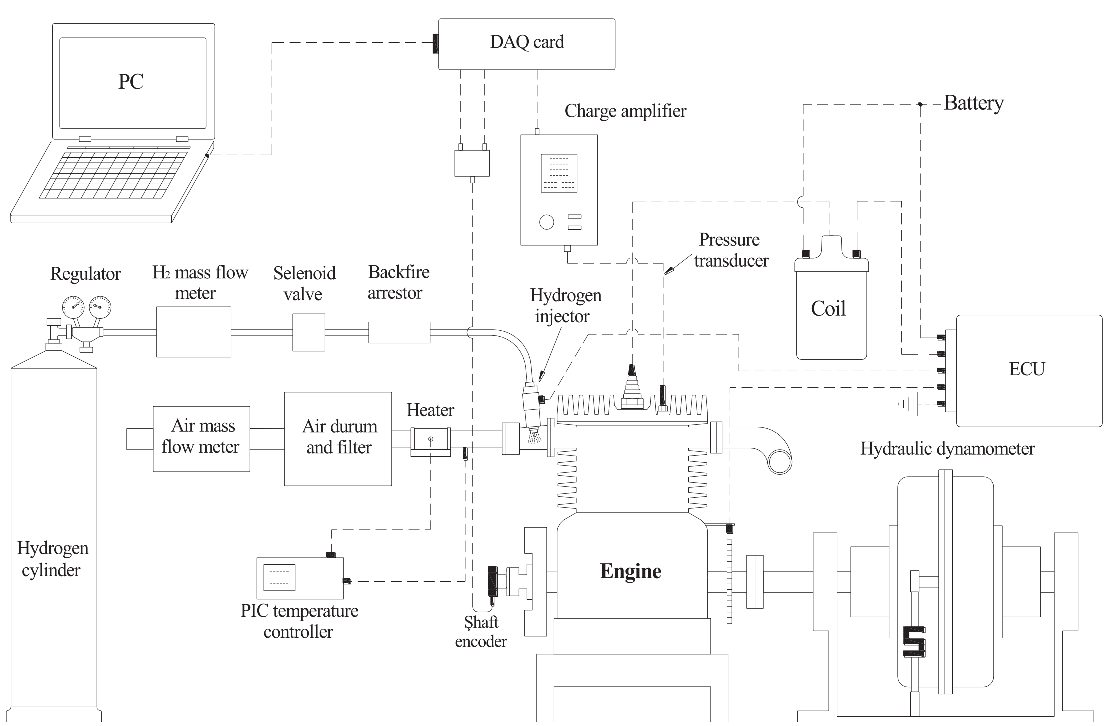

Fig. 1. Schematic diagram of experimental setup.