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An experimental investigation on engine performance and emissions of a single cylinder diesel engine using hydrogen as inducted fuel and diesel as injected fuel with exhaust gas recirculation

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ABSTRACT

Fast depletion of fossil fuels is demanding an urgent need to carry out research work to find out the viable alternative fuels for meeting sustainable energy demand with minimum environmental impact. In the future, our energy systems will need to be renewable and sustainable, efficient and cost-effective, convenient and safe. The technology for producing hydrogen from a variety of resources, including renewable, is evolving and that will make hydrogen energy system as cost-effective. Hydrogen safety concerns are not the cause for fear but they simply are different than those we are accustomed to with gasoline, diesel and other fossil fuels. For the time being full substitution of diesel with hydrogen is not convenient but use of hydrogen in a diesel engine in dual fuel mode is possible. So Hydrogen has been proposed as the perfect fuel for this future energy system. The experiment is conducted using diesel–hydrogen blend. A timed manifold induction system which is electronically controlled has been developed to deliver hydrogen on to the intake manifold. The solenoid valve is activated by the new technique of taking signal from the rocker arm of the engine instead of cam actuation mechanism. In the present investigation hydrogen-enriched air has been used in a diesel engine with hydrogen flow rate at 0.15 kg/h. As diesel is substituted and hydrogen is inducted, the NO_x emission is increased. In order to reduce NO_x emission an EGR system has been developed. In the EGR system a light-weight EGR cooler has been used instead of bulky heat exchanger. In this experiment performance parameters such as brake thermal efficiency, volumetric efficiency, BSEC are determined and emissions such as oxides of nitrogen, carbon dioxide, carbon monoxide, hydrocarbon, smoke and exhaust gas temperature are measured. Dual fuel operation with hydrogen induction coupled with exhaust gas recirculation results in lowered emission level and improved performance level compared to the case of neat diesel operation.

1. Introduction

It is well known that fossil fuel reserves are becoming exhausted at an alarming rate [1]. Moreover, the combustion of such fuels results in the emission of noxious pollutants which threaten the very survival of life in this planet [1]. The main pollutants from the conventional hydrocarbon fuels are unburned/partially burned hydrocarbon (UBHC), carbon

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monoxide (CO), oxides of nitrogen (NO_x), smoke and particulate matter [1]. Thus, it is very important to identify some clean burning, renewable, alternative fuels to ensure the safe survival of internal combustion engines [1]. However, it is not possible to have a common alternative fuel for universal application in the existing engines that have been designed to operate on petroleum-based fuels [1]. Efforts to operate these engines on any non-petroleum fuel are likely to give rise to problems characteristic of any ''converted system'' [1]. A lot of research is being carried out throughout the world to evaluate the performance, exhaust emission and combustion characteristics of the existing engines using several alternative fuels such as hydrogen, compressed natural gas (CNG), alcohols (methanol and ethanol), LPG, biogas, producer gas, bio-diesels developed from vegetable oils, and a host of others. As the fuel of the future, the expert studies indicate the hydrogen. Hydrogen may become an important energy carrier for sustained power consumption with reduced impact on the environment. It can be used in combustion devices or fuel cells without any carbon emissions and minimal emissions of other pollutant gases. When hydrogen is burned, hydrogen combustion does not produce toxic products such as hydrocarbons, carbon monoxide, oxide of sulfur, organic acids or carbon dioxide, instead its main product is water. Like electricity, hydrogen is an energy carrier and must be produced from another substance. Hydrogen is not widely used today but it has great potential as an energy carrier in the future. SI engines are suitable for hydrogen but in recent time CI engines are also in the process of modification to run with hydrogen [2]. It is important to mention here that since hydrogen has an auto-ignition temperature of about 576° C, it is not possible to achieve ignition of hydrogen by compression alone [2]. Some sources of ignition have to be created inside the combustion chamber to ensure ignition [2]. Combustion triggering devices such as installation of glow plugs in the combustion chamber and the preliminary addition of fuel to the combustion chamber through either pilot injection or a small leak are the few solutions to the problem. Das [2], after exhaustive tests on the research engine with various fuel induction techniques, has concluded that timed manifold injection is the most pragmatic mode of hydrogen fuelling. The actuation mechanism played a very important role in the development of a TMI-operated hydrogen engine. Both the hydraulically operated and the cam-actuated injection systems were developed on the research Engine [2]. Masood et al. [3] studied the effect of blending hydrogen with diesel in different proportions on combustion and emissions. It was concluded that the hydrogen–diesel co-fuelling will solve the drawback of lean operation of hydrocarbon fuels such as diesel, which are hard to ignite and results in reduced power output, by reducing misfires, improving emissions, performance and fuel economy [3]. In the absence of carbon, sulfur, and lead, the exhaust emissions from hydrogen-operated engine are free from host of noxious pollutants such as carbon monoxide, carbon dioxide and other greenhouse gases, hydrocarbons, sulfur oxides, smoke, lead or other toxic metals, sulfuric acid, ozone and other oxidants, benzene and other carcinogenic compounds and formaldehydes [3]. There is minimal amount of CO, CO_2 and HCs in the exhaust gas because of the burning of lube oil [3]. The only real pollutant is NO and NO_2, thus NO_x. This high level of NO_x is due to high combustion temperature in hydrogen fuelled engine. Heffel conducted six experiments on a 2-l, 4-cylinder Ford ZETEC internal combustion engine developed to operate on hydrogen fuel [4]. All the experiments were conducted at a constant engine speed of 1500 rpm and each experiment used a different fuel flow rate, ranging from 0.78 to 1.63 kg/h. The results of these experiments demonstrated that using EGR is an effective means to lowering NO_x emissions [4]. Cooled EGR gives lower thermal efficiency than hot EGR but makes possible lower NO_x emissions [5]. The combustion noise and thermal efficiency of the dual fuel engine are found to be affected when EGR is used in the dual fuel engine [6]. Abu-Hamdeh designed spiral fin heat exchanger pipes to study the effect of cooling the EGR of diesel engines on the chemical composition of the exhaust gases and the reduction in the percentages of pollutant emissions [7]. The NO_x concentration was reduced due to the effect of the cooled EGR on decreasing the combustion temperature [7]. Saravanan et al. [8] used hydrogen-enriched air as intake charge in a diesel engine adopting exhaust gas recirculation (EGR) technique with hydrogen flow rate at 20 l/min. Usage of hydrogen in dual fuel mode with EGR technique resulted in lowered smoke level, particulate and NO_x emissions. The use of EGR is, therefore, believed to be most effective in improving exhaust emissions in hydrogen fuelled engine.

