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Experimental Analysis on the Effect of Hydrogen Supply Systems in a Diesel Dual Fuel Engine

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ABSTRACT

An experimental investigation on dual fuel (DF) operation of a diesel engine with hydrogen as the main fuel and diesel as the pilot fuel has been performed. The focus has been made on gaseous fuel delivery system for performance enhancement during DF operations. Two techniques of hydrogen delivery namely, manifold port induction and manifold port injection are compared in the DF engine. In the case of manifold induction, the gas is introduced with the help of a gas mixture in the intake manifold, whereas in the case of manifold injection, the gas is introduced with the help of an injector. The injector is located close to the intake valve and its timing is controlled through an electronic control unit. It was found that hydrogen manifold injection improves the diesel substitution and thermal efficiency of the DF engine as compared to manifold induction technique. The diesel substitution was improved by 2.3% and 1.5% at low and high loads respectively. Similarly, the brake thermal efficiency was improved by 0.4% and 0.5% at low and high loads respectively.

1. Introduction

The continuously increasing energy demand of the world has brought unprecedented situations of energy insecurity and environmental instability in the past couple of decades. It has been well understood that sole reliance on fossil sources is unsustainable and a prudent mix of renewable energy sources is indispensable. In this context, hydrogen is considered as the future fuel due to its unique properties and potential to zero emissions [Kelly, 2014; Hudson et al., 2009; Das, 2002]. However, utilization of hydrogen in internal combustion engines (ICEs) poses some technical challenges such as knocking, backfire and safety concerns [Das, 2002; Das, 1990; Verma et al., 2017]. In addition to that the major issues with the use of renewable energy sources are their lack of availability and uncompetitive economics against the fossil based energy sources. These challenges can be effectively tackled for the near terms if the renewable fuels can be utilized in combination with the fossil fuels in the existing engines. In this context, dual fuel (DF) engine technology is an excellent option, which can utilize hydrogen as the gaseous fuel in the existing diesel engines. In the wake of recent developments in hydrogen as the future fuel or its blend with CNG to lower the engine emissions, DF engine could be a better alternative [MNRE, 2019; Mehra et al., 2017]. In the DF engines, small amount of pilot fuel (e.g. diesel) is required to initiate the combustion and bulk combustion is achieved with the gaseous fuel [Karim, 1980; Papagiannakis et al., 2010; Verma et al., 2018]. Utilization of hydrogen in the DF mode is constrained by excessive engine knock, backfire and high levels of NOx emissions. Mathur et al. [1993] tried charge dilution as a possible technique to improve the performance. It was found that helium was better able to control the engine knock, whereas, water showed highest level of improvement in diesel substitution. Saravanan et al. [2007] investigated on a hydrogen-diesel DF engine with hydrogen port injection as the gaseous fuel delivery system. It was found that optimization of injection timing and injection duration of hydrogen supply had great effect on both the performance and emission characteristics of DF engine. It was found that highest thermal efficiency and significant reduction in smoke emission were observed at full load engine condition with optimized injection parameters. Saravanan and Nagarajan [2008] studied hydrogen-air enrichment in DF engine and found that 90% hydrogen substitution showed highest efficiency, however resulted in knocking. It was reported that smooth operations were found with 30% hydrogen substitution and performance was also improved. The DF operation is also affected by the methodology of introducing the gaseous fuel in the engine. Chintala and Subramanian [2013] found that there is a critical distance at which the gaseous fuel must be introduced to avoid fuel accumulation and backfire. Jemni et al. [2011] studied the effect of intake manifold design using numerical simulation in a diesel engine converted to LPG gas fuelled. They found that the geometry of intake manifold plays vital role in fuel-air mixing and their distribution and ultimately affects the engine performance. Verma

