# An Experimental Study of Effect of Hydrogen Blending on the Smoke Emission from Diesel Engine

# دراسة عملية لخلائط الهايدروجين وتأثيرها على التلوث الدخاني المنبعث من محرك ديزل

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## Abstract

An experimental study on performance parameters and smoke emission of a diesel engine was carried out at the different hydrogen energy blending. A single cylinder air- cooled direct injection diesel engine was tested at constant engine speed (1500 rpm).Two important load conditions; full load and half load were tested. At these loads, different quantities of hydrogen fuel are inducted into intake air manifold of the engine. In term of energy, the hydrogen energy percentages were varied from 0% (i.e. 100% diesel fuel) to 35%. Up to 20% hydrogen energy fraction, the results showed that the smoke opacity clearly decreases by 33% and 43% for full and half load respectively. Also, the performance parameters have small improvement except the brake specific energy consumption BSEC (kJ/kWhr) was increased.

It was inferred that the best hydrogen energy fraction can be blended with intake air manifold is in the range (20%-25%) for both loads. This hydrogen energy provides high performance parameters and very low smoke opacity.

**Key words:** Hydrogen energy, diesel engine, smoke opacity, performance parameters.

## الخلاصة

أجريت دراسة عملية لمعالم الأداء والتلوث الدخاني المنبعث من محرك ديزل عند مزج نسب مختلفة من غاز الها يدروجين. محرك الديزل الذي أجريت عليه التجارب هو محرك رباعي الاشواط, ذو أسطوانة واحدة, تبريد بالهواء وحقن مباشر للوقود عند سرعة محرك ثابتة (1500 rpm). نوعين من أحمال المحرك المهمة تم أختبارها هو الحمل العالي والمتوسط. عند هذه الأحمال, كميات مختلفة من وقود الهايدروجين أدخلت الى المحرك عن طريق مشعب دخول الهواء. في مصطلح الطاقة, نسب طاقة الهايدروجين التي أضيفت الى المحرك تتغير من (0% i.e. 100 diesel- 35%). النتائج أظهرت أن نسب طاقة الهايدروجين المضافة لحد (20%) تقلل بوضوح عتومية الدخان بنسبة 33% عند الحمل العالي ونسبة 43% عند الحمل المتوسط. كذلك أن هذه النسبة تحسن معالم الأداء قليلا ما عدا أستهلاك الطاقة النوعي المكبحي فأنه يزداد.

أن أفضل نسبة طاقة هايدروجين ممكن أن تمزج في مشعب دخول الهواء هي بين (20%-25%) لكل من الحملين العالي والمتوسط بحيث تعطي معالم أداء عالية وعتومية دخان جدا قليلة.

**الكلمات الرئيسية:** طاقة الهايدروجين, محرك ديزل, عتومية الدخان, معالم الأداء

## 1- Introduction

During the last decade, the use of alternative fuel for diesel engines was received renewed attention. The interdependence and uncertainty of petroleum-based fuel availability have created a need for investigating the possible use of alternative fuels. In recent years, the emphasis to reduce pollutant emissions from petroleum-based engines are motivated the development and testing of several alternative fuels. The alternative fuels aspiring to replace the petroleum based fuels are LPG, CNG, H2, vegetable oils, biogas, producer gas and LNG.

Hydrogen gas induction inside the intake air manifold of practical combustion engines (such as gasoline, natural gas, diesel engines) is currently under widespread investigation [1-6] due to some reasons associated with hydrogen combustion;

- High potential to lower smoke, soot particulate, unburnt hydrocarbons, CO and $CO_2$ emissions.
- High energy content per volume when stored as a liquid.
- Potential to lower noise problem especially in diesel engine.
- High flame burning speed.

In addition to the preceding reasons, hydrogen is presently available. There are a number of different ways of producing hydrogen gas. It can be derived from natural resources such as coal and fossil oil or from renewable resources based on solar energy. Also, it can be made commercially from electrolysis.

