Research Article

Journal of Environmental Nanotechnology

Effect of Injection Timing on Performance and Emission of a Diesel Engine using Fuelled by Hydrogen Gas

Ram Narayan Bhagat[1*], Kunja Bihari Sahu[1], Surendra Kumar Ghadai[1], Chandra Bhushan Kumar[2] and Ashis Kumar Saha[2]

[1]Department of Mechanical Engineering, Kalinga Institute of Industrial Technology, Bhubaneswar, OR, India
[2]Department of Mechanical Engineering, University College of Engineering and Technology, Vinoba Bhave University, Hazaribag, JH, India
Received: 02.06.2024 Accepted: 22.07.2024 Published: 30.09.2024
*bhagat14@gmail.com

ABSTRACT

The injection timing of pilot fuel in diesel engine working on dual fuel mode with gaseous fuel is a very important parameter at the start of ignition which affects performance and emissions of the engine. In this regard, the experiments were conducted on single cylinder 4-stroke, direct ignition diesel engine with a power of 3.50 kW at a constant speed of 1500 RPM. Kirloskar model TV1 with diesel as pilot fuel and hydrogen as gaseous fuel was employed. Experiments were conducted with the aim to determine the effect of advancing (21° bTDC) and retarding (17° bTDC) diesel fuel injection timing on the engine performance and emissions at various load conditions with the standard injection timing of 19° bTDC. The brake thermal efficiency (BTE) and exhaust emissions like NO_x, carbon monoxide (CO), carbon dioxide (CO_2) and hydrocarbon (HC) were analyzed with hydrogen (H_2) as gaseous fuel. The results showed that dual mode (diesel and H_2 gas) retards injection timing (17° bTDC) and gives a net increase in BTE efficiency at all load conditions with lower (20%) hydrogen substitution. At higher H_2 substitution (40%), BTE is better for dual standard (19° bTDC) injection timing at all load conditions. Further NO_x (ppm), HC (ppm), CO (%) and CO_2 (%) emissions are significantly reduced with dual retard (17° bTDC) injection timing of the pilot fuel.

Keywords: Hydrogen fuel; Injection timing; Dual fuel diesel engine; Ignition delay; Brake thermal efficiency.

1. INTRODUCTION

Usage of conventional fuels has increased in the past decades. In spite of its depletion, the world still faces the challenges of global warming. Approximately 1,71,000 kg of coal, 116, 000, 000 L of gas and 186, 000 L of petroleum oil is being consumed per second (Montgomery, 2017; Watts *et al.* 2019). Unsustainable use of energy sources warns of potential lack of energy in the near future. Internal combustion (IC) engine with power less than 185 kW consumes around one third of the petroleum fuel extracted as well as emits harmful gases, one of the major causes of environmental pollution. Environmental considerations on depletion of fossil fuel have led to numerous investigations on renewable sources of fuel such as ethanol, H_2 and biodiesel. Among these, hydrogen has the capacity to propel the transportation sector and helps in reducing the greenhouse gas (GHG) emissions.

Renewable nature of hydrogen and its high energy content per unit mass make it the best alternative for the petroleum originated fuels. Its combustion gives out no harmful emissions as well as it reduces the reliance on conventional fuels. Recently, interest on using hydrogen as a substitute fuel in compression ignition (CI) engines is rising. Research on the use of hydrogen fuel in the diesel engine working on dual fuel mode targets to lower the exhaust emissions by changing the operating parameters such as, valve timing and atomization rate (Asfar and Hamed, 1998).

Several parameters affect the performance of diesel engine according to research carried out in several countries (Staat and Gateau 1995; Desantes *et al.* 1999; Ganapathy *et al.* 2009). Engine performance based on the effect of injection timing and operating parameters has been extensively examined by researchers. At times, adverse outcomes are observed when the engine is operated on gaseous fuels because of its physio chemical properties. Table 1 shows the various physico- chemical properties of diesel and gaseous fuel hydrogen (H_2) (Hamasaki *et al.* 2001; Ramadhas *et al.* 2005).

Using natural gas as the primary fuel, Nwafor (2007) had examined the injection timing of pilot fuel on the efficiency and emission characteristics of diesel engine. Knocking tendency of the engine limited the maximum quantity of pilot fuel. By increasing the mass flow rates of pilot fuel, knocking tendency was decreased and advanced injection timing compensated for the longer ignition delay and slow burning rate of gaseous fuelled engine.

The need of advanced injection timing came in place of standard dual timing as it not only reduces the delay period, it also decreases carbon monoxide (CO) and carbon dioxide (CO_2) emissions. Brake specific fuel consumption also increases with advanced injection timing. Low speed and low loading conditions favour advanced timing, whereas at high load conditions, the temperature becomes a crucial factor. As the temperature and pressure change considerably close to top dead centre (TDC), fuel injection pressure and fuel injection timing play a critical role in ignition delay and combustion characteristics of the engine (Taylor, 1985; John, 1998).