From the above literature survey it has been found that no significant work has been carried out on the timed manifold injection technique (TMI) of hydrogen used in single cylinder diesel engine. Moreover, not much significant work has been carried out on effect of exhaust gas recirculation to minimize NO_x in hydrogen fuelled diesel engine. The objective of the intended experimental work is to examine the effect of dual fuel operation with exhaust gas recirculation on the exhaust emission and performance characteristics of an existing diesel test engine using diesel–hydrogen blend. The project does not envisage any major modification in the main components of the engine, but will only make the fuel induction system compatible with the introduction of hydrogen and air into the engine. One exhaust gas recirculation system is to be developed which will be capable for changing EGR percentage.

2. Experimental setup

The engine used for the experiment is a four stroke, water cooled, single cylinder, vertical diesel engine running at a rated power of 5.2 kW and at a rated speed of 1500 rpm. The specifications of the engine are shown in Table 1. The diesel engine was fired on no load initially and it was let to run for a period of time until it reached steady-state conditions, denoted by the constant cooling water outlet temperature. The following readings are taken after the engine reaches the steady-state condition.

1. Exhaust gas temperature.
2. The difference in liquid level in the manometer.
3. Time for 5 ml fuel consumption of diesel.
4. NOx, HC, CO and CO_2 emissions.
5. Smoke intensity.

Table 1 – Specification of the engine.

Make	Kirloskar oil engines limited
Type	Single cylinder, vertical, four stroke cycle, single acting, totally enclosed, high speed compression ignition diesel engine.
Compression ratio	17.5:1
Power development	5.2 kW at 1500 rpm
Bore	80 mm
Stroke	120 mm

Then the engine running on diesel as the main fuel was taken on load in steps by means of the Eddy current dynamometer and after attaining the steady-state conditions all the above-mentioned readings are taken. This procedure is repeated for 20%, 40%, 60% and 80% loading. The engine was again allowed to attain steady-state conditions at no load. Then hydrogen is supplied from a high-pressure cylinder to an outlet pressure of 1 bar using hydrogen pressure regulator. Then hydrogen is allowed to pass through flame trap, which is used to suppress the flashback if any into the intake manifold. The hydrogen from the flame trap is sent into the inlet manifold via surge tank. The solenoid valve is activated by the new technique of taking signal from the rocker arm of the engine instead of cam actuation mechanism. By keeping the flow of hydrogen as 0.15 kg/h, the performance and emissions of the hydrogen-enriched engine without EGR are studied. In this case also readings are taken in 20% load, 40% load, 60% load and 80% load. At the end of this process, hydrogen flow rate is reduced to zero and the engine is made to run at steady-state condition using diesel at no load condition. For EGR operation the quantity of exhaust gas is regulated by a control valve, which is installed in the EGR loop. An air box is provided in EGR loop to dampen the fluctuation of recirculated exhaust. An orifice is installed in the EGR loop after the air box in order to measure the flow rate of recirculated exhaust. There is an EGR cooler placed before the air box. The schematic diagram of EGR system is shown in Fig. 1. Figs. 2 and 3 show schematic diagram of experimental setup and photographic view of the engine setup. The engine was run by using hydrogen enrichment (0.15 kg/h hydrogen flow) with 10% EGR and 20% EGR. In both these cases (i.e. 10% EGR and 20% EGR) above-mentioned readings are taken in no load, 20% load, 40% load, 60% load and 80% load.

