Journal of the Energy Institute xxx (2016) 1–15

Contents lists available at ScienceDirect

Journal of the Energy Institute

journal homepage: http://www.journals.elsevier.com/journal-of-the-energy-institute

Water injection for higher engine performance and lower emissions

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ARTICLE INFO

Article history:
Received 23 April 2015
Received in revised form
30 November 2015
Accepted 1 December 2015
Available online xxx

Keywords:
CFD simulation
GDI engine
k-ε turbulence model
NOx emission
Water injection

ABSTRACT

The influence of variable water injection by mass on the performance and emission characteristics of a gasoline direct injection (GDI) engine under light load conditions has been investigated and the results are presented in this paper. The study involved the injection of water into the cylinder at an angle of 640 °CA over an injection duration of 10 °CA. Gasoline was directly injected into the cylinder with a fixed injection timing duration starting from 660 °CA to 680 °CA and determined the flow rate of fuel. The results indicated that a 15% water injection by mass used together with fuel gave the best engine performance due to the increase in the indicated mean effective pressure and efficiency resulting from the cooling of certain parts of engine. Water injection also demonstrated a decrease in the NOx emissions (ppm), as well as soot emissions.

1. Introduction

The higher thermal efficiencies attained by an internal combustion engines could be linked to the use of higher compression ratios. However, the use of high compression ratios leads to higher combustion temperatures and creates conducive conditions for the formation of nitrogen oxide (NOx) emissions. Many studies have shown that the formation of NOx increases as the compression ratio increases [4,16]. For a gasoline engine, the increase in compression ratio, would lead to the formation of NOx emissions because of the near-stoichiometric air–fuel ratio used to ensure that the conversion efficiency of the catalytic converter used for converting NOx emissions remains fairly high [2].

Additionally, the higher compression ratios employed by internal combustion engines leads to higher temperature at the latter stages of the compression stroke and a higher local temperature at the earlier stage in the combustion and expansion processes, resulting in a rapid NOx reaction rate. Minimizing NOx formation via gasoline direct injection is well-known, and has been studied by many researchers [7,11,13,21]. The method of introducing a water injection system would be one of the perfect solutions to reduce NOx formation [18,23]. The thermal-dissociation process of water will form hydroxide and hydrogen at high temperature, which absorbs the heat during combustion [20]. The water not only absorbs the heat of intake gas for decreasing the temperature, but also to provides oxygen for burning the fuel. The injected water also reduces the local temperature of the combustion flame and leads to lower NOx emissions.

Fundamentally, water injection in the spark-ignition (SI) engine helps in controlling the temperature and pressure of the combustion process. Hence, this method is useful for controlling unwanted emissions. An improvement in the volumetric efficiency of an engine and its power output may also be achieved via water injection technology. Water or steam injection systems have been used in gas turbine engines since the last century [14]. In reality, its application in internal combustion engine running on conventional fossil-based petroleum fuels is rare. Moreover, a water injection system is also considered as cheaper and simpler solution for improving the power output of an SI engine.

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http://dx.doi.org/10.1016/j.joei.2015.12.003
1743-9671/

Please cite this article in press as: W. Mingrui, et al., Water injection for higher engine performance and lower emissions, Journal of the Energy Institute (2016), http://dx.doi.org/10.1016/j.joei.2015.12.003

The effect of water injection on the performance of an SI engine with hydrogen as fuel was investigated by [18]. The emission related problems and the effects of injected water into the cylinder of an engine on air–fuel mixture and combustion were studied and discussed the study. The experimental engine had a single cylinder and four (4) valves, and was manufactured by the Ford Motor Company. The study [18] concluded that water injection was a better technique for reducing NOx emissions. At high load, water injection was delayed and prolonged the combustion phase, which required an advanced spark timing setting in order to maintain its power output. Furthermore, Gadallah et al. [12] implemented a similar study on a hydrogen fueled direct injection SI engine in combination with the use of a water injection system. A water injector was installed adjacent to a spark plug on a single cylinder engine with the amount of injected water ranging from 4 to 14 mg/cycle using different compression ratios. The study demonstrated that water injection during the latter stages of the compression stroke improved the indicated thermal efficiency and reduced NOx emissions.