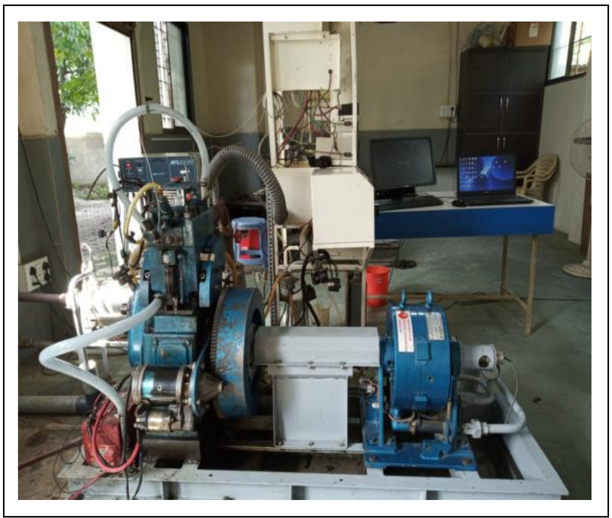

Fig. 1(a): Real setup of the experiment

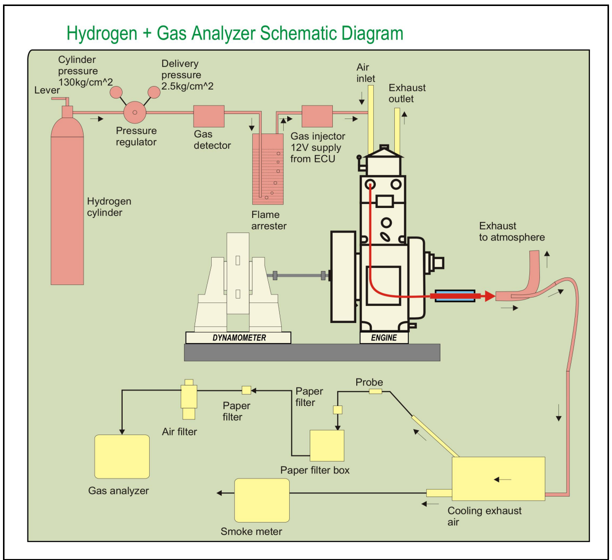

Fig. 1(b): Graphic representation of the experimental setup

Retarding injection timing of pilot fuel resulted in lower efficiency and higher emissions. Nevertheless, advancing the fuel injection timing was a possible way to tackle the problem of lower thermal efficiency and higher carbon-based emissions. In (2019), Pal *et al.* investigated the effect of injection timing of pilot fuel using plastic fuel blending with diesel on the performance and emissions of diesel engine. The engine operation was not smooth with 30% substitution of diesel fuel with plastic fuel. Abd *et al.* (2002) have reported lower thermal efficiency and higher unburned percentage of fuel working with dual fuel engine. However, induction of gases at low load conditions improved the thermal efficiency of the engine, whereas emissions were also reduced with advanced injection timing of pilot fuel.

In the present work, effect of static injection timing on the performance and emission of diesel engine working on dual fuel mode with hydrogen was carried out extensively. Load, static timing, percentage of hydrogen fuel were some of the input variables. Brake thermal efficiency (BTE), carbon dioxide, hydrocarbon, oxides of nitrogen (NO_x), carbon monoxide were the output parameters examined. Comparison between diesel and dual fuel operation on the basis of above variations was conducted.

Table 1. Details about Engine

S. No.	Details of engine specification	
1	Details of engine	Compression ignition TV1 Single cylinder, 4-stroke, Model Kirloskar
2	Cylinder	1
3	Length of stroke (mm)	110
4	Bore of cylinder (mm)	87.50
5	Swept volume (cm^3)	661.45
6	Engine speed (RPM)	1500
7	Compression ratio (CR)	18
8	Injection pressure (bar)	224.11
9	Injection timing before top dead centre (bTDC) (degree)	19
10	Power of engine (kW)	3.50

2. EXPERIMENTAL SETUP AND TESTING

Compression ignition engine of power 3.5 kW operating at a constant speed of 1500 revolution per minute (RPM), single cylinder, 4-stroke was used for the experimental study. A real and systematic view of the setup is represented by Fig. 1(a) and Fig. 1(b), respectively. Parameters and specification of the diesel engine for a better understanding of the experimental study is provided in Table 1. Gaseous fuel (H_2) was supplied to the engine through intake manifold and the diesel fuel supplied by the conventional way. The engine was attached to a cylinder, which stored the H_2 gas at 125 bar and a pressure regulator connected to it regulated the supplied pressure at 2.5 bar.

3. RESULTS AND DISCUSSION

4.1 Brake Thermal Efficiency (BTE)

Fig. 2(a) and 2(b), depict BTE (%) of diesel engine for pure diesel fuel (19° bTDC), dual (diesel and hydrogen fuel) standard (19° bTDC), dual advanced (21° bTDC) and dual retard (17° bTDC) injection timings with various load (2%, 18%, 36%, 53% and 69%) conditions by using diesel as pilot fuel and hydrogen (20% and 40%) as gaseous fuel. The retard injection timing (17°) showed (Fig.2(a)) increase in BTE as compared to pure diesel fuel (19°), dual standard (19°) and advanced (21°) standard at all load conditions. The dual retard injection timing (17%) gave a net increase in BTE at all load conditions. The rise in cylinder temperature with dual retard (17°) in injection timing may be the reason of increase in the emissions at all load conditions.