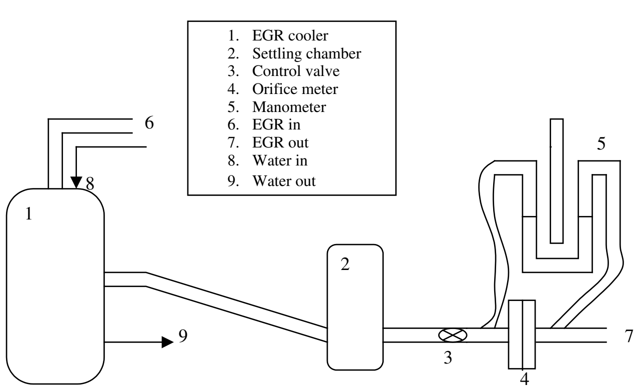

Fig. 1 –

3. Results and discussion

In this experiment performance parameters such as brake thermal efficiency, volumetric efficiency, BSEC are determined and emissions such as oxides of nitrogen, carbon dioxide, carbon monoxide, hydrocarbon, smoke and exhaust gas temperature are measured. The experiment was carried out keeping hydrogen flow constant at 0.15 kg/h in absence of EGR, with 10% EGR and 20% cooled EGR.

3.1. *Brake thermal efficiency*

The variation of brake thermal efficiency with load for neat diesel, diesel with 0.15 kg/h of hydrogen enrichment without EGR, with 10% EGR and 20% EGR is shown in Fig. 4. The brake thermal efficiency for hydrogen with diesel as ignition source is 34.1% at 80% load with a flow rate of hydrogen 0.15 kg/h, whereas that of baseline diesel fuel is 30.2%. In the experiment it is observed that as flow rate of hydrogen started increasing there is decrease in flow rate of diesel. It indicates that hydrogen is taking part in the combustion and increase in thermal efficiency is attributed to enhanced combustion rate due to high flame velocity of hydrogen. In low load range (0 to 20% loading) difference between η_h and η_d is very less where η_h is the efficiency when hydrogen is used along with diesel and η_d is the efficiency when neat diesel is used. It indicates that in low load range combustion efficiency of hydrogen in the presence of diesel is low. In between 20% and 40% loading the increase in difference between η_h and η_d is almost linear. Almost constant difference is maintained in midrange load (40–60% loading). In high range load (60–80% loading) increase in difference between η_h and η_d is less compared to the 20–40% range. So combustion efficiency of hydrogen in presence of diesel is high in 20–40% load range. Use of EGR has a negative effect on engine efficiency that increases with its percentage. At 80% load with 10% EGR brake thermal efficiency is 32.3% and with 20% EGR it is 30.8. Due to presence of EGR, oxygen concentration of the intake air is reduced having a significant negative effect on combustion. This explains the reduction of brake thermal efficiency in case of EGR.

3.2. *Volumetric efficiency*

Fig. 5 shows the variation of volumetric efficiency with load for neat diesel, diesel with 0.15 kg/h of hydrogen enrichment without EGR, with 10% EGR and 20% EGR. The volumetric efficiency obtained for 0.15 kg/h hydrogen enrichment without EGR is 78.9% compared to neat diesel fuel of 80.1% at 80% load. This decrease in volumetric efficiency is due to the fact that hydrogen being much less dense than air displaces an appreciable amount of it while being inducted inside the cylinder. When EGR is applied, there is further decrease in volumetric efficiency. With 10% EGR it is 63.9% and with 20% EGR it is 50.2% at 80% load. Figure shows that volumetric efficiency decreases with the increase in EGR percentage at each load up to 80% loading. When exhaust gas is recirculated

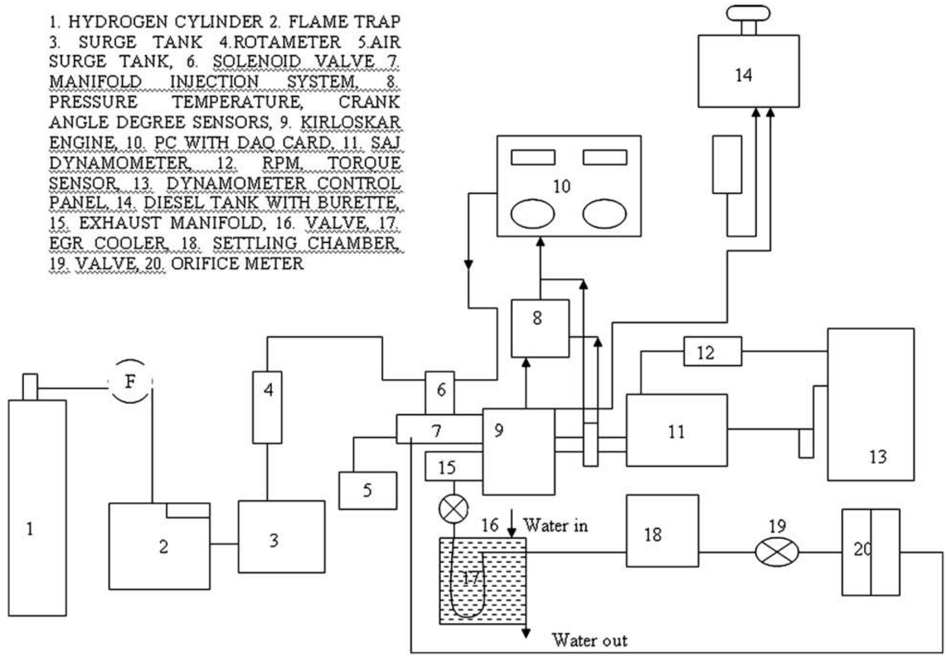

Fig. 2 –

to the intake manifold, it displaces a portion of the incoming air. This results in a reduction in volumetric efficiency. In this experiment intake manifold has been modified for the induction of hydrogen and exhaust gas. So there is restriction offered to fresh charge, which further decreases volumetric efficiency.

