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ORIGINAL ARTICLE

Performance and specific emissions contours throughout the operating range of hydrogen-fueled compression ignition engine with diesel and RME pilot fuels

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Abstract This paper presents the performance and emissions contours of a hydrogen dual fueled compression ignition (CI) engine with two pilot fuels (diesel and rapeseed methyl ester), and compares the performance and emissions iso-contours of diesel and rapeseed methyl ester (RME) single fueling with diesel and RME piloted hydrogen dual fueling throughout the engines operating speed and power range. The collected data have been used to produce iso-contours of thermal efficiency, volumetric efficiency, specific oxides of nitrogen (NO_X), specific hydrocarbons (HC) and specific carbon dioxide (CO_2) on a power-speed plane. The performance and emission maps are experimentally investigated, compared, and critically discussed. Apart from medium loads at lower and medium speeds with diesel piloted hydrogen combustion, dual fueling produced lower thermal efficiency everywhere across the map. For diesel and RME single fueling the maximum specific NO_X emissions are centered at the mid speed, mid power region. Hydrogen dual fueling produced higher specific NO_X with both pilot fuels as compared to their respective single fueling operations. The range, location and trends of specific NO_X varied significantly when compared to single fueling

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cases. The volumetric efficiency is discussed in detail with the implications of manifold injection of hydrogen analyzed with the conclusions drawn.

Nomenclature

Abbreviations

BMEP	brake mean effective pressure
CI	compression ignition
CO	carbon mono oxide
CO_2	carbon dioxide
HC	hydrocarbons
IC	internal combustion
NO_X	oxides of nitrogen
RME	rape methyl ester
SI	spark ignition

1. Introduction

Limited reserves and the increasing environmental impact of the conventional fossil fuels have recently been two majors concerns of the researchers [1,2]. Two strategies have been evolved to meet these challenges: the use of alternate fuels to reduce the dependence on fossil fuels [3,4] and the development of clean burning fuels to meet the strict emissions targets [5]. Owing to its superior combustion characteristics, hydrogen has received particular attention [6–8].

Approximately 95% of the hydrogen currently produced is by steam reforming of natural gas (a catalytic thermo-chemical conversion process). Renewable hydrogen-production methods, such as electrolysis of water using renewably generated electricity [9], pyrolysis [10], photo-biological water splitting, photo-electro-chemical [11] water splitting, solar thermo-chemical water splitting and biomass steam gasification [12] are techniques yet to be fully realized [13] but make hydrogen a viable alternative to fossil derived fuels, or as a substitute fuel for at least a portion of the overall energy supplied to these engines, e.g. in dual fuel mode operation [14,15].

Owing to the high auto-ignition temperature of hydrogen, it is difficult to ignite a hydrogen/air mixture on the basis of mixture temperature alone. The ignition of hydrogen is achieved through a spark plug in spark ignition (SI) whereas a high cetane liquid fuel is injected at the end of compression to start the ignition in compression ignition (CI) engines. This mode of operation in CI engines is referred to as dual fueling [14,15]. Some studies have theoretically [16] and others have experimentally [17]assessed the effect of pilot fuel quantity in dual fueling mode. Studies have been conducted with diesel piloted hydrogen combustion [18] and biodiesel piloted hydrogen [14]. Comparison between these two pilots has been made [19] but at a very limited range of engine operating conditions. Also, studies [20] have indicated that the ignition delay is affected if the percentage of H_2 in fuel mixture is varied.

Hydrogen has a high burning velocity which leads to increased in-cylinder pressures and higher temperatures, resulting in increased NO_X emissions. This effect may be reduced by making the mixture leaner using hydrogen's property to be flammable over a very wide range of concentrations in air (from 4% to 75%) [21–23]. This allows for the application of learner combustion, resulting in a reduction of temperature and pressure, and lower NO_X emissions [24]. However, the initiation and development of the multiple turbulent flames require an H_2–air mixture richer than the lean flammability limit [25]. Most studies have limited the enthalpy fraction of hydrogen to a maximum of 15% [22,26]. The upper limit of hydrogen addition with manifold injected hydrogen is determined by the quenching gap of the hydrogen flame which can travel past the nearly-closed intake valve and more readily backfires into the engine's intake manifold [27]. There is a need to examine the performance and emissions of a naturally aspirated CI hydrogen dual fueled engine at higher hydrogen enthalpy fractions. The maximum enthalpy fraction in this study is 30%.

Hydrogen has been shown to increase flame stability [26] and improve thermal efficiency [28]. It is believed that the high diffusion coefficient of hydrogen leads to highly turbulent flame propagation rate [26,29,30]. The addition of hydrogen to increase the flame stability has been studied extensively because of the belief that flame propagation is the key factor in improving combustion [24,26,31,32]. Engine speed is often neglected in these studies, but it is clearly one of the key factors in mixing, flame propagation and the residence time. Increased engine speed enhances turbulence and hence affects mixing and flame propagation characteristics. On the other hand the residence time is reduced, therefore the overall effect of hydrogen addition on combustion should be examined with changing speeds. Measurement of NO_X emissions offers an indirect indication of combustion temperatures. The effect of hydrogen addition on combustion and hence the thermal efficiency with varying amounts of hydrogen has been studied previously [22,25] but often limited to one engine speed and a small range of loads.

A number of studies have examined different emissions of hydrogen in dual fueled CI engines. Some of these studies have considered engine operation at one speed only [22,25,28,33]; others have considered two speeds only [34,14]. The general trend exhibited in these studies is an increase in NO_X emissions and a decrease in HC, CO and CO_2 when compared to single fueling with their respective pilot fuels. The increase in NO_X emissions with increasing hydrogen addition are attributed to increased flame temperature, and the reductions in HC, CO