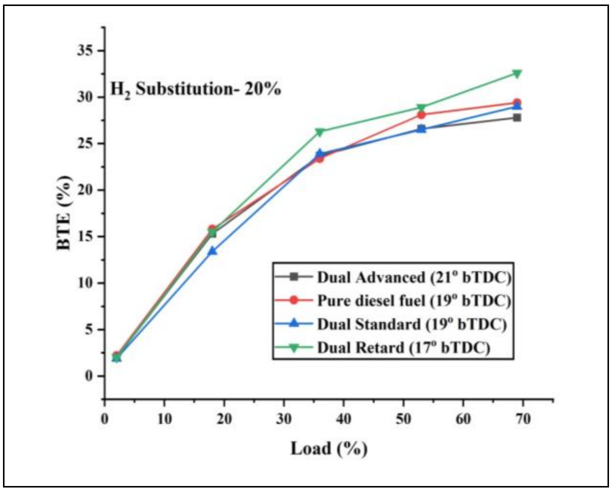

Fig. 2(a): Variation of BTE (%) and load (%) with different injection timings by using 20% H_2 substitution

However, as the gaseous fuel (H_2) substitution increases up to 40% Fig.2(b), the BTE is better for dual standard (19° bTDC) injection timing at all load conditions as compared with dual advanced (21° bTDC), pure diesel fuel (19° bTDC) and dual retard (17° bTDC) standard. At higher load conditions, hydrogen, which has a higher burning velocity and diffusivity, consumes most of the available oxygen. As a result, the diesel fuel burns poorly, leading to a decrease in efficiency when 40% of the fuel is substituted with hydrogen gas (Dhole *et al.* 2014).

4.2. Formation of NO_x

Figs. 3(a) and 3(b) show the plot of NO_x formation for pure diesel fuel (19° bTDC), dual standard (19° bTDC), dual advanced (21° bTDC) and dual retard (17° bTDC) injection timing. At lower substitution of hydrogen fuel (20%), dual retard injection (17°) timing (639 ppm) is evidence for the lower NO_x formation up to medium load (36%) conditions (Fig.3 (a)) as compared with pure diesel fuel (19° bTDC) operation (996 ppm), dual standard (19° bTDC) injection (1041 ppm) and dual advanced (21° bTDC) timing (942 ppm). However, at higher load conditions (69%), lower NO_x (1204 ppm) formation was recorded, with pure diesel fuel operation (19° bTDC) as compared with 2462 ppm, 1945 ppm and 2771 ppm for dual advanced (21° bTDC), dual retard (17° bTDC) and dual standard (19° bTDC) injection timings, respectively.

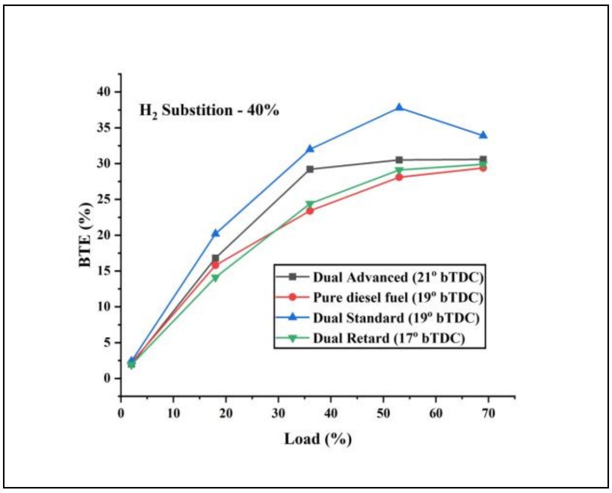

Fig. 2(b): BTE (%) versus load (%) with variation in injection timing by using 40% H_2 substitution

However, the formation of NO_x at higher (40%) substitution of hydrogen fuel was lower for dual advanced (21° bTDC) injection timing (Fig.3(b)), up-to medium load (36%) conditions. The NO_x formation at medium load condition for dual advanced standard (21° bTDC) was 568 (ppm) as compared to 874 (ppm), 613 (ppm), 996 (ppm) with dual retard (17° bTDC), dual standard (19° bTDC) and pure diesel fuel (19° bTDC), respectively. Further at higher load conditions, the formation of NO_x is lower (1204 ppm) for pure diesel fuel (19° bTDC) as compared to 2379 (ppm), 2931 (ppm) and 1370 (ppm) for dual advanced (21° bTDC), dual standard (19° bTDC) and dual retard (17° bTDC) injection timings, respectively.

The oxides of nitrogen, NO and NO_2 when combined is known as NO_x. Reaction between atmospheric nitrogen and oxygen results in the formation of NO_x inside the engine cylinder. High combustion temperatures and near-stoichiometric regions favour the formation of NO_x during fuel spray, which is controlled by local conditions (Liew *et al.* 2010; Koten, 2018).

