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An experimental investigation of central injection based hydrogen dual fuel spark ignition engine

Automobile industry is steadily moving away from traditional fossil fuels towards more sustainable and eco-friendly alternatives. Alternative to traditional fuels include hydrogen, which has the potential to satisfy the current energy demand in automotive field. However, design and fabrication of engines using pure hydrogen has many technological challenges. Combination of traditional fuels and hydrogen can reduce engine emissions including hydrocarbon (HC), carbon monoxide (CO), significant decrease in the carbon di oxide and methane. Additionally, the dual fuel engines provide the necessary savings with higher specific fuel consumption. However, dual fuel engines have a number of disadvantages such as pre-ignition, increase in NO_x emissions, lower brake power and reduced brake thermal efficiency. In the present study, a single cylinder 110 cc spark ignition engine is procured and is retrofitted to admit hydrogen gas at specified pressures. The engine performance is measured using a mechanical load specifically designed for the engine. Brake power, torque, brake thermal efficiency, brake specific fuel consumption and other performance parameters are measured. The results from the engine is compared to the MATLAB model to study the inner working of the dual fuel engine to understand the pre-ignition characteristics. The results follow similar trends presented in the literature, the deviations in our study can be attributed to the type of engine selected and experimental errors. The highest increase in brake thermal efficiency and brake specific fuel consumption is 15.6 % and 22.5% respectively at 3500 rpm. The CO, and CO_2 emissions have reduced by 86%, 26% respectively and increase of 16% in NO_x is observed due to increase in combustion temperature.

Keywords: Spark ignition engine, hydrogen central injection, brake thermal efficiency, brake specific fuel consumption.

1.0 Introduction

The introduction of electric vehicles the internal combustion engine (ICE) powered vehicles are facing stiff competition. The market share and adoption of electric vehicles including battery electric vehicles (BEV), hybrid electric vehicles (HEV), and plug-in hybrid electric vehicles (PHEV) depend on a variety of factors. These factors include the payback period, the total cost of ownership, battery life cycle, charging times and electric charging infrastructure (Palmer et al. 2018). Market penetration of electric vehicles is bolstered with the government incentives and is expected to improve in the coming decade. However, ICE based on petroleum fuels are essential for the applications that cater to agriculture, defense, construction, maritime transport and other heavy industries. ICE based vehicles and equipment converts the chemical energy in the high energy density fuel to useful mechanical work. The storage of fuels are still easier compared to storage of electric potential in batteries. The ever increasing cost, and the decline in the availability of fossil fuels has forced the industry to look into alternative to liquid fuel petroleum products. And ICE can operate with a combination of alternative fuels including, ammonia (Cardoso et al. 2021), biogas(Musthafa 2020), natural gas (Krishna 2018), hydrogen (Singh 2020), acetylene (Masood et al. 2017), methanol (Huang et al. 2021), producer gas, vegetable oil or biodiesel. This versatility of ICE can cater to niche applications in further technological generations. None the less, the emissions from these ICEs need to be studied, and reduction in harmful gases released to atmosphere has to be reduced significantly (Joshi and Gosai n.d.).

2.0 Types of fuels and their comparison

The fuel properties have a significant role in charge mixture combustion behaviour. The comparison of fuel properties are shown in Table 1. It can be seen that compared to the liquid fuels, hydrogen is extremely low density fuel with high lower heating value. This poses challenges in fuel blending in SI engine. Strategies commonly employed includes the direct injection of hydrogen into the engine cylinder and the central injection of hydrogen through the carburetor of the SI engine.

The exhaust from traditional fuels used in automotive applications such as petrol and diesel contain carbon dioxide, unburnt hydrocarbons and carbon monoxide. In particular, the diesel engines produce more pollutants compared to petrol

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Table 1: Comparison of common properties of fuels

Fuel properties	Diesel	Petrol	Hydrogen
Chemical formula	$C_{12}H_{26}$	C_8H_{18}	H_2
Density, kg/m^3	815	720	0.08988
Mol. Wt, kg/kmol	170	114	2.016
LHV, MJ/kg	42.5	42	119.96
Stoich. A/F, kg/kg	14.5	14.7	34.3
Ig. T, ^oC	355	-43	500
Ad. flame temp. ^oC	1720	2104	2210
S %	0.5	0.5	0

engines. The ICE produces higher CO_2, CO, NO_x, and unburnt hydrocarbons (UHC) during acceleration of the vehicle (Šarkan, Kuranc, and Kuèera 2019). In particular diesel engines produce higher NO_x and particulate matter emissions compared to petrol engine for the same work delivered. Researchers therefore have focused on hydrogen introduction to diesel engines using either diesel or diesel blends as fuel rather than petrol engines.