The concept of using hydrogen as an alternative to diesel fuel in diesel engines is a recent one. The self-ignition temperature of hydrogen is 858 K. Hence hydrogen cannot be used directly in CI engine without the assistance of a spark plug or glow plug [7]. This makes hydrogen unsuitable for a diesel engine as a sole fuel. One of the alternative methods is to adopt hydrogen-enrichment or hydrogen-induction technique, which uses diesel as a pilot fuel for ignition purpose. Hydrogen substitution by 10-20 % of energy share in diesel reduces substantially the smoke, particulate and soot emissions. Hydrogen powered I.C. engines produces more or similar power compared to diesel. The problems of pre-ignition and backfire are less severe and knock can be eliminated compared to spark ignited engines that make the hydrogen usage to be safer in CI mode rather than SI mode [8]. The properties of hydrogen compared with diesel fuel are given in Table 1[4].

Table (1) Properties of hydrogen compared with diesel.

| Properties | Diesel fuel | Hydrogen fuel |
|---|---|---|
| Auto-ignition Temperature (K) | 530 | 858 |
| Minimum ignition energy (mJ) | - | .02 |
| Flammability limits (volume %in air) | 0.7–5 | 4–75 |
| Stoichiometric air fuel ratio on mass basis | 14.5 | 34.3 |
| Limits of flammability (equivalence ratio) | - | 0.1–7.1 |
| Density at 16 ◦C and 1.01 bar (kg/m$^3$) | 833–881 | 0.0838 |
| Net heating valve (MJ/kg) | 39 | 120 |
| Flame velocity (cm/s) | 30 | 265–325 |
| Quenching gap in NTP air (cm) | - | 0.064 |
| Diffusivity in air (cm$^2$/s) | - | 0.63 |
| Research Octane number | 30 | 130 |
| Cetane number | 40-55 | - |

Problems related to combustion noise, vibration and the high NOx and smoke emissions have been reduced with the engine development and exhaust gas after treatment techniques. The use of the exhaust gas recirculation (EGR) technology is an effective way of reducing NOx emissions but it is normally associated with higher smoke and particulate emissions as well as with increased fuel consumption [9-12].

The exhaust of diesel engines contains soot particles that are generated in the fuel rich zones within the cylinder during the combustion. These are seen as the exhaust smoke and are undesirable odorous pollution. Maximum concentration of soot particulate emissions occurs when the engine is under high load. At this load, maximum fuel is injected to supply maximum power, resulting in a rich mixture and high specific fuel consumption. This can be seen in the heavy exhaust smoke emitted when a truck accelerates up a hill or from stop [13].

The soot particles consist of gaseous hydrocarbons and solid carbon particles. A fraction of these hydrocarbons such as polycyclic aromatic hydrocarbons (PAHs), known for their ***carcinogen*** properties, are adsorbed on soot particles surface. Soot particles after surface growth have approximately of 200 nm in diameter. These ultra-small particles are one of the hazardous to human health because they are easily penetrated deep into the lungs [14-15].

## 2- Experimental set-up

The basic test rig for diesel engine manufactured by (TQ Education and Training Ltd.) consists of four stroke diesel engine type TD113, hydraulic dynamometer type TD115 and instrumentation unit type TD114. The instrumentation unit is designed to stand beside the diesel engine. It contains the fuel system measurement and viscous flow meter used to measure the consumption of air. Engine torque was measured by using hydraulic dynamometer and transmitted to a torque meter located on the instrumentation unit. The torque meter was calibrated according to calibration curve giving by TQ- equipment. The diesel engine specifications were inserted in table (2). The absorption smoke meter, MOD. SMOKY (ST1006/S06/004) was used to measure the smoke opacity in diesel exhaust. The experimental setup photograph view is shown in figure (1).