Induction of hydrogen fuel in diesel engine reduces NO_x formation as claimed by Karagöz *et al.* (2016). There is a direct relation between temperature and load: as the load on the engine increases, the temperature of the cylinder also rises, leading to an increase in NO_x formation (Momirlan and Veziroglu 2005; Bashir *et al.* 2015; Talibi *et al.* 2017). At lower load conditions, hydrogen enrichment consistently reduces NO_x emissions. However, under high load conditions, NO_x emissions initially decrease with the addition of H_2 upto 0.60 litre per minute in the inlet air. Beyond this level, NO_x emissions increase with further hydrogen enrichment. This increase is due to better combustion of the fuel inside the cylinder, which raises the temperature and, consequently, the NO_x emissions.

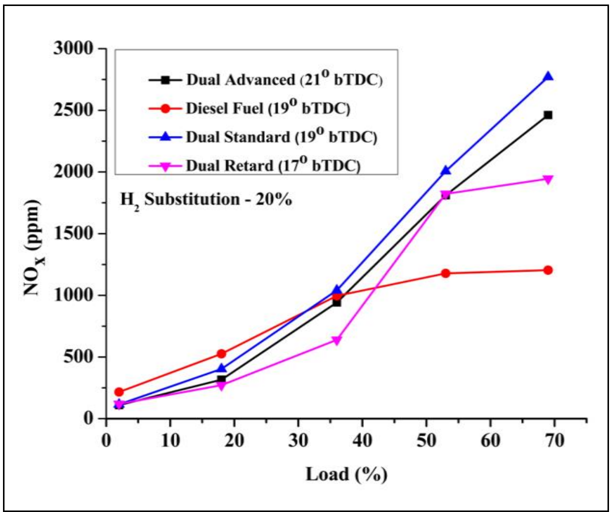

Fig. 3(a): NO_x (ppm) versus load (%) with variation in injection timings for 20% H_2 substitution

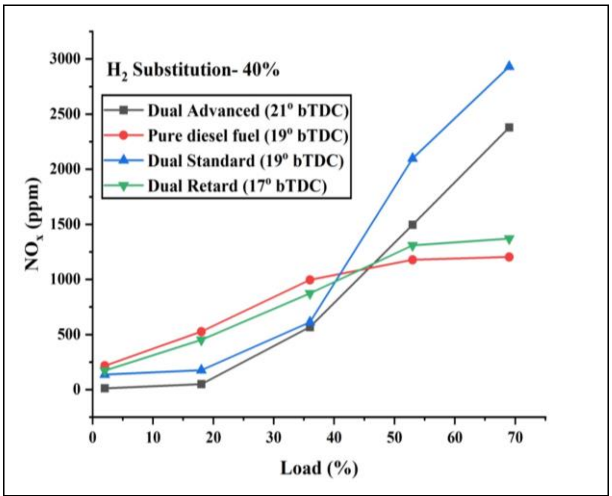

Fig. 3(b): NO_x variation with load (%) for different injection timings at 40% H_2 substitution

NO_x emissions increase as the load increases from 53% to 69%. Large volume of H_2 burns quickly raising the temperature of the cylinder. As more fuel burns with higher engine load, NO_x emissions increase. The peak combustion temperature is high and gases at elevated temperature spend more time in the cylinder, leading to increased NO_x emissions (Saravanan *et al.* 2008; Deb *et al.* 2015).

4.3 Formation of Carbon Monoxide (CO)

Carbon monoxide (CO) in exhaust relates to the fuel-air ratio as well as fuel combustion efficiency inside the cylinder. Figs. 4(a) and 4(b), compared carbon monoxide (%) formation for diesel fuel with the dual standard (19° bTDC), dual advanced (21° bTDC) and dual retard (17° bTDC) injection timings with pure diesel fuel (19° bTDC) operation at various load conditions. The dual retard injection timing (0.041%) showed a significant reduction in CO emission up to 53% load conditions with lower H_2 (20%) substitution, as compared to dual standard (0.075%), dual advanced (0.067%) and pure diesel fuel (0.045%) operation. However, at higher load (69%) conditions, there was marked difference in CO concentration for pure diesel fuel (0.035%) injection timing as compared with retard injection (0.045%) timing, dual advanced (0.102%) and dual standard (0.081%) for dual fuel operation. The rise in cylinder temperature with retard (17°) and pure diesel fuel (19°bTDC) in injection timing may be the reason for decreased CO emissions at all load conditions.