Many experimental and numerical studies of compression ignition diesel engines available in literature. The beneficial effects of introduction of hydrogen gas to a compression ignition (CI) is reported to be reduced with the use of exhaust gas recirculation (Rahman et al. 2017). In direct injection technique it is reported that the hydrogen introduction to a CI engine at an crank angle of 10^o before TDC produces the best results with reduction in O_2 emissions. EGT increases by 10% and IMEP increases due to increase in peak pressure (Adnan, Masjuki, and Mahlia 2009). Numerical investigation

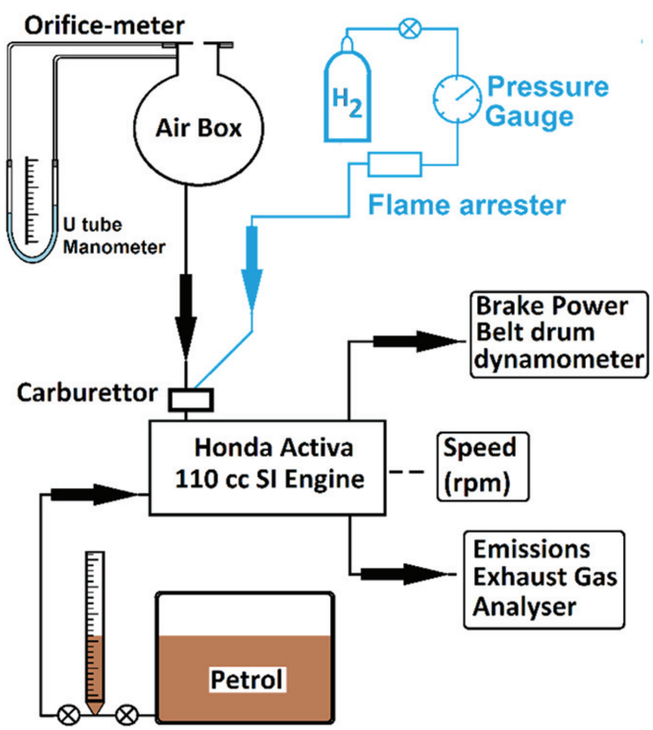

Fig.1: Schematic of a SI engine test rig

of tri-fuel engine with diesel, methane and hydrogen fuel is reported to show improved flame propagation of methane with increase in the H_2 : CH_4 ratio (Mansor, Abbood, and Mohamad 2017). An experimentation with modified SI engine using blend of ethanol and hydrogen with central injection is reported to have reduced the UHC in the range of 15 to 40% (Yousufuddin and Mehdi 2008). An increase in engine speed, BTE, EGT, NO_x is reported due to hydrogen direct injection through manifold in a CI engine (Hamdan et al. 2015). It is recommended that the hydrogen injection should be after the diesel injection process (Hamdan et al. 2015). The highest increase in BTE is reported in a CI engine at 75% load with reduced CO, CO_2 and NO_x emissions (Loni et al. 2021).

Similar to CI engines, SI engines have shown an increase in BTE, BSFC, and NO_x and reduction in UHC (Baiju B, Gokul S, Schin Sunny, Ranjith C. M 2014). Load tests on SI engines with hydrogen injection is reported to reduce UHC more prominently during the no load condition, 33% reduction in CO emissions, and increased BTE is reported (H. Razali, K. Sopian, S. Mat 2016). To better understand the performance of SI engine with hydrogen injection, a MATLAB simulation is performed.

3.0 Hydrogen injection MATLAB model

Prior to the start of the design and fabrication of components for the retrofit of the engine, a mathematical simulation model was developed to understand the working of such an engine. A generic engine block was connected with throttle position, and fuel indicator. The engine shaft was connected to a torque converter, simple gear mechanism, rear wheel and the vehicle dynamics block. The model was able to provide the engine power developed and the velocity. The engine starting power is used to calculate the BTE, and other relevant engine parameters.