3.3. *Brake specific energy consumption*

Fig. 6 shows the variation of brake specific energy consumption with load for neat diesel, diesel with 0.15 kg/h of hydrogen enrichment without EGR, with 10% EGR, and 20% EGR. It can be observed that BSEC without EGR is 6458.48 whereas the BSEC of neat diesel is 11854.71, with 10% EGR it is 6713.42 and with 20% EGR it is 7350.77. All these readings

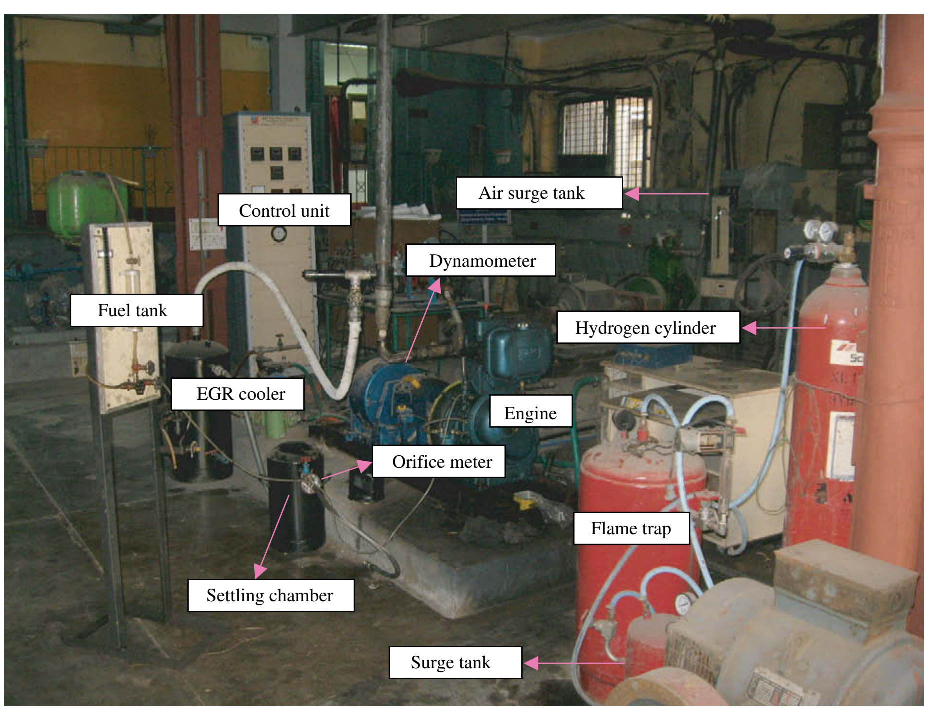

Fig. 3 –

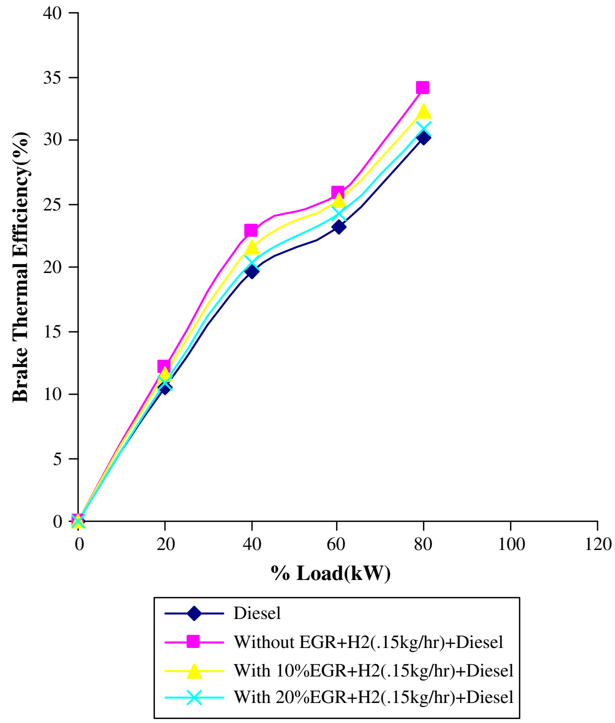

Fig. 4 –

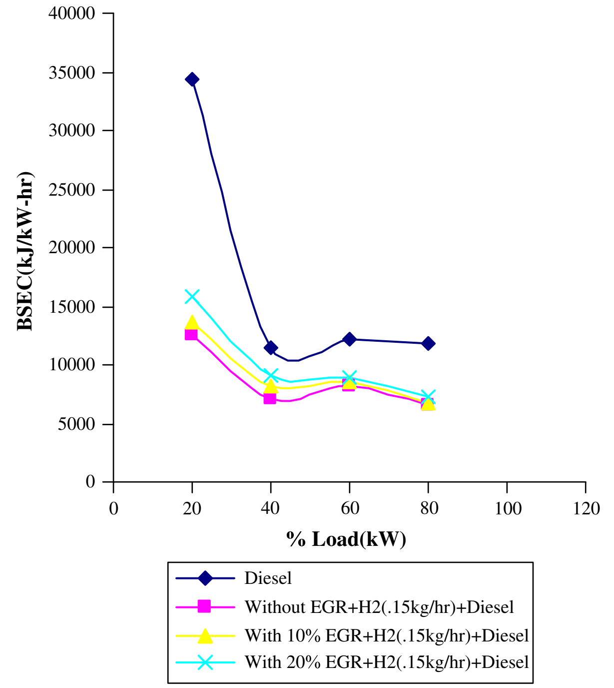

Fig. 6 –

are at 80% load of rated load. BSEC decreases with the increase in brake power. This trend is maintained in all four cases viz neat diesel operation, 