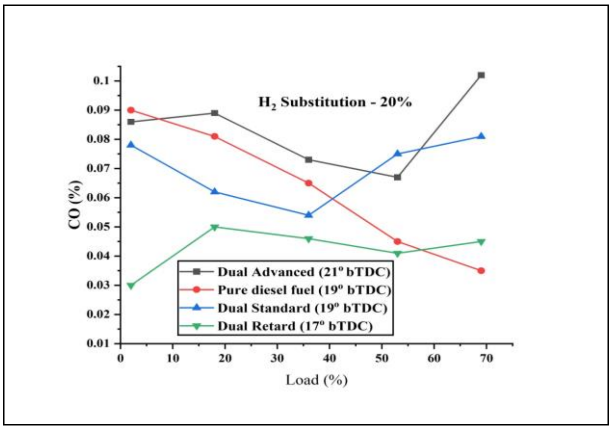

Fig. 4(a): CO (%) versus load (%) with various injection timings at lower (20%) H_2 substitution

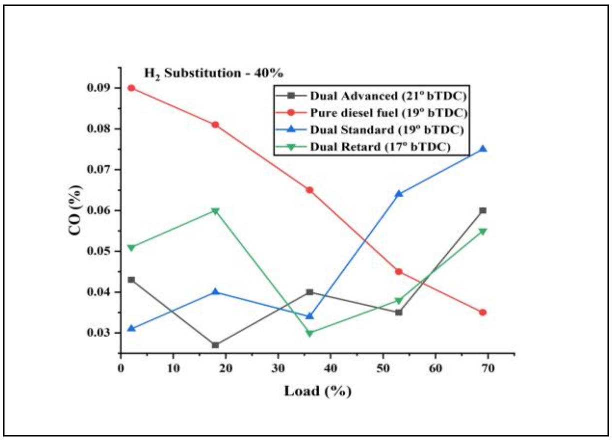

Fig. 4(b): CO (%) variation with load (%) for different injection timings at higher (40%) H_2 substitution

Similar results were obtained at higher load conditions with higher hydrogen (40%) substitution. High flame speed of hydrogen increases cylinder pressure as well as improves combustion. Karagöz *et al.* (2016) explained the decrease in carbon monoxide emissions with dual fuel mode. A homogeneous ignitable mixture forms before combustion because of high diffusion coefficient of hydrogen and increase in oxygen reachability.

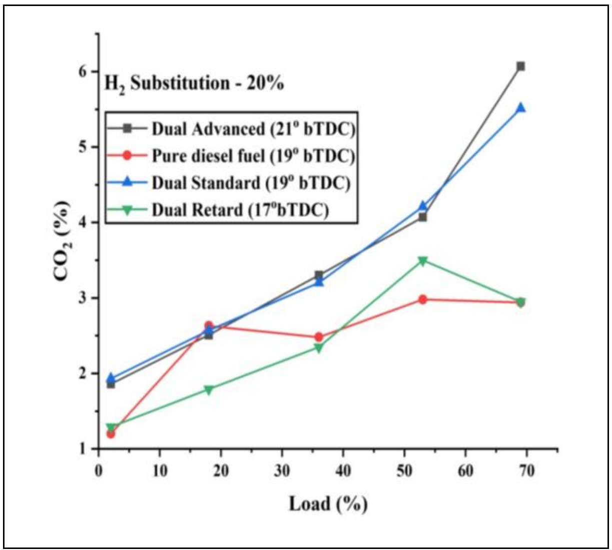

Fig. 5(a): CO_2 (%) versus load (%) with variation in injection timings at lower (20%) H_2 substitution

4.4. Carbon Dioxide (CO_2) Emissions

Figs. 5(a) and 5(b) represent carbon dioxide (CO_2) emissions. The retard injection timing (17° bTDC) produced low emission of CO_2 (2.35%) with lower hydrogen (20%) substitution as compared with dual advanced (3.30%), pure diesel fuel (2.48%) and dual standard (3.20%) injection timing at medium load (36%) load conditions. Emissions of CO_2 was high in exhaust, with engine running on dual advanced (6.07%) injection timing with dual fuel mode, at high load (69%) conditions. Combustion efficiency of the system was measured in terms of CO_2 emission. High CO_2 emissions and less hydrocarbon emissions are desirable under any working mode. Further with 40% hydrogen substitution of gaseous fuel, dual advanced (0.81%) showed diminished production at lower load (2%) conditions as compared with pure diesel fuel (1.2%), dual standard (1.16%) and dual retard (1.64%) injection timings. However, lower production of carbon dioxide was noted at higher load (69%) conditions.

Lower CO_2 emissions were observed because of hydrogen fuel. Combustion duration shortens but combustion efficiency rises depending on the increase in H/C ratio in total fuel with hydrogen. The high diffusion coefficient of hydrogen helps in improving the heterogeneity of diesel fuel as well as forms a uniform pre-mixed ignitable mixture. Specific CO_2 emissions cut down with hydrogen addition (White *et al.* 2006; Szwaja and Grab, 2009; Ghazal, 2013). When the load on the engine was high (69%), CO_2 emission increased (as the engine needs more fuel to satisfy the load). Conversion of CO to CO_2 occurred more due to high temperature at high load condition (Yilmaz and Gumus, 2018).