4.0 SI engine test rig

The schematic of the test set up is shown in Fig.1. The air intake, is measured using the orificemeter and a air box arrangement, fuel flow rate is manually measured using graduated cylinder flow meter, hydrogen pressure gauge and rotameter designed for hydrogen flow is used to measure the flow of hydrogen. The brake power is measured with belt drum dynamometer, engine speed is measured with a non-contact type tachometer, and emissions are measured using exhaust gas analyser.

The hydrogen and air mixing was carried out in a component attached to the air inlet side of the carburetor. To avoid the hydrogen backflow, detailed steady state flow analysis was carried out using ANSYS fluent software.

Fig.2 shows the details of the simulation. Fig.2a shows the CAD model of the mixer, 2b shows the fluid flow passage in the mixer. Fig.2c shows the fluid flow lines, as can be seen the lines are not intersecting and mixing process is smooth.

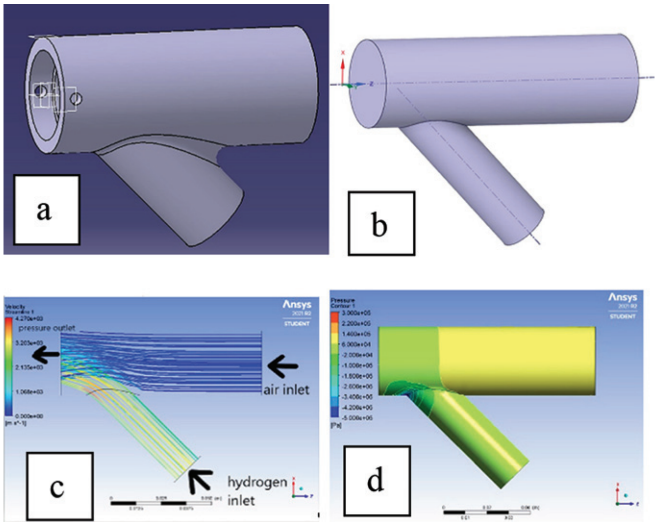

Fig.2: (a) component (b) flow passage (c) flow lines and (d) pressure contours of hydrogen and air mixer

Fig.2d shows the pressure distribution in the mixer. There are no adverse pressure differences and a slight negative pressure at the flow direction corner of the intersection. This indicates the existence of a recirculation zone closed to the inlet of the carburetor air intake.

Fig.3 shows the image of the fabricated hydrogen and air mixer. The blueline in the image shows the hydrogen connection and the orange flexible tube connection is the air intake from the air box. The material used for the mixer is aluminium with grub screws used for connection with the carburetor. Fig.3 also shows the acetylene in line flame arrester used in the hydrogen line before the mixer.

Following the assembly, retrofit of the engine, tests were performed at constant speeds, with and without the injection of hydrogen. The BTE, and BSFC are calculated using the following relations:

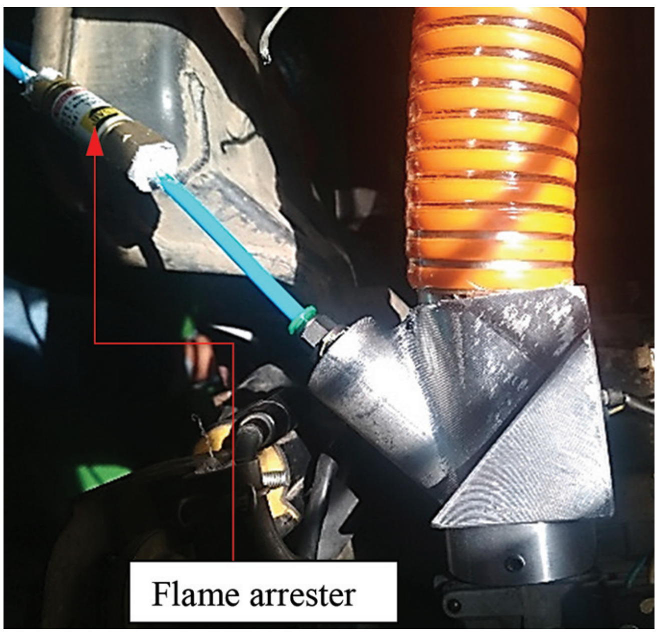

Fig.3: Image of hydrogen and air mixer

$$BTE = \frac{BP}{\dot{m}_f \times C_v}$$

where, *BP* is the measured brake power, $\dot{m}_f$ is the fuel mass flow rate, a combination of both petrol and hydrogen fuel is considered. However, the mass of hydrogen is miniscule compared to that of the petrol mass intake. C_v is the calorific value of the fuel, is calculated based on the rule of mixture method.

$$BSFC = \frac{\dot{m}_f}{P}$$

where, is the fuel consumed in grams, and is the power developed by the engine.