Table (2)Engine specifications

| **Specifications of the test engine** | | |
|---|---|---|
| No. | Parameters | Specifications |
| 1 | General details | Single cylinder, four stroke, Compression ignition, vertical, Air cooled, direct injection |
| 2 | Bore | 70 mm |
| 3 | Stroke | 65 mm |
| 4 | Swept volume | 250 cm3 |
| 5 | Charging | Natural aspiration |
| 6 | Maximum power | 4.2 kW at 3750 rpm |
| 7 | Manufacturer | TQ Education and Training Ltd. |

The schematic diagram of experimental set up is shown in figure (2). Hydrogen was stored in a high pressure cylindrical storage tank at pressure of 13.7 Mpa which is fitted with fine control pressure regulator. Hydrogen gas from pressure regulator was passed through controlled ball valve. Then, the gas was allowed to pass through hydrogen flow meter which was connected to precise inclined manometer to measure the volume flow rate of hydrogen in (mm $H_2O$) at atmospheric pressure and temperature. This flow meter was calibrated inside the laboratory using the more accurate basic principle method of measuring the dislocated hydrogen volume with time. The hydrogen flow rate was then converted into (liter/min) with error of (± 0.041) according to calibrated equation. Then hydrogen gas was allowed to pass through a damping tank (22.5 liter) which was used to eliminate any fluctuation that may occur in the manometer reading because of very high compressibility of hydrogen. The hydrogen was then allowed to pass through the flame trap. The flame trap works as a non-return valve to prevent any flame back in the fuel line and serves as a visible indicator to see the hydrogen flow. Since the hydrogen gas is very sensitive to any slight compression inside the fuel system, the effect of water head in the flame trap on the inducted gas measurement was taken into account. After that, hydrogen was passed to the two- way ball valve; one end was connected to the engine intake air manifold and the other was leaving into atmosphere to remove any hydrogen gas which is present in the fuel system during engine shutoff time. The schematic diagram of hydrogen fuel induction is shown in figure (3).

In this work, direct injection, natural aspiration, air cooled four stroke diesel engine was tested with different quantities of hydrogen blends at two important operating loads (full and half loads). The hydrogen gas was inducted directly into intake air manifold. By varying the hydrogen energy fraction (0% (i.e. 100% diesel fuel), 5%, 10%, 15%, 20%, 25%, 30%, 35%), the smoke opacity was investigated with relation to the performance parameters at constant engine speed (1500 rpm).

## 3- Results and discussion

In the present work, different quantities of hydrogen fuel are inducted into intake air manifold of the single cylinder direct injection air cooled diesel engine. The performance and smoke emission at two important loads (full and half) with constant engine speed (1500 rpm) were studied and compared with baseline diesel operation. Table (3) shows measured data of experimental work which was used to infer the performance engine parameters and smoke pollutants at the constant engine speed 1500 rpm with full and half engine loads. The diesel engine was loaded using hydraulic dynamometer test.