0.15 kg/h hydrogen enrichment without EGR, with 10% EGR and with 20% EGR. But BSEC in case of hydrogen enrichment without EGR is less compared to that of neat diesel operation. This is due to better mixing of hydrogen with air resulting in complete combustion of fuel. When EGR is applied BSEC increases and goes on increasing with the increase in EGR percentage. This increase in BSEC is due to the negative effect of EGR on combustion which leads to incomplete combustion and fall

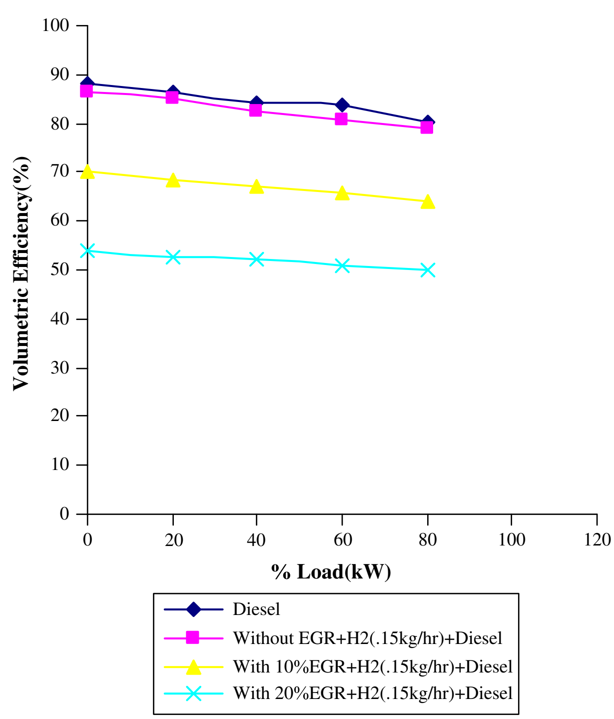

Fig. 5 –

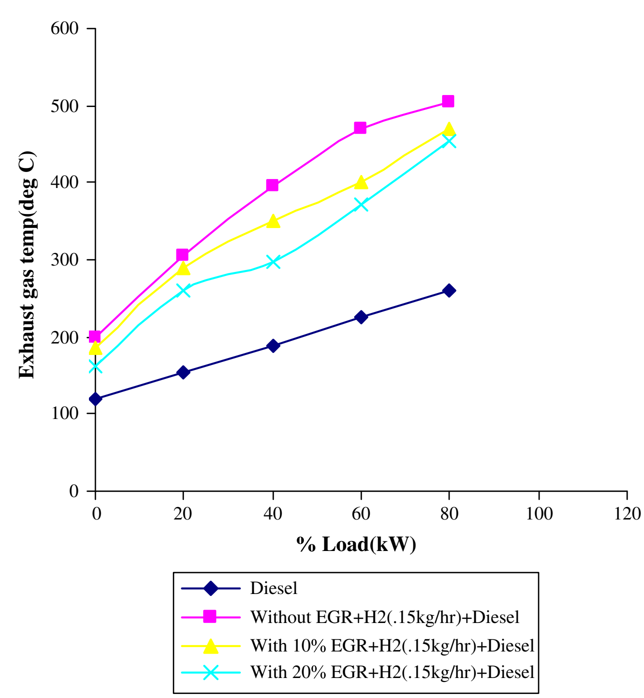

Fig. 7 –

of speed and to keep the engine run on constant speed requires more of BSEC compared to without EGR.