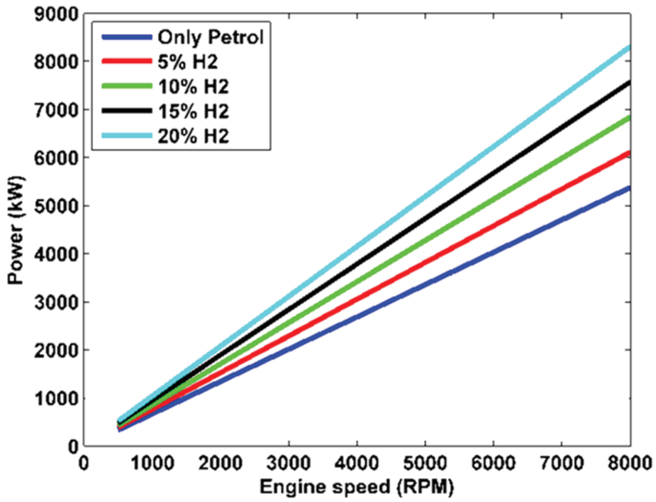

Fig.4: Power versus engine speed calculated by the MATLAB Simulink simulation

5.0 MATLAB simulation and engine test results

Fig.4 shows the results from the MATLAB simulations. It can be seen that an increase in the power output is clearly shown in the simulation and the power developed increases linearly till 8000 rpm as specified by the engine manufacturer. The simulation results clarified the engine behaviour with and without the inclusion of hydrogen. The power increase due to hydrogen inclusion increases with the increase in engine speed. This behaviour can be possible due to the rapid combustion of hydrogen, the increased engine combustion temperature. The increase in NO_x production further corroborates the engine behaviour predicted by the model. But due to practical considerations, engine condition, design, the introduction of hydrogen beyond 10% is avoided in this study.

Fig.5 shows the plot of BTE vs engine speed comparison for engine running only on petrol and with hydrogen inclusion. An increase of 15.6% at 3500 rpm, and 6.8% in 4500 rpm can be observed from the graph. The engine speed increases in response to introduction of hydrogen. But as the

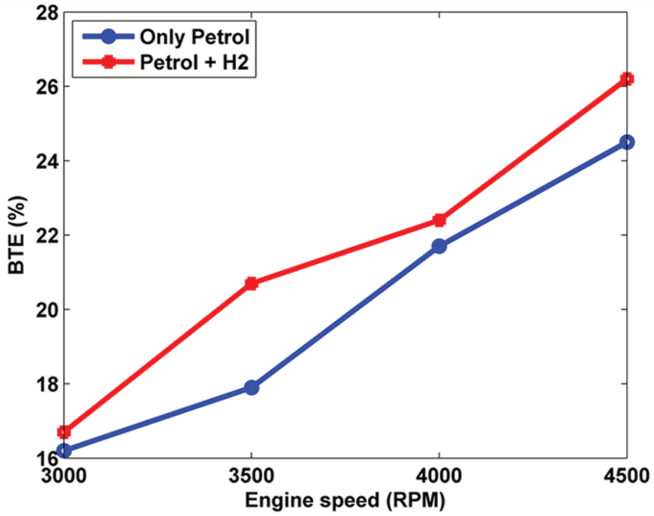

Fig.5: Brake thermal efficiency vs engine speed

speed is maintained constant, the petrol consumption reduces due to the dual fuel introduction. This is the primary reason for the increase in the BTE for hydrogen dual fuel engine.

BSFC trend for hydrogen based dual fuel SI engine is shown in Fig.6. The hydrogen introduction has reduced BSFC considerably. In particular a decrease of 22.4% at 3500 rpm can be observed from the graph. The fuel consumption curves show similar trends as shown in literature (Navale, Kulkarni, and Thipse 2018)

Exhaust gas analysis was conducted for the engine running with petrol and with hydrogen inclusion. A significant decrease was found in CO and CO_2 emissions. CO emissions were reduced by 86%, and CO_2 was reduced by 26%. The NO_x emissions was increased by 16%. The increase in NO_x can be attributed to the increase in combustion temperature due to the introduction of hydrogen.