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et al. [2017] reported that in the DF mode, introduction of gaseous fuel in the intake manifold replaces air and hence lowers the volumetric efficiency. This effect is vital at higher engine loads, where rich fuel-air ratio exists and affects the combustion. Bedoya et al. [2009] studied the effect of mixing system using simple 'T' shaped mixture and a specially designed supercharged and longer length of intake manifold in a biogas DF engine. It was found that specially designed mixture offered improved thermal efficiency and diesel substitution. In the spark ignition (SI) engine configuration, Das [2002] examined various fuel induction techniques for hydrogen supply. It was found that the time manifold injection was the most suitable to counter undesirable combustion phenomena. Similar results with timed manifold injection were found with acetylene fumigated diesel DF engine reported by Lakshmanan and Nagarajan [2010]. Yi et al. [2000] studied on a four cycle, water cooling, spark ignition engine with objective of optimized mixture formation for hydrogen engine. They investigated the performance of the engine with intake port injection and in-cylinder injection methods of hydrogen delivery. It was found that intake port injection technique give better thermal efficiency and engine stability at low load operation. Whereas, in-cylinder injection method better performs at high load at wide open throttle conditions. Verhelst and Sierens [2001] studied a hydrogen fuelled spark ignition with sequential timed multipoint injection system. It was found that optimization of injection parameters are crucial at low load and speed conditions but relatively less important at high load and speed conditions. Injection timing was found very useful to control the problem of backfire in hydrogen engines. The literature shows that utilization of hydrogen in IC engines is subjected to various combustion anomalies such as backfire and engine knock. Injection methods has been found as crucial technique to achieve improved performance and safe operation of hydrogen engines. There are large number of works available concerning various hydrogen supply methods in spark ignition engine, however, this area is relatively less studied in case of DF engines. As the operation of a DF engine is significantly affected by the methodology of gaseous fuel supply, an experimental investigation is presented in this article to compare hydrogen port induction and hydrogen port injection techniques.

2. Material and methods

The experiments were performed in a single cylinder, four-stroke diesel engine for which the specifications are given in Table 1. The conventional diesel engine was slightly modified to operate in DF mode with diesel and hydrogen as the pilot fuel and main fuel respectively. This required that the engine intake system be modified to supply gaseous fuel. It is also important to keep the hardware modification simple but safe due to operation with hydrogen. The pilot diesel fuel is supplied in conventional direct injection method with the help of a diesel injector. The gaseous fuel supply system consists of a high pressure hydrogen cylinder, pressure regulator, gas piping arrangement, safety devices and manifold gas mixture. The intake manifold was modified to incorporate this manifold gas mixture and gas supply line was connected. In the case of hydrogen port induction, gas mixture is placed in the intake line near intake manifold. The gas is supplied from the high pressure cylinder, mixes with the incoming air and supplied to the engine. In the case of hydrogen port injection technique, a hydrogen injector is placed very near to intake valve and controlled by an electronic circuit and in-house computer code. The schematic diagram of the experimental setup is shown in Fig. 1.

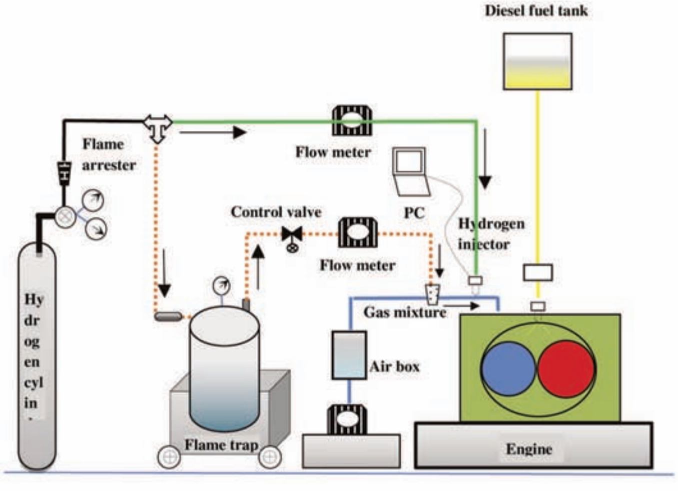

Figure 1: Schematic diagram of the experimental setup

Table 1: Specification of experimental diesel engine

Parameters	Technical specifications
Make & model	Kirloskar TAF1
Type	Single cylinder
Bore & stroke	87.5 × 110 mm
Swept volume	661 cm^3
Compression ratio	17.5:1
Rated brake power	6 bhp / 4.4 kW
Rated speed	1500 rpm