A study [10] based on a single cylinder experimental engine used two kinds of fuel: pure gasoline and 35% volume butanol–gasoline blend + 1% H2O addition. The experiment covered two operational modes with full and partial loads at 6500 rpm and 8500 rpm, respectively. The results demonstrated that engine performance, brake specific fuel consumption (BSFC), CO and HC emissions of the dual fuel were better than those of the pure gasoline under the test conditions considered. In another study [17] the effects of hydrous ethanol (with a high water content up to 40%) on the performance and emissions of a small spark ignition engine for a generator was investigated. The result indicated that CO, HC and NOx emissions after the catalytic converter were lower than the EPA limit for the model year 2011, with 5% water content in ethanol, a constant engine speed of 3600 rpm and a stoichiometric air–fuel ratio. The study also indicated that there was an overall decrease in efficiency and NOx emissions as opposed to an increase in the brake specific fuel consumption (BSFC), HC, CO, formaldehyde and acetaldehyde emissions by increasing the water content in the cylinder at constant load. For 16% of water, the NO emissions could be reduced by 30% and the engine worked normally with a gasoline–alcohol fuel spray containing up to 30% ethanol and 16% water [6].

Wu et al. [26] presented a novel concept for combining the water injection process with an oxygen-fueled internal combustion engine cycle for enhancing thermal efficiency. The water was injected into the cylinder after being heated by passing it through the engine coolant and exhaust gas systems. Heat waste stored in exhaust gas was recovered for doing work and the achievement higher thermal efficiency. Calculated results showed that the thermal efficiency reached 53% and 67% when the water injection temperature was 120 °C and 200 °C, respectively. Moreover, the indicated thermal efficiency increased from 32.1% to 41.5% under similar test conditions with an increase in both engine load and water injection mass.

The water injection technique also has been applied for many years for controlling NOx emissions in compression ignition engines. Kohketsu et al. [15] focused on the effect of NOx and PM emission in traditional diesel engines by using stratified fuel-water sprays. Using water injection in combination with EGR, Euro V emission levels could be achieved by heavy duty engines [22]. In addition, this system is also used to increase the working stability under higher compression ratios [17].

Boretti [3] used water injection in combination with turbocharging, with ethanol as a fuel to explore the possibility of reducing the tendency to detonate, increasing the charge efficiency, and controlling the temperature of gases flowing to turbine. The possibility of the engine using higher compression ratios and boost pressures was also investigated by a study reported by Cesur et al. [5] and involved investigations on an original engine in combination with water injection under selected operating conditions. Together with water, steam was injected into the engine. The optimum steam ratio in comparison with the fuel mass was fixed at 20%, with the investigation focusing on the performance and emission parameters. The presence of water injected into the cylinder may improve atomization and mixing which leads to increase in the combustion efficiency and, in effect, higher engine output [9,24].

In this investigation, simulations were carried out to analyze the effect of water injection on the performance and emissions of a gasoline direct injection engine. The major objective was to determine the best water mass in comparison with fuel mass for better engine performance and emission control. Moreover, water was added as absorbent which could potentially help to control the peak temperature during combustion. The vaporization of water is expected to reduce the temperature of the gas charge at the latter stages of the compression stroke. The vaporized water also had the potential of decreasing the concentrations of both oxygen and nitrogen. The ignition delay and combustion duration using water injection was also changed, with its influence studied and discussed.

2. Study procedure

The engine model had an axisymmetric cylinder with the inlet and exhaust valves located about the cylinder axis. To obtain a flow field and combustion characteristics, the ensemble-average for differential form of continuity equations, momentum equations, energy equations were solved with the appropriate boundary conditions. The finite volume method was employed for numerical solving of the governing equations to the relevant boundary conditions. The upwind technique was employed to discretize the convective terms. The computer terms were developed by using the SIMPLE algorithm. Turbulent flow conditions were considered. The standard k-ε turbulence model for fluid flow, turbulent combustion and spray model were utilized.

Fame engine plus had been employed for producing 3D hexahedral cells for engine moving mesh, which involved the intake port and valves, the cylinder head, the combustion chamber, the exhaust port and valves. The number of cells was about 168,498 at top dead centre (TDC) position and around 436,286 cells at bottom dead centre (BDC) position; while about half of the cells of the computational mesh around the valves and combustion chamber were concentrated to obtain accurate results.

An important consideration of engine simulation is computational time. In this work, the required CPU time for generating the moving mesh from 360 °CA of the intake stroke to 1080 °CA of the exhaust stroke was around 43 h and around 48 h for simulating the engine processes at an engine speed of 2000 rpm on an 3.4 CPU RAM 8 GB computer.

The simulation was started from 360 °CA at the top dead centre of the intake stroke and finished at 1080 °CA of the exhaust stroke. The inlet mass flow rate, intake temperature, outlet pressure, and the cylinder head temperature, were used as boundary conditions based on available AVL data. The initial pressure was fixed at 120 kPa while an initial temperature of 1014 K was used as the initial conditions. An initial density of 1.19 kg/m^3 of gas was used with the assumption that the working fluid was fresh air for the simulation process. The initial value of the turbulent kinetic energy k was set equal to 5% of the kinetic energy and the turbulence length scale was assumed to 0.001 m.

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