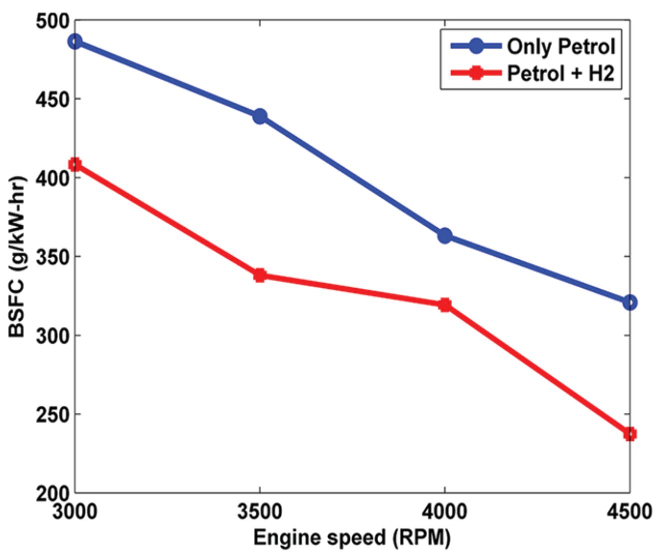

Fig.6: BSFC vs. engine speed

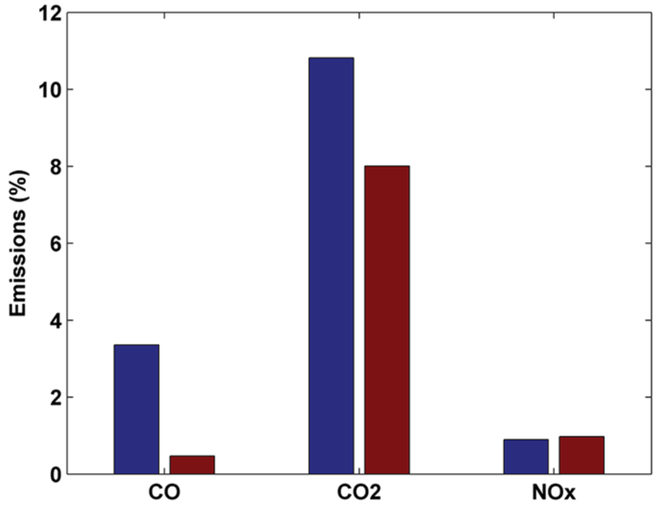

Fig.7: The results from exhaust gas analysis

6.0 Conclusions

Experimental set up and engine: Honda 110 cc engine selected, existing test set up is modified to accommodate the engine. The initial tests on the engine showed the power developed is lower than the MATLAB simulations. This could be due to the condition of the engine, wear characteristics of used engine. Intake manifold for carburetor is modified based on the fluid flow simulation. Hydrogen intake at 45% inlet angle is found to be safe without any hydrogen backflow. Tests are performed with and without hydrogen inlet, with fuel volumetric flow rate, air intake measurement at varying load conditions. The experiments are conducted using 3 lean mixtures with carburetor adjustment. Engine shows higher brake thermal efficiency values for the speeds between 3000 to 5000 rpm. The brake specific fuel consumption is similarly lower for the engine using H_2. The best performance was found to be at 3500 rpm, which is beneficial as the maximum usage of the engine is around this speed. Emission tests conducted clearly show a big difference in CO and CO_2 emissions as expected. NO_x emissions increases marginally. This could be due to the increase in the combustion temperature of the engine.

7.0 Nomenclature

BTE	Brake thermal efficiency [%]
BSFC	Brake specific fuel consumption [BSFC]
BTDC	Before top dead center
CI	Compression ignition
EGR	Exhaust gas recirculation
EGT	Exhaust gas temperature [^{o}C]
SI	Spark ignition

References

1. Adnan, R., H. H. Masjuki, and T. M.I. Mahlia. (2009): “An Experimental Investigation of Unmodified Di

Diesel Engine with Hydrogen Addition." ICEE 2009 - Proceeding 2009 3rd International Conference on Energy and Environment: Advancement Towards Global Sustainability (December): 45–49.