Table (3) Experimental data at constant engine speed 1500 rpm

| Load % | T (N.m) | $m_a$ (kg/h) | $m_D$ (kg/h) | $Q_{H2}$ (l/min) | $m_{H2}$ (g/h) | $T_{exh.}$ ($C^o$) | SO % | $[H2/(H2+D)]_E$ |
|---|---|---|---|---|---|---|---|---|
| Full Load 95% | 10.0 | 6.25 | 0.432 | 0 | 0 | 450 | 0.48 | 0% |
| | 10.1 | 6.25 | 0.432 | 1.471 | 7.389 | 455 | 0.44 | 5% |
| | 10.4 | 6.25 | 0.432 | 3.106 | 15.600 | 465 | 0.40 | 10% |
| | 10.5 | 6.25 | 0.432 | 4.933 | 24.776 | 480 | 0.35 | 15% |
| | 11.0 | 6.25 | 0.432 | 6.989 | 35.100 | 500 | 0.32 | 20% |
| | 12.5 | 6.25 | 0.432 | 9.318 | 46.800 | 530 | 0.30 | 25% |
| | 13.0 | 6.25 | 0.432 | 11.981 | 60.171 | 560 | 0.22 | 30% |
| | 13.7 | 6.25 | 0.432 | 15.053 | 75.600 | 575 | 0.10 | 35% |
| Half Load 50% | 6.25 | 5.2 | 0.254 | 0 | 0 | 260 | 0.21 | 0% |
| | 6.4 | 5.2 | 0.254 | 0.858 | 4.310 | 265 | 0.21 | 5% |
| | 6.6 | 5.2 | 0.254 | 1.812 | 9.100 | 270 | 0.20 | 10% |
| | 6.7 | 5.2 | 0.254 | 2.877 | 14.452 | 280 | 0.16 | 15% |
| | 7.0 | 5.2 | 0.254 | 4.077 | 20.475 | 285 | 0.12 | 20% |
| | 8.0 | 5.2 | 0.254 | 5.436 | 27.300 | 290 | 0.10 | 25% |
| | 8.5 | 5.2 | 0.254 | 6.989 | 35.100 | 310 | 0 | 30% |
| | 9.0 | 5.2 | 0.254 | 8.781 | 44.100 | 325 | 0 | 35% |

Figure 4 shows the variation of hydrogen blending in (l/min) inducted into intake air manifold of diesel engine with hydrogen energy fraction. The hydrogen energy fractions during the full and half load engine tests were varied from [0% (i.e.100% diesel) to 35%]. The quantity of diesel fuel injected at full load is greater than that at half load and then, it was need to high quantities of hydrogen blends at full load. The hydrogen energy fraction is defined below;

**Hydrogen energy fraction = (Energy $_{H2}$)/ (Energy $_{H2}$ + Energy $_{Diesel}$)**

At full load, the figure (4) shows that the highest hydrogen blending was 15.05 l/min and at half load was8.781 l/min, in turn; the highest hydrogen mass blends at atmospheric induction are being 0.075 kg/hr. and 0.044 kg/hr. respectively. These small quantities of hydrogen induction do not have clear effect on the air aspiration ability of the engine during the suction stroke as shown in figure (5). The figure shows that the volumetric efficiency is approximately constant with increasing hydrogen induction at two tested engine loads. The engine power depends on the amount of air sucked into the cylinder, so any reduction in volumetric efficiency will reduce the power. Small reduction in volumetric efficiency can be seen in figure (5) at full load and high hydrogen energy fraction. However, the engine brake torque and brake power as shown in figures (6, 7) respectively are observed to have obvious increasing at high hydrogen energy fraction. This can be attributed to the fact [5-7] that the hydrogen blending is enhancement the combustion processes inside the combustion chamber. Figure (8) shows the variation of the exhaust gas temperature with hydrogen energy fraction. The temperature of exhaust gases gradually increases with hydrogen energy fraction. This is mainly due to enhance the rate of combustion and high hydrogen flame speed.

Figure (9) shows that as the hydrogen energy fraction was increased the smoke opacity obviously decreases for both loads. The high cylinder temperature and oxygen availability affect soot oxidation enhancing. The hydrogen fuel has high self-ignition temperature (858 K) which is well above the self- ignition temperature of diesel fuel. Thus, the burning of heterogeneous charge of diesel fuel and air is to be earlier than burning of homogeneous charge of hydrogen fuel and air. Therefore, the combustion of later charge helps to complete burning of most soot particulate formed. Also, the increase of exhaust gas temperature especially at full load helps to increase the particulate oxidation through the exhaust passages. Hence, it was found, up to 20% hydrogen energy fraction, that the smoke opacity measured in the exhaust passages clearly decreases from 48%and 21% with pure diesel (i.e. 0% hydrogen energy fraction) to a value of 10% and 4% at full and half loads respectively as shown in figure (9). In addition, the increasing of hydrogen blend increases the (H/C) ratio which, in turn, participates to reduce the rate soot particulate formation. Therefore, the overall effect of increasing the soot oxidation and reduction the soot formation are to suppress the smoke opacity.