The engine was started with the conventional diesel injection and required engine load was applied to the engine. The engine was allowed to properly warm up before the gas supply was started and as a result, pilot fuel supply was automatically reduced to control the engine speed. The gas supply was increased to maximum limit which is defined as the maximum diesel substitution (DS) as following:

$$DS(\%)=\left[\frac{\dot{m}_{D,D}-\dot{m}_{D,DF}}{\dot{m}_{D,D}}\right]\times 100 \tag{1}$$

where $\dot{m}_{D,D}$ and $\dot{m}_{D,DF}$ are the diesel fuel flow rates at diesel only (single fuel) and DF modes respectively. The experimental results are presented at two engine loads of low load that is BMEP of 1.16 bar and high load that is BMEP of 5.32 bar in this paper.

Results and discussion

The variation in diesel substitution with two different modes of hydrogen fuel supplies viz. port induction and port injection is shown in Fig. 2. It was found that the diesel substitution increased with hydrogen port injection as compared to port induction both at low and high loads. The diesel substitution was improved by 2.3% and 1.5% at low (BMEP of 1.16 bar) and high loads (BMEP of 5.32 bar) respectively. It is more important to achieve improvements in the diesel substitution at high loads with hydrogen as the main gaseous fuel. This is because very low diesel substitution was found at high loads as compared to low loads owing to server knocking. With higher hydrogen addition at high load in DF mode, the combustion rate is significantly enhanced leading to engine knock. Another important reason for lower diesel substitution is decreased volumetric efficiency with hydrogen DF combustion and backfire. The addition of hydrogen in the intake manifold was found to cause frequent backfire, especially at high loads. Furthermore, hydrogen being significantly less dense than the air, replaces some amount of air and lowers the volumetric efficiency.

The variation in volumetric efficiency with two different modes of hydrogen fuel supplies viz. port induction and port injection is shown in Fig. 3 for low and high loading conditions. It is clearly evident that port injection technique improves the volumetric efficiency and helps in the

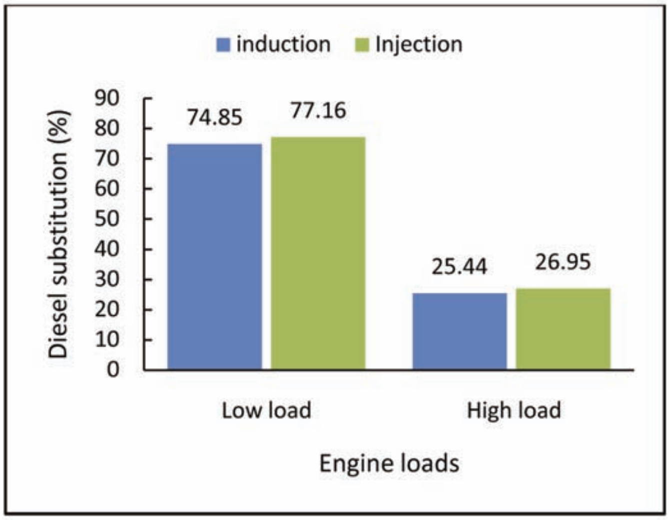

Figure 2. Variation in the diesel substitution with hydrogen port induction and port injection techniques at low and high loads

