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Effect of pilot fuel quantity and type on performance and emissions of natural gas and hydrogen based combustion in a compression ignition engine

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ABSTRACT

Natural gas and hydrogen have been extensively tested in dual fuel mode in a compression ignition engine. Many studies conclude that the emissions, especially those oxides of nitrogen (NO_x) are expected to form in the region around the pilot spray where high temperatures exist and the equivalence ratio is close to stoichiometric. The effect of changing the pilot fuel quantity has not been widely reported. This study investigates the effect of changing pilot fuel quantity, and type and the effect of this change on various combustion (ignition delay, in-cylinder pressure and rate of energy release) and emission (specific NO_x and hydrocarbons) parameters. Dual fueling of natural gas and hydrogen exhibit an increased ignition delay compared to the ignition delay exhibited by the pilot fuel at similar operating conditions. For dual fueling cases, the ignition delay is reduced as the quantity of pilot fuel is increased.

1. Introduction

Development of alternative fuels to replace the conventional fuels in IC engines is an active area of research. Fuels derived from different resources (especially but not exclusively renewable ones) have been tested in IC engines with their performance and emissions characteristics investigated to assess their suitability as substitute fuels. Both natural gas and hydrogen have long been considered alternative fuels for the transportation sector and have fueled vehicles for decades.

When compared to the reserves of crude oil on volume basis, natural gas has much larger reserves, estimated to be 5288.5 trillion cubic feet [1]. The cleanliness of any burning process is indicated by the amount of soot or smoke produced, natural gas qualifies this test owing to its lower carbon content. Natural gas is generally a mixture of primary alkanes with methane (CH_4) contributing around 95%.

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Nomenclature

γ	specific heat capacity ratio
Abbreviations	
ATDC	after top dead center
BMEP	brake mean effective pressure
CA	crank angle
CI	compression ignition
IC	internal combustion
RME	rape methyl ester

An initial source of ignition is required to ignite both natural gas and hydrogen-air mixtures in unmodified CI engines. This is due to lower cetane number (high octane number) of natural gas [1–4] and high auto-ignition temperature of hydrogen. To ignite these gaseous fuel in compression ignition engine, various ignition strategies have been employed. A glow plug or a high cetane liquid fuel such as diesel [5–8] or a biodiesel [6,9–11] have been widely used as an initial source of ignition using the piloted dual fuel concept [12]. All of these studies consider a fixed quantity of pilot fuel, hence the effect of varying quantity of pilot fuel remains to be investigated.

Natural gas has high specific heat capacity ratio (γ). Due to this, the temperature of the in-cylinder charge is lowered and hence ignition is delayed which is critical from an emissions perspective [13,14]. These studies have considered a variety of pilot fuels but were limited to a fixed quantity of pilot fuel. They present a good comparison of how different pilot fuels perform under certain operating conditions but lack an account on what will be the effect if the pilot fuel quantity is varied.

When compared to baseline single fueling case, the natural gas based dual fueling mode exhibit a slight reduction in brake thermal efficiency at lower loads [5,7,15–17]. Higher thermal efficiency values were reported at higher loads for natural gas dual fueling [18].

Hydrogen has been shown to increase flame stability [16] and improve thermal efficiency [19]. It is believed that the high diffusion coefficient of hydrogen leads to highly turbulent flame propagation rate [16]. 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 [16,20–23]. All of these studies highlight one or the other important aspect of the natural gas and hydrogen based dual fueling cases but the effect of changing the pilot fuel quantity and type on various combustion and emissions parameters has not been reported.

Concerning total brake specific fuel consumption, it is revealed that it becomes inferior under dual fuel operation compared to normal diesel operation at the same engine operating conditions. At high load, the values of total brake specific fuel consumption under dual fuel operation tend to converge with that of normal diesel operation [5]. The concept of multi ignition centers that result from the pilot fuel igniting the gaseous fuels in case of dual fueling modes requires an investigation on how changing the number of ignition centers (of course by injecting a different quantity of pilot fuel) shall affect the total brake specific fuel consumption and hence power and emissions characteristics. The lower heating value of the fuel also affects brake specific fuel consumption. It is worth investigating how two pilot fuels with different lower heating values shall perform in dual fuel mode from the brake specific fuel consumption perspective.

NO_x is a strong function of local temperatures. It has been reported that most of the NO_x are formed in the region around the pilot spray where high temperatures exist and the equivalence ratio is close to stoichiometric [24]. Natural gas based dual fueling results in lower NO_x emissions when compared to the NO_x concentration under normal single fuel operation. At the same time, a significant decrease in soot emissions under dual fuel operation has also been reported. On the other hand, CO and HC emissions levels have been reported to be considerably higher compared to normal diesel operation [5,13–15,25]. How would these different emissions parameters change if both the quantity as well as the type of the pilot fuel are changed, remain to be investigated and reported.

Hydrogen has high burning velocity which can lead to increased in-cylinder pressures and higher temperatures, resulting in increased NO_x emissions. Hydrogen is flammable over a wide range of concentrations in air (from 4% to 75%) [8,9,26]. This wider flammability can be used to prepare leaner mixtures resulting in lower in-cylinder temperatures and pressures and hence reduced NO_x emissions [21].

However, the initiation and development of the multiple turbulent flames requires a H_2-air mixture richer than the lean flammability limit [27]. Most studies have limited the enthalpy fraction of hydrogen addition to a maximum of 15% [9,16]. The upper limit of hydrogen addition with manifold injected hydrogen is determined by the quenching gap of hydrogen flame which can travel past the nearly-closed intake valve and more readily back fires into the engine's intake manifold [28]. Using different quantities of the pilot fuels to achieve a certain BMEP in hydrogen dual fueling can be helpful in quantifying the effect of wider flammability and smaller quenching gap on different performance and emissions parameters.

Most of the studies reported on natural gas and hydrogen dual fueling lack one or the other important aspect. They are either confined to one type of gaseous fuel (either hydrogen or natural gas) or one type of pilot fuel (either diesel or a biodiesel). These two dual fueling cases with two different pilot fuels have hardly been reported in a single study. Changing the quantity of pilot fuel in natural gas and hydrogen based dual fueling is yet to be investigated, compared and reported. This study is an effort to fill all these gaps in the literature on natural gas and hydrogen based dual fueling of compression ignition engines. The study was conducted at two different engine speeds and the effect of variation in engine speed on different performance and emissions parameters has also been discussed.

The same engine can be used as a power source for different power applications, each with its own different load characteristics. For instance the same engine can be used to power: two different-size cars; a small marine vessel; an electricity generator; and in several other applications. The procedure of selecting the engine (prime mover) while considering the engine's contours of thermal efficiency on the power-speed range of the engine, and concurrently the load line of the powered device, has been briefly described in Ref. [6]. The engine is a standard test engine, typical of the majority