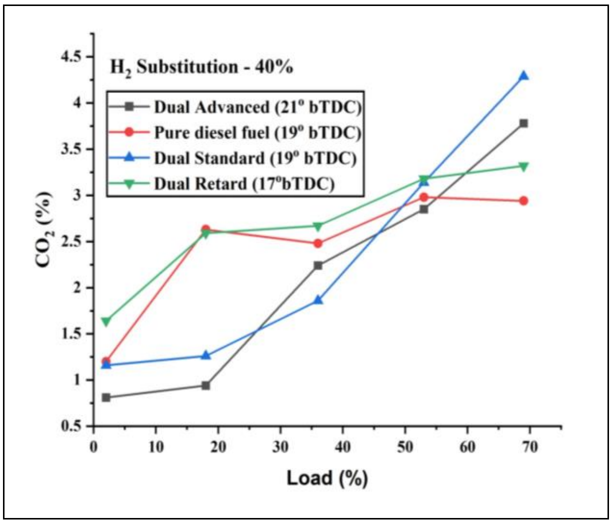

Fig. 5(b): CO_2 (%) versus load (%) with different injection timings at higher (40%) H_2 substitution

4.5. Hydrocarbon Emissions

Fig. 6(a) and 6(b) depict hydrocarbon (HC) emissions of the diesel engine operating with hydrogen fuel for conditions like dual advance (21° bTDC), pure diesel fuel (19° bTDC), dual standard (19° bTDC) and dual retard (17° bTDC) at various load conditions. The parent diesel fuel mode (19° bTDC), gave the least possible HC emission (3 ppm) at lower load (2% of full load) conditions as compared with dual advanced (31 ppm), dual retard (25 ppm) and dual standard (28 ppm) injection timings with lower (20%) hydrogen substitution. Further, beyond low load (2%) conditions, dual retard (17° bTDC) showed lowest HC emission (17 ppm) up to 53% load conditions as compared with dual advanced (32 ppm), dual standard (38 ppm) and pure diesel fuel (24 ppm) injection timing. However, at higher load (69%) conditions, pure diesel fuel (13 ppm) showed lowest HC emission as compared with dual advance (47 ppm), dual standard (43 ppm) and dual retard (28 ppm) at lower (20%) substitution of H_2 fuel (Fig. 6(a)).

The plots of HC emission with higher (40%) substitution of H_2 fuel for different injection timings (Fig. 6(b)) were comparable as presented in Fig. 6(a). Pure diesel fuel operation (19° bTDC), offered a notable decrease in HC at lower and higher load conditions. The HC emission at lower (2%) load conditions (3 ppm) was less as compared with dual advance (6 ppm), dual standard (17 ppm) and dual retard (7 ppm). Further, at higher load (13 ppm) conditions HC emission was less as compared with dual advanced (29 ppm), dual retard (14 ppm) and dual standard (19^{o} bTDC). However, at medium load (36%) conditions, HC emissions were lowest for dual standard (23 ppm) injection timings as compared with dual advanced (24 ppm), dual retard (27 ppm) and pure diesel fuel (26 ppm) injection timings.

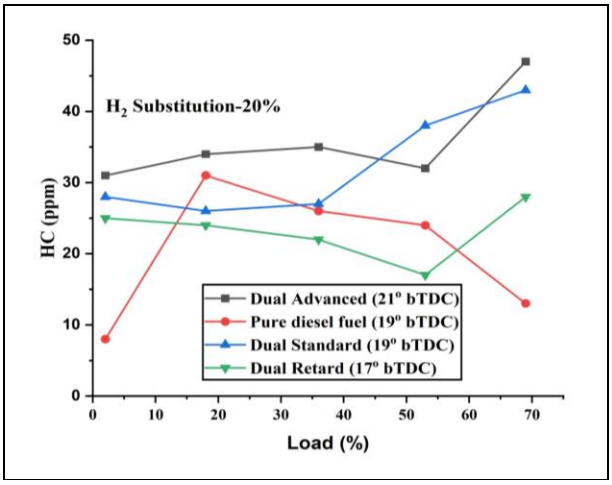

Fig. 6(a): Hydrocarbon (ppm) versus load (%) and injection timings with lower (20%) substitution of gaseous fuel (H_2)

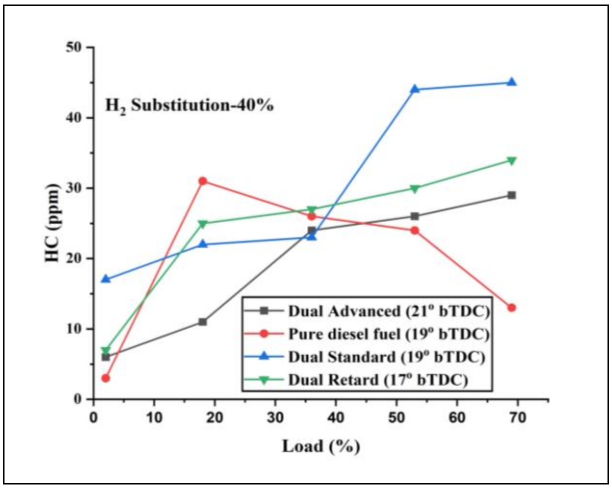

Fig. 6(b): Hydrocarbon (ppm) versus load (%) and injection timings at higher (40%) substitution of gaseous fuel (H_2)