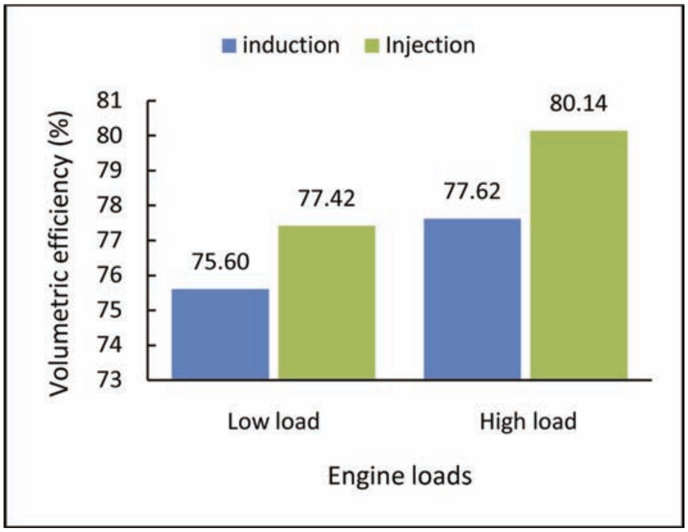

Figure 3. Variation in the volumetric efficiency with hydrogen port induction and port injection techniques at low and high loads

better diesel substitution. The volumetric efficiency is increased as the hydrogen is discontinuously supplied and replaces lesser amount of air. The effect of hydrogen fuel induction techniques (port induction and port injection) on engine brake thermal efficiency is shown in Fig. 4 for low and high loads. It was found that the brake thermal efficiency was improved by 0.4% and 0.5% at low and high loads respectively with hydrogen port injection technique. This could mainly be due to improvement in the diesel substitution with hydrogen port injection. The higher amount of gaseous fuel causes better homogeneity of the mixture formation. Furthermore, hydrogen has significantly higher flame speed than the diesel fuel which leads to much faster rate of energy release and improves combustion. As a result of these effects, the thermal efficiency of hydrogen port injection DF engine is improved as compared to port induction.

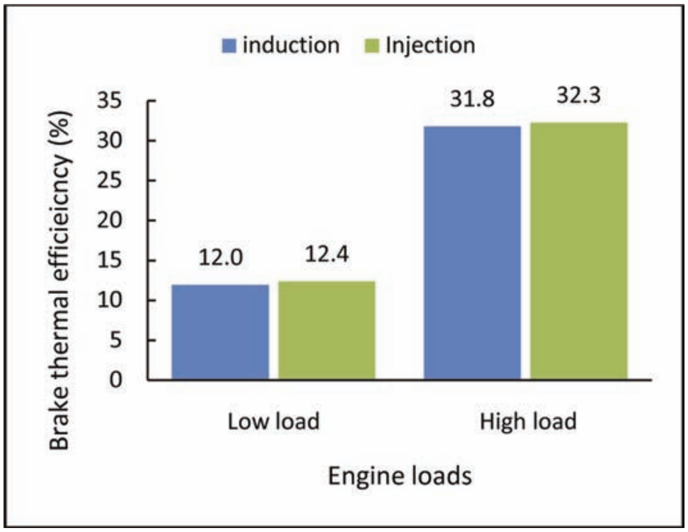

Figure 4. Variation in the brake thermal efficiency with hydrogen port induction and port injection techniques at low and high loads

The variation in specific energy consumption with hydrogen port induction and port injection strategies are shown in Fig. 5. It confirms that the combined (pilot fuel+main fuel) energy consumption from DF engine with hydrogen port injection is lower than the port induction strategy. The specific energy consumption was found higher with the lower load as compared to higher load. This is because of relatively leaner air-fuel mixture at low load, which lead to slower combustion and produces lower conversion efficiency. Whereas, at high load, rich air-fuel mixture produces high temperature combustion and lead to lower specific energy consumption.

