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Experimental investigation of autoignition of hydrogen-air charge in a compression ignition engine under dual-fuel mode

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ABSTRACT

High amount of hydrogen substitution in a compression ignition (CI) engine under dual fuel mode is limited due to more probability of autoignition of hydrogen-air charge and knocking problem. The study deals with analysis of autoignition of hydrogen-air charge in a 7.4 kW rated power output of CI engine under dual fuel mode (diesel-hydrogen) at 100% load (Case I) and 50% load (Case II). Experimental results indicate that the significant increase in in-cylinder temperature is the predominant factor for auto-ignition of hydrogen-air charge. The in-cylinder temperature increased due to combustion advancement with hydrogen addition into the engine. Computational fluid dynamics (CFD) simulation study also confirms the combustion advancement with hydrogen addition in the engine. Experimental tests were extended further with water injection into the engine under dual fuel mode (Case III). A clear conclusion emerged from the study is that the hydrogen-air charge gets autoignite without any external ignition aid when the reactants temperature is about 953 K ± 8 K. It could also be observed that knock limited hydrogen energy share in the engine at 100% load was increased from 18.8% with conventional dual fuel mode to 60.7% with water injection due to decrease in in-cylinder temperature.

1. Introduction

Hydrogen (H_2) is being considered as a supplementary fuel for internal combustion engines in order to yield the twin benefits of energy efficiency improvement and emissions reduction [1,2]. The Ministry of New and Renewable Energy, Government of India envisaged in its roadmap that one million automotive vehicles are to be fueled with hydrogen by 2020 [3]. The comparative analysis of hydrogen, electric and biofuel transitional pathways to a future sustainable road transport in a renewable-based energy system shows that hydrogen scenario could be advantageous in reducing fuel import and consumer total fuel costs [4]. Hydrogen as a fuel is more suitable for spark ignition (SI) engines due to its high octane number [5]. As hydrogen fueled SI engines face major setbacks of power drop and back firing, a dedicative system needs to be developed for effective utilization of hydrogen in SI engines [6]. In an alternative way, hydrogen could be used in compression ignition (CI) engines under dual fuel mode (hydrogen-diesel) without power drop and back firing problems. In addition, there is no need of major engine hardware modifications for a CI engine to be operated under dual fuel mode. Hydrogen based dual fuel engines offer significant benefits such as high energy efficiency [7], high combustion efficiency, lower specific energy consumption [8], near zero carbon based emissions (hydro carbon (HC), carbon monoxide (CO) and smoke/particulate matter), and less greenhouse gas emissions (CO_2, CH_4 and N_2O) [4,9]. Several investigations were reported on utilization of hydrogen in CI engines under dual fuel mode with exploration of improved performance and emission characteristics. For example, energy efficiency improved about 14% with 20% hydrogen addition in a single cylinder direct injection CI engine (7.4 kW rated power at 1500 rpm) under dual fuel mode [10]. Yadav et al. found 11.6% improvement in thermal efficiency of a CI engine (4.4 kW rated power at 1500 rpm) with an addition of 120 g/h hydrogen under dual fuel mode due to better combustion characteristics of hydrogen [11]. The maximum brake thermal efficiency of 39.53% was obtained with hydrogen addition in a CI engine (5.2 kW rated power at 1500 rpm) at 60% load [12]. Wu H-W and Wu Z-Y reported a significant improvement in thermal efficiency of a CI engine under dual-fuel mode with 30% hydrogen energy share at 100% load [13]. Edwin et al. also confirmed the same that thermal efficiency of a CI engine increased from 29.9% with base diesel mode to 31.6% with 10.1% hydrogen energy share at 100% load [14].

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The reasons for this improvement could be due to better mixing characteristics of these gaseous fuel with air resulting in better combustion. Even though there are significant benefits in terms of thermal efficiency improvement and emissions reduction, hydrogen based dual fuel engines have a severe problem of knocking with high amounts of hydrogen substitution [10,15–17]. The literature information on the maximum amount of hydrogen substituted in CI engines under dual-fuel mode are summarized in Table 1 [1,7]. It could be observed from the table that the maximum hydrogen energy share achieved is in the range from 6% to 20% at moderate and high loads (BMEP range: 5 bar–9.2 bar). But, higher amount of hydrogen about 30% can be substituted in the engine at low load (BMEP: 2.2 bar). It could be concluded from the information given in the table that the hydrogen energy share in CI engines decreases with increase in engine load. Hydrogen energy share in a 7.4 kW rated power output of compression ignition engine with water addition at 100% load can be increased from 18.8% to 48.4% [10].

