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Multi-objective optimization of operating parameters for hydrogen-fueled spark-ignition engines

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ABSTRACT

This work deals with the engine performance and emissions of a single cylinder spark-ignition (SI) engine fueled by hydrogen. Advanced simulations of the combustion process were performed using a commercial software package. The extended Zeldovich mechanism with coefficients for carbon-free fuel was utilized to investigate the most accurate formation rate of nitrogen oxide (NOx) emissions within the engine. The first part of this work focuses on simulating the engine performance and emissions at different equivalence ratios. Different techniques that have significant effects on engine performance and emissions such as exhaust gas recirculation and ignition timing, were also were studied. A thorough explanation of the relationship between the performance, emissions, and the operating parameters considered is presented. The second part of this work focuses on optimization of the operating parameters. The best operating conditions for hydrogen engines were obtained by solving the multi-objective problem of maximizing engine power and efficiency while minimizing the NOx.

Introduction

In recent years, a lot of attention has been given to alternative sources of energy due to the pollution associated with fossil fuels as well as rising concerns about shortages. One of the main strategies to improve the combustion processes of internal combustion engines (ICEs) is to discover useful ways to decrease exhaust emissions without major modifications to the design. With the growing needs to conserve fossil fuels and minimize emissions, various alternative fuels have been studied. Compared to other fuels such as natural gas, biodiesel, and ethanol, hydrogen (H_2) has unique combustion properties. Hydrogen can be directly used in spark-ignition (SI) engines as a single fuel because it has a spark plug for ignition. In addition, hydrogen has the widest flammability range, so an engine fueled by hydrogen can run on a very lean mixture with high efficiency. Consequently, NO_x emissions can be reduced at lower equivalence ratios [1,2]. Hydrogen also has very low ignition energy, which ensures that timely ignition

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occurs even with a fairly weak spark and permits a hydrogen engine to ignite lean mixtures. The combustion duration of hydrogen-air blends is appreciably shorter than other fuel-air mixtures due to hydrogen having the highest flame speed. Because hydrogen has no carbon in its structure, no carbon-based pollutants are formed and emitted from hydrogen-powered engines. Oxides of nitrogen (NOx) are the only unwanted emissions of hydrogen combustion. Many studies of IC engines using hydrogen have been carried out in the past [3–6]. Experimental [3] and computational investigations [6] have studied the performance of SI engines fueled by hydrogen and have estimated the combustion and pollutant characteristics under different engine operating conditions.

Due to the higher combustion temperatures, NOx formation is an inherent problem in hydrogen engines. One way to reduce NOx is called exhaust gas recirculation (EGR), which is a promising engine technology for IC engines. The EGR mechanism recirculates a significant amount of the engine's exhaust gas back to the cylinders. Several studies have been conducted in the area of hydrogen combustion using the EGR technique [6–9]. EGR is used to regulate the engine load and reduce NOx. In CI and homogenous charge compression ignition (HCCI) engines, high levels of EGR are common practice [9–13]. However, in gasoline engines, less EGR levels are used due to severe decrease in the flame speed. Recently, higher EGR rates have been conducted in SI engines using other fuels such as natural gas and hydrogen [14–17]. More specifically, the use of EGR in SI engines fueled by hydrogen aims at decreasing the NOx and regulating the engine load with no throttling necessary. The primary goal is achieved by higher specific heat capacity of the mixture diluted with exhaust gases, thereby decreasing the maximum combustion temperature. The secondary goal (engine load regulation) is accomplished due to the wide flammability limits of hydrogen by appropriately adjusting the EGR rate up to a certain point. Beyond this limit, significant cycle-to-cycle variations as well as some amount of unburned fuel appears in the exhaust, causing a decrease in combustion efficiency [18,19].

Another common method to reduce NO_X is modifying the ignition timing (IT) or spark timing. Ignition timing is a factor that has a significant effect on engine performance and emissions. Advancing the spark timing up to a certain point causes the combustion to occur earlier, and as a result, the in-cylinder pressure and temperature increase. This causes engine power and NOx to increase as well [20,21]. Both EGR and IT methods are effective in reducing the NOx formation by reducing the in-cylinder temperature, but as a side effect, the power is also significantly reduced. The designer would like maximum power and minimum NOx while the commonly adopted measures to reduce NOx also cause the power to decrease. Therefore, this method becomes a classical multi-objective optimization problem with conflicting objectives.

The study in Ref. [22] focuses on the effect of the compression ratio, equivalence ratio, and engine speed on the engine performance and emissions of a SI engine fueled by hydrogen. An analytical model was developed and validated against the experimental data of the engine. The equivalence ratio was varied between 0.5 and 1.3. As a result, the engine operating at lean mixture tended to decrease the engine power and NOx emissions for all compression ratios due to a reduction in the volumetric lower heating value of the intake mixture and decreasing combustion temperature. At richer mixtures, the engine power and the concentration of NO emission also decreased due to decreasing combustion efficiency and amount of oxygen. An experimental study [23] on the performance and emission characteristics of an SI engine fueled by natural gas–hydrogen mixture found that the break thermal efficiency and NOx emissions increased with hydrogen addition to natural gas; however, at lean and rich mixtures, the break thermal efficiency and NOx emission were found to reduce. Effect of spark timing on performance and emissions was considered in Ref. [24]; advance ignition timings were considered as a solution to engine knock at equivalence ratio of 0.55 by reducing the combustion rate. However, highly retarded spark timing resulted in higher residual gas temperature at the higher equivalence ratios, and as a result, the backfiring could take place in the engine. Additionally, advance ignition timing causes lowering the rate of pressure rise, so the power and the break thermal efficiency decrease.

Several studies researched the optimization of IC engines. Optimization studies can broadly be categorized as geometry optimization or optimization of operating conditions. Geometry optimization typically involves using an optimization algorithm to find the best cylinder geometry that minimizes certain fitness functions. The study in Ref. [25] parameterized the cylinder geometry for a direct-injection diesel engine. Eight different parameters were used to optimize three fitness functions (HC, NOx, and soot) for different operating conditions as well (load and speed). This was similar to a previous study [26] that included nine parameters, three of which related to the geometry. Genetic algorithms (GA) were used to minimize the same emissions and the fuel consumption as well. The more recent study in Ref. [27] focuses on stoichiometric diesel combustion targeted towards lowering the gross indicated specific fuel consumption. The emissions were not considered as optimization objectives due to the claim that they are manageable with after treatments. The study in Ref. [28] was conducted for a CI engine fueled with dimethyl ether. Eleven decision variables were used, including some related to operating conditions, with the objectives being the same as Ref. [26]. The study in Ref. [29] introduces neural networks (NN) to reduce the computational time needed by GAs. Neural networks were used to estimate the efficiency and NOx for a spark-ignition engine. Several engine parameters were used as inputs, but the geometry was fixed. The study in Ref. [30] is a more comprehensive version that uses GA-NN methods to optimize the NOx, soot, and gross indicated mean effective pressure. Three different piston bowl geometries were considered.

The problem with geometry optimization is that implementation of the results could be very difficult given that new geometries are usually proposed. In the short term, it is more practical to consider finding the optimum (in the context of multiple conflicting objectives) operating conditions for existing engine geometries. It is necessary to adopt a multi-objective approach in order to find multiple suitable points from a Pareto-optimal front in order to give the designer a wide range of suitable operating points. This would allow the