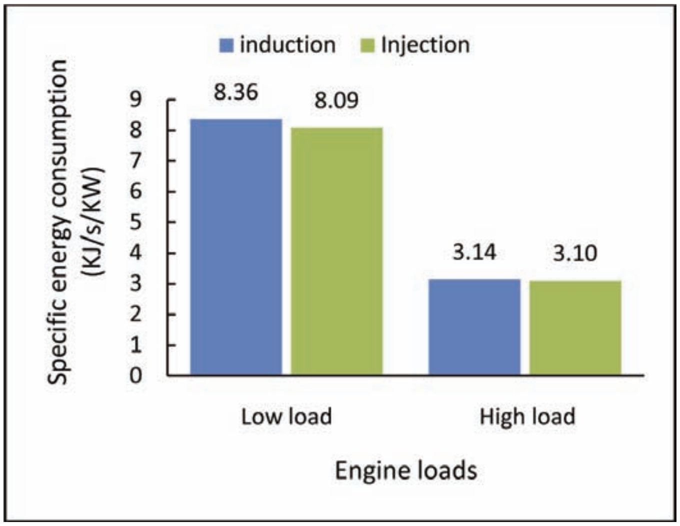

Figure 5. Variation in the specific energy consumption with hydrogen port induction and port injection techniques at low and high loads

The variations in engine emissions with hydrogen induction and port injection strategies at low and high loads are shown from Fig. 6 to Fig. 8. Variations in HC emissions is shown in Fig. 6, which shows slight reductions in emissions with hydrogen port injection method. The main reason for this reduction could be higher diesel substitution with port injection that replaces higher amount of diesel and therefore lower HC emission. Furthermore, increase in hydrogen fraction in combustible mixture improves it combustion quality and hence higher amount of HC can be oxidized in the combustion chamber. The variations in smoke emissions is shown in Fig. 7, which shows reduction at high load, however, no changes at low load. The obvious advantage of hydrogen-diesel DF engine is its lower smoke emissions. Hydrogen being a carbon free fuel together with premixed charge (hydrogen-air) in dual fuel operation eliminates the cause of smoke emission from diesel engines. However, due to pilot diesel fuel, some amount of smoke formation is inevitable but it is significantly reduced with hydrogen-diesel DF engine. It can also be seen that smoke emission is drastically increased at high load compared to low load. This is because of significant reduction in diesel substitution at high load and higher amount of pilot fuel leads to higher smoke emissions. Nevertheless, hydrogen port injection can further reduce smoke emission from DF engine. Variation in NOx emissions is shown in Fig. 8, which showed increased values with hydrogen port injection compared to

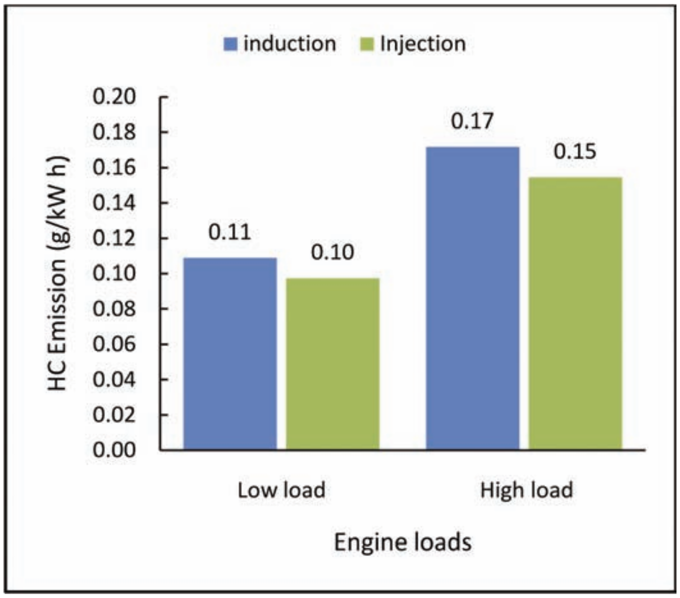

Figure 6. Variation in HC emission with hydrogen port induction and port injection techniques at low and high loads