The emission of hydrocarbon in the exhaust showed an efficient combustion of diesel fuel with pure diesel fuel operation (19^{o} bTDC). The experimental observations showed that larger percentage of hydrogen gas runaway at low (2%) and high load (69%) with dual fuel mode conditions at low and high substitution of gaseous fuel (H_2) due to slow burning rates of hydrogen gas. As the mass flow rate of gaseous fuel (H_2) was predetermined, it was impossible to reduce diesel fuel at a desired limit. The hydrocarbon emissions in diesel engine with hydrogen fuel were dependent on a number of factors like quenching, lean combustion, wall wetting and poor mixture preparation. Overlapping of the wider valve of diesel engine resulted in more amount of fresh discharge with the combustion product since a mixture of gas and air gets inducted during the induction process (Nwafor, 2007).

4. CONCLUSION

In this study, evaluation of NO_x, CO, CO_2, HC emissions and brake thermal efficiency was carried out at variable load conditions of the diesel engine by changing the mass flow rate of gaseous hydrogen fuel. Through intake manifold gaseous fuel was inducted and the diesel fuel was directly injected to the combustion chamber. Each test was performed and analysed with 20% and 40% hydrogen substitution. Following conclusions were drawn from the experiments conducted:

Addition of gaseous fuel (H_2) had a positive effect on BTE (%) as well as exhaust emissions of the engine. However, emission of NO_x decreased at lower and medium loads with addition of H_2 fuel at different injection timings but it increased with 69% load as compared with diesel fuel operations. Further, dual retard injection (17^{o} bTDC) timing, gave net positive effect on the BTE (%) and reduced the harmful emissions like NO_x, CO, CO_2 and hydrocarbons as compared with pure diesel fuel injection timing. This could be because of increased mean gas temperature during the time of injection of diesel fuel.

FUNDING

There is no funding source.

CONFLICT OF INTEREST

The authors declared no conflict of interest in this manuscript regarding publication.

REFERENCES

Abd, A. G .H., Soliman, H. A., Badr, O. A., and Abd, R. M. F., Effect of injection timing on the performance of a dual fuel engine, *Energy Convers Manag*, 43(2), 269–277(2002)

Asfar, K.R., and Hamed, H., Combustion of fuel blends, *Energy Convers Manag*, 39(10), 1081–1093(1998). https://doi.org/10.1016/S0196-8904(97)00034-4

Bashir, M., Ali, H., Ali, M., and Siddiqui, A., An experimental investigation of performance of photovoltaic modules in Pakistan, *Therm Sci*, 19(suppl. 2), 525–534(2015). https://doi.org/10.2298/TSCI130613134B

Deb, M., Sastry, G.R.K., Bose, P.K., and Banerjee, R., An experimental study on combustion, performance and emission analysis of a single cylinder, 4-stroke DI-diesel engine using hydrogen in dual fuel mode of operation, *Int J Hydrog Energy*, 40(27), 8586–8598(2015). https://doi.org/10.1016/j.ijhydene.2015.04.125

Desantes, J. M., Arrègle, J., Ruiz, S., and Delage, A., Characterisation of the Injection-Combustion Process in a D.I. Diesel Engine Running with Rape Oil Methyl Ester,. 1999-01–1497 (1999)

Dhole, A.E., Yarasu, R.B., Lata, D.B., and Priyam, A., Effect on performance and emissions of a dual fuel diesel engine using hydrogen and producer gas as secondary fuels, *Int. J. Hydrog Energy*, 39(15), 8087–8097(2014). https://doi.org/10.1016/j.ijhydene.2014.03.085

Ganapathy, T., Murugesan, K., and Gakkhar, R. P., Performance optimization of Jatropha biodiesel engine model using Taguchi approach, *Appl. Energy*, 86(11), 2476–2486(2009). https://doi.org/10.1016/j.apenergy.2009.02.008

Ghazal, O. H., Performance and combustion characteristic of CI engine fueled with hydrogen enriched diesel, *Int. J. Hydrog. Energy*, 38(35), 15469–15476(2013). https://doi.org/10.1016/j.ijhydene.2013.09.037

Hamasaki, K., Tajima, H., Takasaki, K., Satohira, K., Enomoto, M. and Egawa, H., Utilization of Waste Vegetable Oil Methyl Ester for Diesel Fuel,. 2001-01–2021 (2001)

John, B. H., Internal combustion engine fundamentals. McGraw Hill, (1998)

Karagöz, Y., Sandalcı, T., Yüksek, L., Dalkılıç, A. S. and Wongwises, S., Effect of hydrogen–diesel dual-fuel usage on performance, emissions and diesel combustion in diesel engines, *Adv. Mech. Eng.*, 8(8), 168781401666445(2016). https://doi.org/10.1177/1687814016664458

Koten, H., Hydrogen effects on the diesel engine performance and emissions, *Int. J. Hydrog. Energy*, 43(22), 10511–10519(2018). https://doi.org/10.1016/j.ijhydene.2018.04.146