3.4. *Exhaust gas temperature*

The variation of exhaust gas temperature with load for neat diesel, diesel with 0.15 kg/h of hydrogen enrichment without EGR, with 10% EGR and 20% EGR is shown in Fig. 7. It is observed that with increase in load, exhaust gas temperature also increases. The exhaust gas temperature for hydrogen enrichment is 505 °C at 80% load with a flow rate of hydrogen 0.15 kg/h whereas that of diesel is 260 °C. This increase in exhaust gas temperature in case of hydrogen enrichment is due to enhanced combustion rates of hydrogen. Temperature of exhaust gas is found to be lower when EGR is applied and it goes on decreasing with the increase in EGR percentage. At 80% load with 10% EGR it is 470 °C and with 20% EGR it is 453 °C. The possible reason for this temperature reduction may be relatively lower availability of oxygen for combustion and higher specific heat of intake air mixture.

3.5. *Carbon dioxide*

The variation of Co_2 emission with load for neat diesel, diesel with .15 kg/h hydrogen enrichment without EGR and the same with 10% EGR and 20% EGR is shown in Fig. 8. Co_2 emissions in case of hydrogen enrichment are lower compared to that of diesel. At 80% load Co_2 emission for hydrogen enrichment without EGR is 4.7% by volume whereas that of neat diesel is 7.9% by volume. The Co_2 emission in case of hydrogen enrichment is lowered because of better combustion of hydrogen fuel and also due to the absence of carbon atom in hydrogen molecule. Due to the use of EGR, CO_2 emissions increase and go increasing with the increase in EGR percentage. At 80% load CO_2 emission for 10% EGR is 4.8% by volume and that of 20% EGR is 5.6% by volume. The reason of this increase in CO_2 emissions in case of EGR is the presence of CO_2 in exhaust gas.

3.6. *Carbon monoxide*

Fig. 9 depicts the variation of carbon monoxide with load. At 80% load CO emission for neat diesel operation is .85% by volume, while it is .58% by volume with 10% EGR and .68% by volume with 20% EGR. In case of .15 kg/h hydrogen enrichment without EGR CO emission is .46% by volume. Hydrogen does not contain any carbon. This is the reason for low CO emission in case of hydrogen enrichment, and the registered amount being only due to pilot diesel and lube oil. In case of EGR CO emission increases due to oxygen deficient operation. With the increase of EGR rate, reaction speed and in cylinder temperature are decreased. At the same time, more exhaust gas reduces the O_2 concentration. All the reasons weaken the oxidation reaction and produce more CO emission.

3.7. *Hydrocarbon*

Fig. 10 shows the variation of HC with load for neat diesel, diesel with .15 kg/h hydrogen enrichment without EGR and the same with 10% EGR and 20% EGR. It can be observed that HC emission for hydrogen enrichment without EGR is 55 ppm whereas that of neat diesel is 130 ppm, with 10% EGR it is 108 ppm and with 20% EGR it is 114 ppm. All these readings are at 80% load. The reduction in HC emission in case of hydrogen enrichment without EGR is due to the absence of carbon in hydrogen. In case of EGR there is lower excess oxygen