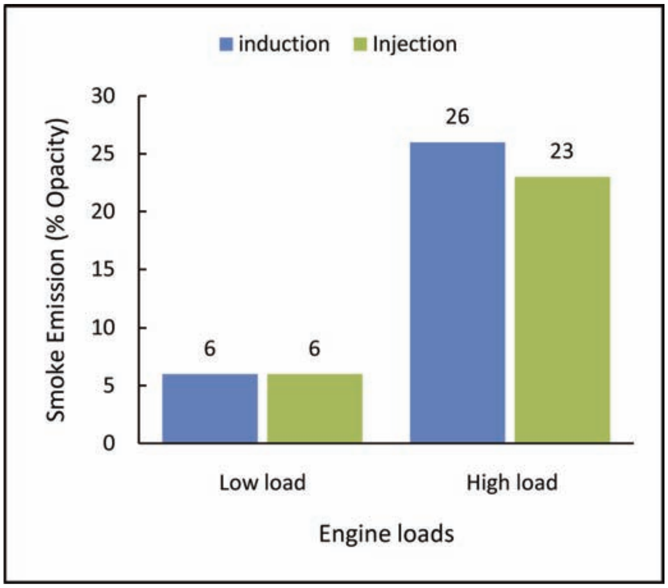

Figure 7. Variation in smoke emission with hydrogen port induction and port injection techniques at low and high loads

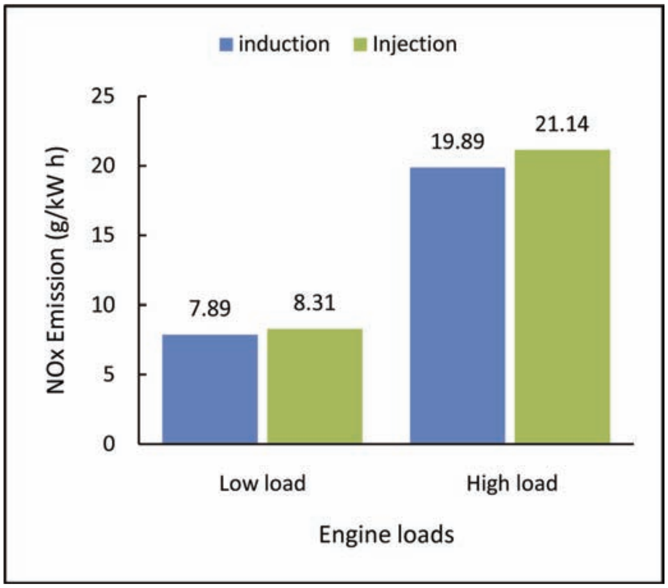

Figure 8. Variation in NOx emission with hydrogen port induction and port injection techniques at low and high loads

Table 2: Fuel properties for diesel and hydrogen

Properties	**Diesel**	**Hydrogen**
Chemical formula	$C_nH_{1.7n}$	H_2
Lower heating value (MJ/kg)	43.01	119.93
Density at 1 atm and15 °C (kg/m^3)	840	0.083
Stoichiometric A/F ratio		
(kg of air/kg of fuel)	14.6	34.36
Cetane number	51	-
Octane number	-	>120

hydrogen induction technique. NOx emission is highly sensitive to combustion temperature and in addition to that species concentrations and time availability also play a crucial role. As discussed earlier, hydrogen port injection method causes better combustion, improved volumetric efficiency and higher combustion temperature. These could be the possible reasons for increase in NOx emissions with hydrogen port injection method.

Conclusions

An experimental investigation of diesel-hydrogen DF operation of diesel engine is presented with focus on strategies to supply the gaseous fuel. The comparison is made between hydrogen with hydrogen port induction and port injection techniques and results are presented at low and high loads. It was found that the hydrogen port injection technique provides improved diesel substitution and volumetric efficiency as compared to port induction technique. In addition to that it was also possible to better tackle the combustion anomaly of backfire with the port injection technique. As a result, improved brake thermal efficiency and better combustion can be achieved along with increased utilization of hydrogen at high load in DF engines. It was also found that hydrogen port injection technique offers some emission benefits due to reduction in HC and smoke emissions, however NOx emission was slightly increased.

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