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# Thermodynamic modeling of partially stratified charge engine characteristics for hydrogen-methane blends at ultra-lean conditions

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ABSTRACT

A thermodynamic model considering flame propagation is presented to predict SI engine characteristics for hydrogen-methane blends. The partially charge stratification approach which involves micro direct injection of pure fuel or a fuel–air mixture, to create a rich zone near the spark plug, is proposed as a method to improve engine performance. Presented approach was validated with experimental data for the natural gas at lean condition. The model was generalized to predict the performance of engine for a variety of hydrogen contents in hydrogen-methane blends. Hydrogen molar concentrations of 0%, 15%, 30%, and 45% were used in the simulations. Results showed that partially charge stratification improves engine performance by increasing indicated mean effective pressure and decreasing specific fuel consumption. The results indicated that increasing mole fraction of hydrogen content would improve the PSC effect on engine performance. An advantage of the presented model is the flexibility and simplicity that make it possible to investigate several effects such as mixture distribution and fuel constituents on engine performance more practical than other types of simulation.



## 1. Introduction

The unique properties of $H_2$ make several advantages in comparison with hydrocarbon fuels. The use of $H_2$ as a fuel in internal combustion engines is attractive because of its wide flammability range, stable ignition, large flame propagation velocity and small quenching distance [1]. Hydrogen has also a higher Rate of Heat release per unit mass relative to hydrocarbon fuels [2]. Hydrocarbon emissions would be eliminated in the lack of carbon in the fuel. The high flame velocity of hydrogen, short ignition delay and high auto-ignition temperature, decreases the knock probability relative to gasoline. Therefore the research octane number (RON) for hydrogen (RON > 120 [3,4])is higher than gasoline (RON = 91–99 [2]).However, hydrogen fuel increases the $NO_x$ emissions due to the higher flame temperature.

Stable combustion at ultra-lean conditions, makes it possible for hydrogen-fueled engines to operate with very low amount of emissions. In addition, lean burn also improves engine thermal efficiency by improving combustion quality, reducing heat transfer loss and increasing possibility of applying higher compression ratios. However, slower flame

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propagation speed, increased cycle-by-cycle variations and instability of combustion process are some difficulties of lean burn operation. Several works were done to study the characteristics of lean hydrogen–hydrocarbon mixtures. Combustion characteristics of lean mixture of hydrogen–natural gas or hydrogen–methane have been investigated more than other blends [5–10]. Bauer et al. [11] investigated the effect of hydrogen addition on the performance of methane-fueled SI engine. They did their experiments on a single cylinder engine with mixtures of hydrogen–methane blends by hydrogen volume concentration of 0, 20, 40 and 60%. Each blend was tested at speeds of 700 and 900 rpm, full and part loads, and equivalence ratios from stoichiometric to the partial burn limit. These results were used in a driving cycle simulation. Huang et al. [12] studied the effect of fuel injection timing relative to ignition timing on natural gas direct-injection combustion. The influence of injection timing on charge stratification was investigated by them. They concluded that early injection leads to relatively lower CO concentration in the combustion products while late injection gave relatively lower $NO_x$. Deng et al. [13] studied combustion and emission characteristics of hydrogen–natural gas blends. They concluded that the addition of hydrogen can significantly reduce $COV_{imep}$ and extend the lean burn limit. It was also shown that the combustion duration would be reduced and higher thermal efficiency would be achieved.

Ma et al. [14] investigated the effects of hydrogen addition on cycle-by-cycle variations in a lean burn natural gas spark-ignition engine. They concluded that the coefficient of variation in both maximum pressure and indicated mean effective pressure can be reduced by hydrogen addition. This effect would be more obvious when the engine is further leaned out. Ma et al. [15] also studied the extension of lean limit operation through hydrogen enrichment in a natural gas spark-ignition engine. They concluded that engine's lean operation limit could be extended through adding hydrogen. Wang et al. [16] investigated on the characteristics of direct injection combustion fueled by natural gas–hydrogen mixtures in a constant volume vessel. They studied the effects of hydrogen addition and turbulence intensity on the natural gas–air turbulent combustion. Their results showed that the turbulent combustion rate was increased significantly by increasing hydrogen fraction in the fuel blends when hydrogen fraction was over 11%. They also concluded that combustion rate was increased remarkably with the induction of turbulence in the bomb. Wang et al. [17] also studied on the factors affecting lean combustion limit of SI engine fueled with compressed natural gas and hydrogen blends. Effects of ignition timing, hydrogen fraction, engine speed, throttle opening, coolant and oil temperature were investigated by them. Their results indicated that lean combustion limit could be obviously extended by adding hydrogen into compressed natural gas. Huang et al. [18] experimentally studied the combustion characteristics of a direct-injection spark-ignited engine fueled with natural gas–hydrogen blends. Their investigation indicated that when the hydrogen fraction in natural gas reaches a certain value, a large improvement in combustion characteristics would appear.

Employing a small chamber for charge stratification and providing relatively rich region around the spark is a solution to increase the stability and reliability of ignition and combustion process [19–21]. The partially stratified charge (PSC) concept includes direct injection of small fraction of fuel near the spark and provides a stratified charge without any auxiliary chamber. This concept is a new approach for direct injection of fuel which was developed by Evans et al. [22,23]. Several experimental efforts were done to investigate and improve characteristics of PSC. Emission and performance of lean burn natural gas engine equipped with PSC spark plug injector was investigated by Reynolds and Evans [22]. They concluded that using PSC concept can be useful for reducing specific fuel consumption, decreasing combustion duration and increasing mean effective pressure in lean conditions. Andreassi et al. [24] applied a single cylinder direct injection for direct injection of a small quantity of natural gas through the spark plug. Numerical analysis of injection, ignition and combustion process of PSC engines were done by Arcoumanis et al. [25]. Chan [26] investigated an experimental/numerical approach of PSC with a constant volume combustion chamber. He concluded that stable combustion could be achieved with PSC at an air-to-fuel ratio of $\lambda = 2.0$. He also concluded that the use of double PSC injection facilitates additional consumption of the bulk fuel.

In the present study a flexible thermodynamic-based simulation is presented to predict (PSC) engine using non-spherical flame propagation model. Investigation of the flame progress characteristics in a non-homogeneous charge system was done to achieve a simple and accurate model. The simulation has proper accuracy to predict ignition and combustion characteristics of a partially stratified charge engine for wide range of charge stratification type and it is capable to be used for methane, hydrogen and their blends.

## 2. Theoretical model

The presented model is a thermodynamic-based two-zone model, including flame propagation. The calculations start from induction stroke and continue with compression, ignition delay, combustion and expansion processes. In this model, the combustion chamber is divided into two zones by flame front. First zone contains unburned and the second one contains burned mixture. The flame front is assumed to travel by turbulent flame speed which is a function of laminar flame speed. Heat transfer between cylinder contents and surrounding surfaces is calculated by Annand correlation [27]. Friction work was calculated using a model that is presented by Ferguson et al. [28].

The ignition delay period was considered as the time needed for burning of 0.1 percent of the total chamber content, as recommended by Benson et al. [29]. The combustion process then starts from spark location and continues to the point at which all the fuel is reacted. In order to consider non-homogeneous fuel–air distribution of partially stratified charge, a non-spherical flame propagation pattern was used which was developed by Aliramezani [30]. The expansion process then starts from end of combustion up to the bottom dead center.

Fig. 1 shows a schematic view of non-homogeneous air–fuel distribution near the spark in partially stratified charge engine.