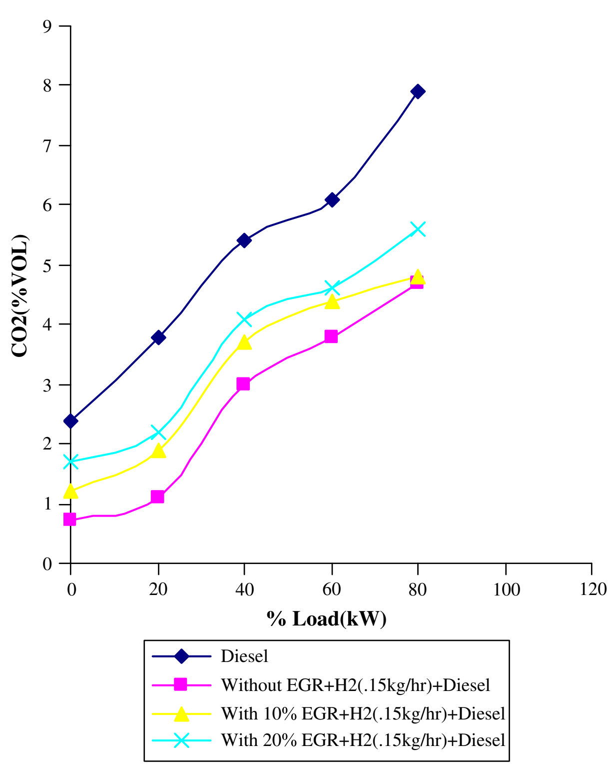

Fig. 8 –

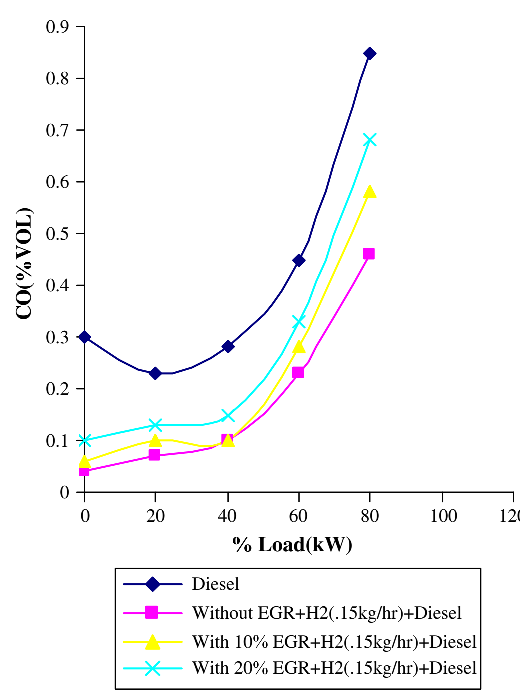

Fig. 9 –

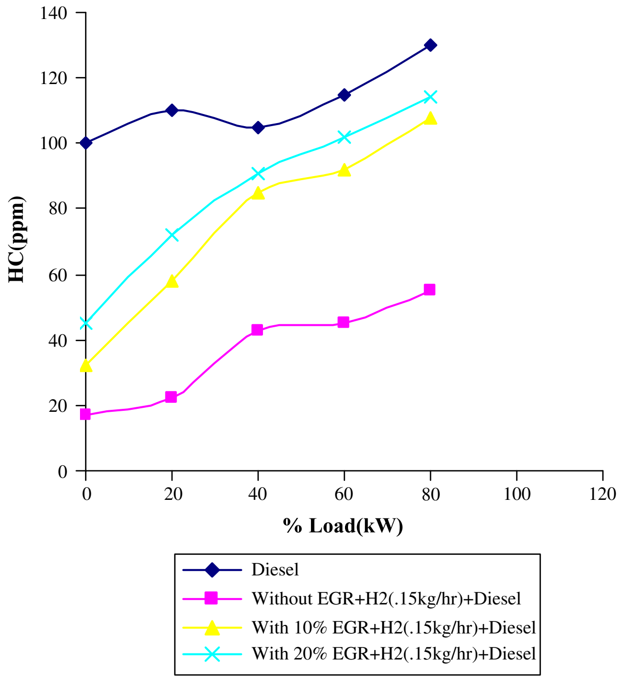

Fig. 10 –

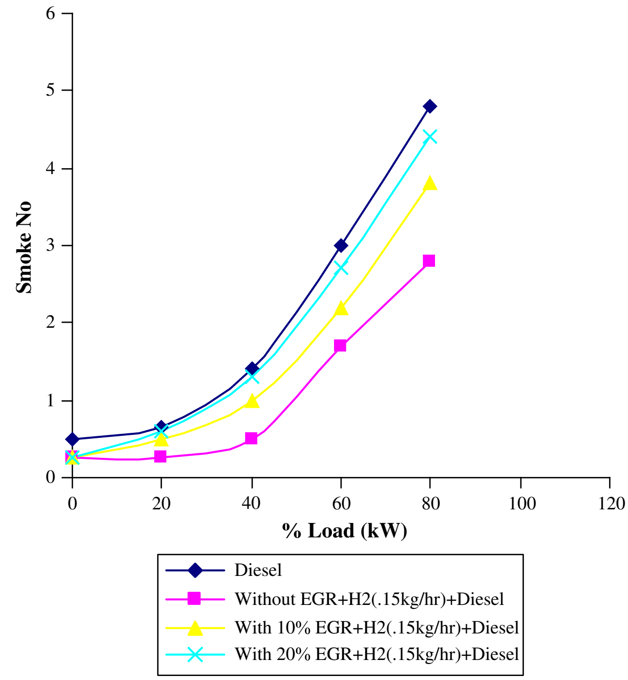

Fig. 11 –

available for combustion. Lower excess oxygen concentration results in rich-air fuel mixtures at different locations inside the combustion chamber. This heterogeneous mixture does not combust properly and results in higher HC emission.

3.8. *Smoke No*

The variation of smoke level with load is shown in Fig. 11. As load increases, diesel engines tend to generate more smoke. It is observed that at 80% load smoke no in case of diesel is 4.8 whereas corresponding values for diesel with .15 kg/h hydrogen enrichment without EGR and the same with 10% EGR and with 20% EGR are 2.8, 3.8 and 4.4, respectively. Hydrogen being devoid of any carbon atoms shows obvious characteristics of reduction in smoke levels. Combustion of hydrogen produces mainly water and does not form any particulate matter. This is why there is low smoke level in case of hydrogen enrichment. Higher smoke level of the exhaust is observed when the engine is operated with EGR compared to without EGR. Smoke level increases with increasing EGR rate and increasing engine load. EGR reduces availability of oxygen for combustion of fuel which results is relatively incomplete combustion and increased formation of particulate matter. This results in higher smoke level in case of EGR.