2. Baiju B, Gokul S, Schin Sunny, Ranjith C. M, Sathyamoorthy U. (2014): "Hydrogen Petrol Mixture SI Engine." *International Journal of Engineering and Advanced Technology* (IJEAT) 3(6): 2249–8958.
3. Cardoso, João Sousa et al. (2021): "Ammonia as an Energy Vector: Current and Future Prospects for Low-Carbon Fuel Applications in Internal Combustion Engines." *Journal of Cleaner Production* 296.
4. H. Razali, K. Sopian, S. Mat, M.R.A. Mansor and N. Amon. (2016): "Hydrogen Mixture with Gasoline for Conventional Motorcycles and Effect on Mass Flow Rate, Brake Thermal Efficiency and Emissions." 13(July): 3681–95.
5. Hamdan, Mohammad O., Mohamed Y.E. Selim, Salah A.B. Al-Omari, and Emad Elnajjar. (2015): "Hydrogen Supplement Co-Combustion with Diesel in Compression Ignition Engine." *Renewable Energy* 82: 54–60.
6. Huang, Yuhan et al. (2021): 143 Renewable and Sustainable Energy Reviews Dual Injection: An Effective and Efficient Technology to Use Renewable Fuels in Spark Ignition Engines.
7. Joshi, Dhruv S, and Dipak C Gosai. "Performance Improvement and Exhaust Emission Control on IC Engine Using Multi Fuels: A Review." 166(I).
8. Krishna, Vemula M. (2018): "Emissions Control and Performance Evaluation of Spark Ignition Engine with Oxy-Hydrogen Blending." *International Journal of Heat and Technology* 36(1): 118–24.
9. Loni, Reyhaneh et al. (2021): "A Review of Industrial Waste Heat Recovery System for Power Generation with Organic Rankine Cycle: Recent Challenges and Future Outlook." *Journal of Cleaner Production* 287: 125070. https://doi.org/10.1016/j.jclepro.2020.125070.
10. Mansor, Mohd Radzi Abu, Mahmood Merzah Abbood, and Taib Iskandar Mohamad. (2017): "The Influence of Varying Hydrogen-Methane-Diesel Mixture Ratio on the Combustion Characteristics and Emissions of a Direct Injection Diesel Engine." *Fuel* 190: 281–91. http://dx.doi.org/10.1016/j.fuel.2016.11.010.
11. Masood, Mohammed et al. (2017): "Acetylene Used as a Fuel in SI Engine." 3(2): 294–97.
12. Musthafa, M. Mohamed. (2020): "Production of Biogas from Multiple Feedstocks and Its Application as a Fuel for Spark Ignition Engines - A Review." *European Journal of Sustainable Development Research* 4(3): 4–9.
13. Navale, S.J., R. R. Kulkarni, and S.S. Thipse. (2018): "Performance Prediction of a Single Cylinder Hydrogen Fuelled Spark Ignition Engine Using Simulation." *In SSRN Electronic Journal*.
14. Palmer, Kate, James E. Tate, Zia Wadud, and John Nellthorp. (2018): "Total Cost of Ownership and Market Share for Hybrid and Electric Vehicles in the UK, US and Japan." Applied Energy 209(July 2017): 108–19. https://doi.org/10.1016/j.apenergy.2017.10.089.
15. Rahman, Md Atiqur, A. M. Ruhul, M. A. Aziz, and Raju Ahmed. (2017): "Experimental Exploration of Hydrogen Enrichment in a Dual Fuel CI Engine with Exhaust Gas Recirculation." *International Journal of Hydrogen Energy* 42(8): 5400–5409. http://dx.doi.org/10.1016/j.ijhydene.2016.11.109.
16. Šarkan, B., A. Kuranc, and Kuèera. (2019): "Calculations of Exhaust Emissions Produced by Vehicle with Petrol Engine in Urban Area." IOP Conference Series: Materials Science and Engineering 710(1).
17. Singh, Abhishek. (2020): "Advanced Numerical Study For Optimization of Petrol-H2-Air Mixer For Internal Combustion Engine." (5): 5–12.
18. Yousufuddin, S., and S. Nawazish Mehdi. (2008): "Exhaust Emission Analysis of an Internal Combustion Engine Fuelled with Hydrogen-Ethanol Dual Fuel." *International Journal of Engineering*, Transactions B: Applications 21(2): 203–10.