1.1. *Review on knocking problem in dual fuel engines*

Generally knocking in a SI engine occurs due to spontaneous ignition of a portion of the end gas mixture in the combustion chamber ahead of the propagating flame. With the use of hydrogen fuel in internal combustion engines, knocking may occur not only at the end stage of combustion process but also at the earlier stage of combustion [5,15,26]. In hydrogen dual fuel engines, knocking combustion was observed by some of the researchers during early stage of hydrogen combustion [5,15,26]. Knocking during combustion is defined as abnormal combustion phenomenon (abnormal rate of pressure rise) which degrades the engine performance. In dual fuel engines, a gaseous fuel (main fuel: hydrogen) is generally injected into the intake manifold during suction stroke and a liquid fuel (pilot fuel: diesel) is directly injected at the end of compression stroke for initiating the combustion [27–29]. First, the diesel fuel gets self-ignited and act as an ignition source for initiating the combustion of hydrogen-air mixture which is spread around the combustion chamber. In contrast, if combustion of the hydrogen-air mixture is initiated by hydrogen itself prior to diesel fuel injection, the combustion would proceed with severe knock. Karim stated that the primary requirement of any gaseous fuel for satisfactory operation under dual fuel mode is that its mixture with air would not autoignite spontaneously during or following the rapid pilot energy release [30]. Hydrogen addition in a CI engine leads to production of knocking or detonation because of its lower ignition energy, wider flammability range, and shorter quenching distance [31]. With hydrogen fuel, knocking problem could happen not only at the end stage of combustion process as in case of SI engines but also at the earlier stage of combustion process [5,26,32,33]. High amounts of hydrogen supply to CI engines under dual-fuel mode create several problems including abnormal rate of pressure rise, high in-cylinder peak pressure, too advanced combustion, high in-cylinder peak temperature, autoignition of premixed hydrogen-air charge, and loss of available work due to advance in start of combustion [16,34–36]. Severe knocking occurs when hydrogen is self-ignited, unlike hydrogen burning under controlled ignition [15,26]. If knock occurs, the engine would be in severe damage including breakage of piston rings, piston melting, and cracking of cylinder head. Therefore, a dual fuel CI engine has to be operated with lower hydrogen energy share in order to avoid knock. Edwin Geo et al. reported the maximum possible hydrogen energy share without knock was about 12.7% in a single cylinder CI engine (4.4 kW rated power at 1500 rpm) [14]. Yadav et al. substituted the maximum hydrogen energy share of 16.4% in a CI engine (4.4 kW rated power at 1500 rpm) without knocking problem [37]. Szwaja et al. concluded that addition of a small amount of hydrogen (i.e. 5% hydrogen energy share) has no effect on knocking [15]. However, with increasing hydrogen energy share, high frequency component of in-cylinder pressure increased substantially to 4 MPa and resulted knocking at about 17% hydrogen energy share in the engine at rated load (with base compression ratio of 17:1) [15]. Similarly, Chintala and Subramanian reported the knocking tendency in a hydrogen based dual fuel engine (7.4 kW rated power at 1500 rpm with compression ratio of 19.5:1) in terms of ringing intensity and concluded in their investigation that about 19% hydrogen share was the maximum amount that could be substituted in the engine at 100% load for knock free operation (with base compression ratio of 19.5:1) [1]. Saravanan and

Table 1
Literature details of the maximum hydrogen energy share in hydrogen dual-fuel engines.

Reference	Engine details	Amount of hydrogen substitution
Saravanan et al. [18]	Nc = 1, CR = 16.5:1, BMEP = 5.4 bar	6.7% energy share
Edwin et al. [14]	Nc = 1, CR = 17.5:1, BMEP = 5.3 bar	12.7% energy share
Mathur et al. [19]	Nc = 1, CR = 17.5:1, BMEP = 4.9 bar	14.8% energy share (without power loss)
de Morais et al. [20]	Nc = 4, CR = 17:1, BMEP = 6.5 bar	20% energy share
Nguyen and Mikami [21]	Nc = 1, CR = 16.7:1, BMEP = 7.3 bar	10% volume of intake air (or) 15% energy share (approx.)
Bose et al. [22]	Nc = 1, CR = 17.5:1, BMEP = 6.4 bar	hydrogen flow rate of 0.15 kg/h (or)17.6% energy share (approx.)
Yadav et al. [11]	Nc = 1, CR = 17.5:1, BMEP = 5.3 bar	16.4% energy share
Christodoulou and Megaritis [23]	Nc = 4, CR = 18.2:1, BMEP = 9.2 bar	8% volume of intake air (or) 12.8% energy share (approx.)
Saravanan et al. [24]	Nc = 1, CR = 16.5:1, BMEP = 5.4 bar	10% energy share
Shin et al. [25]	Nc = 4, CR = 17.3:1, BMEP = 4.9 bar	10% energy share
Varde et al. [17]	Nc = 1, CR = 17.4:1, BMEP: 5.8 bar	14% hydrogen energy share at 5.8 bar BMEP and 17% share at 4.7 bar BMEP
Szwaja et al. [15]	Nc = 2, CR = 17:1, BMEP: 11.2 bar	17% hydrogen energy share (knock limited hydrogen share)