3.9. *NO_x*

Fig. 12 shows the variation of NO_x with load for neat diesel, diesel with .15 kg/h hydrogen enrichment without EGR and the same with 10% EGR and 20% EGR. NO_x emission for hydrogen enrichment without EGR is 1211 ppm compared to neat diesel fuel of 810 ppm at 80% load. The reason for this higher concentration of NO_x in case of hydrogen enrichment without EGR is peak combustion temperature and high residence time of the high temperature gases in the cylinder. Figure depicts that with 10% EGR NO_x formation is 760 ppm at 80% load and that of 20% EGR is 710 ppm. So the NO_x formation decreases with the use of EGR and goes on decreasing with increase in EGR percentage. The exhaust gases mainly consist of inert carbon dioxide, nitrogen and posses high

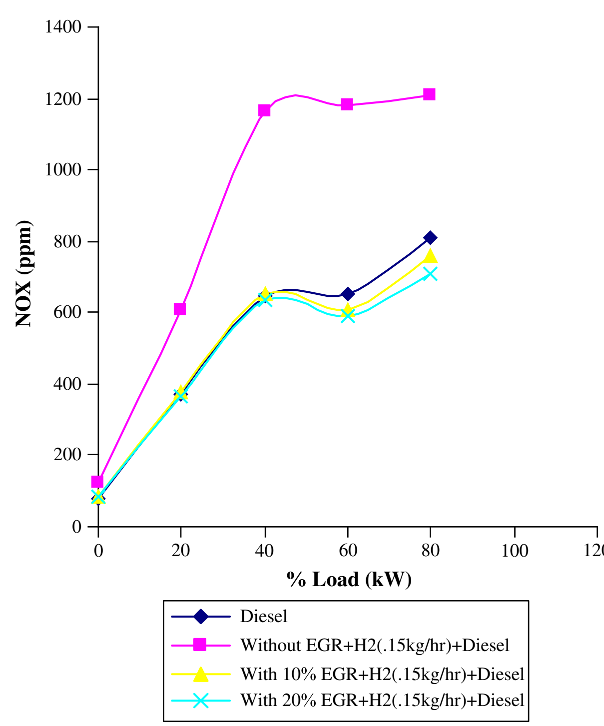

Fig. 12 –

specific heat. When recirculated to engine inlet it can reduce oxygen concentration and act as a heat sink. All the combustion process is delayed with diluted air, premixed combustion, diffusion and late diffusion combustion. Consequently the whole combustion process is shifted further into the expansion stroke, leading to lower combustion temperature. Lower combustion temperature is the reason of decrease of NO_x.

4. Conclusion

A single cylinder compression ignition engine was operated successfully using hydrogen–diesel blend with exhaust gas recirculation. The following conclusions are made on the basis of experimental results.

- The brake thermal efficiency increases by 12.9% without EGR with the supply of .15 kg/h of hydrogen. However, at high rates of hydrogen admission the combustion becomes uncontrolled and hence the thermal efficiency decreases. Use of EGR has a negative effect on engine efficiency that increases with its percentage. This is due to dilution effect of EGR.
- Volumetric efficiency is maximum with neat diesel operation. In case of hydrogen enrichment volumetric efficiency decreases. There is further reduction in volumetric efficiency when EGR is used. The reason for reduction in volumetric efficiency is due to displacement of a portion of the incoming air with exhaust gas and hydrogen.
- BSEC in case of hydrogen enrichment without EGR is less compared to that of neat diesel operation. The reason for reduction in BSEC is due to the higher calorific value of hydrogen and operation of hydrogen fuelled engine under lean burn conditions. The increase in BSEC in case of EGR is due to negative effect of EGR on combustion.
- Due to enhanced combustion rates of hydrogen exhaust gas temperature is high in case of hydrogen enrichment. Temperature of exhaust gas is found to be lower when EGR is applied. This is due to lower availability of oxygen for combustion.
- The smoke level decreases by 42% for hydrogen enrichment without EGR compared to neat diesel operation. The reduction in smoke is due to the absence of carbon in hydrogen structure. When EGR is used smoke level increases but still at low level compared to neat diesel operation. EGR reduces availability of oxygen for combustion of fuel, which results in higher smoke level.
- The CO_2 emission decreases by 40.5% for hydrogen enrichment without EGR compared to neat diesel operation at 80% load. The reason for reduction in CO_2 emission is the absence of carbon in hydrogen molecule. As exhaust gas contains CO_2, EGR increases the CO_2 emission level.
- The CO emission decreases by 45.8% for hydrogen enrichment without EGR compared to neat diesel operation at 80% load. In case of EGR CO emission increases due to oxygen deficient operation but still at low level compared to neat diesel operation.
- The HC emission decreases by 57.69% for hydrogen enrichment without EGR compared to neat diesel operation at 80% load. In case of EGR HC emission increases due to lower excess oxygen available for combustion which results in incomplete combustion but still emission is at low level compared to neat diesel operation.
- EGR technique is useful in reducing NO_x concentration. At 80% load NO_x value for hydrogen enrichment without EGR is 1211 ppm whereas with 20% EGR NO_x value is 710 ppm. The reduction in NO_x is due to the reduction in peak combustion temperature because of presence of inert gas in EGR.

Thus the present experimental investigation on a single cylinder diesel engine with hydrogen–diesel blend has proved to be a viable approach to minimizing pollution load and improved performance. But it is also to be noted that hydrogen combustion with diesel fuel is plagued by the formation of NO_x due to high flame temperature involved. EGR technique is used for reduction of NO_x concentration. In doing so there is decrease in performance level and increase in emission level. That is why low EGR percentage is preferred.

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