Liew, C., Li, H., Nuszkowski, J., Liu, S., Gatts, T., Atkinson, R. and Clark, N., An experimental investigation of the combustion process of a heavy-duty diesel engine enriched with H2, *Int. J. Hydrog. Energy*, 35(20), 11357–11365(2010). https://doi.org/10.1016/j.ijhydene.2010.06.023

Momirlan, M. and Veziroglu, T., The properties of hydrogen as fuel tomorrow in sustainable energy system for a cleaner planet, *Int. J. Hydrog. Energy*, 30(7), 795–802(2005). https://doi.org/10.1016/j.ijhydene.2004.10.011

Montgomery, H., Preventing the progression of climate change: one drug or polypill?, *Biofuel Res. J.*, 4(1), 536–536(2017). https://doi.org/10.18331/BRJ2017.4.1.2

Nwafor, O. M. I., Effect of advanced injection timing on emission characteristics of diesel engine running on natural gas, *Renew Energy*, 32(14), 2361–2368(2007). https://doi.org/10.1016/j.renene.2006.12.006

Pal, S., Chintala, V., Kumar Sharma, A., Ghodke, P., Kumar, S. and Kumar, P., Effect of injection timing on performance and emission characteristics of single cylinder diesel engine running on blends of diesel and waste plastic fuels, *Mater. Today Proc.*, 17209–215(2019). https://doi.org/10.1016/j.matpr.2019.06.420

Ramadhas, A. S., Muraleedharan, C. and Jayaraj, S., Performance and emission evaluation of a diesel engine fueled with methyl esters of rubber seed oil, *Renew Energy*, 30(12), 1789–1800(2005). https://doi.org/10.1016/j.renene.2005.01.009

Saravanan, N., Nagarajan, G. and Narayanasamy, S., An experimental investigation on DI diesel engine with hydrogen fuel, *Renew Energy*, 33(3), 415–421(2008). https://doi.org/10.1016/j.renene.2007.03.016

Staat, F. and Gateau, P., The Effects of Rapeseed Oil Methyl Ester on Diesel Engine Performance, Exhaust Emissions and Long-Term Behavior - A Summary of Three Years of Experimentation,. 950053 (1995)

Szwaja, S. and Grab-Rogalinski, K., Hydrogen combustion in a compression ignition diesel engine, *Int J Hydrog Energy*, 34(10), 4413–4421(2009). https://doi.org/10.1016/j.ijhydene.2009.03.020

Talibi, M., Hellier, P., and Ladommatos, N., The effect of varying EGR and intake air boost on hydrogen-diesel co-combustion in CI engines, *Int. J. Hydrog Energy*, 42(9), 6369–6383(2017). https://doi.org/10.1016/j.ijhydene.2016.11.207

Taylor, C. F., The internal-combustion engine in theory and practice. Cambridge, MIT Press, (1985)

Watts, N., Amann, M., Arnell, N., Ayeb-Karlsson, S., Belesova, K., Boykoff, M., Byass, P., Cai, W., Campbell-Lendrum, D., Capstick, S., Chambers, J., Dalin, C., Daly, M., Dasandi, N., Davies, M., Drummond, P., Dubrow, R., Ebi, K. L., Eckelman, M., Ekins, P., Escobar, L.E., Fernandez Montoya, L., Georgeson, L., Graham, H., Haggar, P., Hamilton, I., Hartinger, S., Hess, J., Kelman, I., Kiesewetter, G., Kjellstrom, T., Kniveton, D., Lemke, B., Liu, Y., Lott, M., Lowe, R., Sewe, M. O., Martinez-Urtaza, J., Maslin, M., McAllister, L., McGushin, A., Jankin Mikhaylov, S., Milner, J., Moradi-Lakeh, M., Morrissey, K., Murray, K., Munzert, S., Nilsson, M., Neville, T., Oreszczyn, T., Owfi, F., Pearman, O., Pencheon, D., Phung, D., Pye, S., Quinn, R., Rabbaniha, M., Robinson, E., Rocklöv, J., Semenza, J.C., Sherman, J., Shumake-Guillemot, J., Tabatabaei, M., Taylor, J., Trinanes, J., Wilkinson, P., Costello, A., Gong, P. and Montgomery, H., The

2019 report of The Lancet Countdown on health and climate change: ensuring that the health of a child born today is not defined by a changing climate, *The Lancet*, 394(10211), 1836–1878(2019). https://doi.org/10.1016/S0140-6736(19)32596-6

White, C., Steeper, R., and Lutz, A., The hydrogen-fueled internal combustion engine: a technical review, *Int. J. Hydrog Energy*, 31(10), 1292–1305(2006). https://doi.org/10.1016/j.ijhydene.2005.12.001

Yilmaz, I. T. and Gumus, M., Effects of hydrogen addition to the intake air on performance and emissions of common rail diesel engine, *Energy*, 1421104–1113(2018). https://doi.org/10.1016/j.energy.2017.10.018