The increasing of hydrogen energy fraction up to 20% at two tested load was accompanied by a small increasing in brake mean effective pressure (BMEP; kpa)as shown in figure (10), increasing the brake specific energy consumption (BSEC; kJ/kWhr) as shown in figure (11) and lowering the duel fuel thermal efficiency as shown in figure (12). These results can be demonstrated that the quantities of hydrogen blends are very small with respect to the quantity of air induction at constant engine speed (1500 rpm). Thus lean mixture was formed and produces low energy. The high energy content of light mass of hydrogen gas inducted (0.000351 kg/h) up to 20% as shown in Table( 3) results in increasing in brake power (see figure 7). However, the brake thermal efficiency is slightly decreased in figure 12. In addition, figure (12) shows that the duel thermal efficiency at half load test is greater than that at full load test through the entire range of hydrogen energy fraction. This is mainly due to ignite rich diesel fuel at full load with unchanged air induction during constant engine speed test (1500 rpm) at full and half loads. The ignition of rich diesel fuel results in incomplete combustion and is associated with high level of smoke pollutant (see figure 9). This needs high quantities of hydrogen blends to improve the combustion processes and inhibit the smoke formation. Therefore, it is recommended to operate the engine at half load which needs low quantities of hydrogen blends to eliminate the smoke and increase the performance parameters.

Beyond 20% hydrogen energy fraction, it is clearly noticed from preceding performance and opacity figures (5-12)at full and half loads that the best hydrogen energy fraction can be inducted to the engine is within the range (20%- 25%), where the BMEP, brake power and thermal efficiency are increased and smoke opacity and BSEC are decreased. But, the duel thermal efficiency decreases at high hydrogen energy fraction. This can be attributed to lower the volumetric efficiency at full load (see figure 5) and the brake power production becomes low with respect to the hydrogen energy blended at two tested.

Figures (13 and 14) show the wireframe variation of smoke opacity with BMEP and hydrogen energy fraction at full and half loads respectively. The figure (13) shows the gradient of BMEP from the region of high smoke opacity at 100% diesel fuel (0% hydrogen energy fraction) to the region of very low opacity and high BMEP. Figure (14) shows gradient of BMEP from the region medium opacity at 0% hydrogen energy to the region with no opacity.

## 4- Conclusion

- Hydrogen energy induction within the range (5%- 20%) results in small increase in performance parameters except the duel thermal efficiency that exhibits small decreasing. However, the smoke opacity clearly decreases by 33% and 43% at full and half load respectively.
- The increasing of hydrogen blend increases the (H/C) ratio and enhances the rate of combustion. Increasing (H/C) ratio helps to reduce the rate of soot formation. High rate of combustion enhances the rate of soot particles oxidation. Hence, the overall effect of soot formation and oxidation reduces the smoke emission.
- The optimum hydrogen energy fraction can be inducted to the diesel engine at two tested load was found within the range of (20%- 25%), where high performance parameters and very low opacity were obtained.

## Nomenclature

| Symbol | Definition |
|---|---|
| T | Diesel engine brake torque (N.m) |
| $m_a$ | Mass flow rate of inducted air (kg/h) |
| $m_D$ | Mass flow rate of diesel fuel (kg/h) |
| $Q_{H2}$ | Volume flow rate of hydrogen inducted (l/min) |
| $m_{H2}$ | Mass flow rate of hydrogen gas (g/h) |
| $T_{exh.}$ | Exhaust gas temperature ($C^o$) |
| SO | Smoke opacity in exhaust gases (%) |
| BMEP | Brake mean effective pressure (kpa) |
| BSEC | Brake specific energy consumption (kJ/kWhr) |
| [H2/(H2+D)] | Hydrogen energy fraction |

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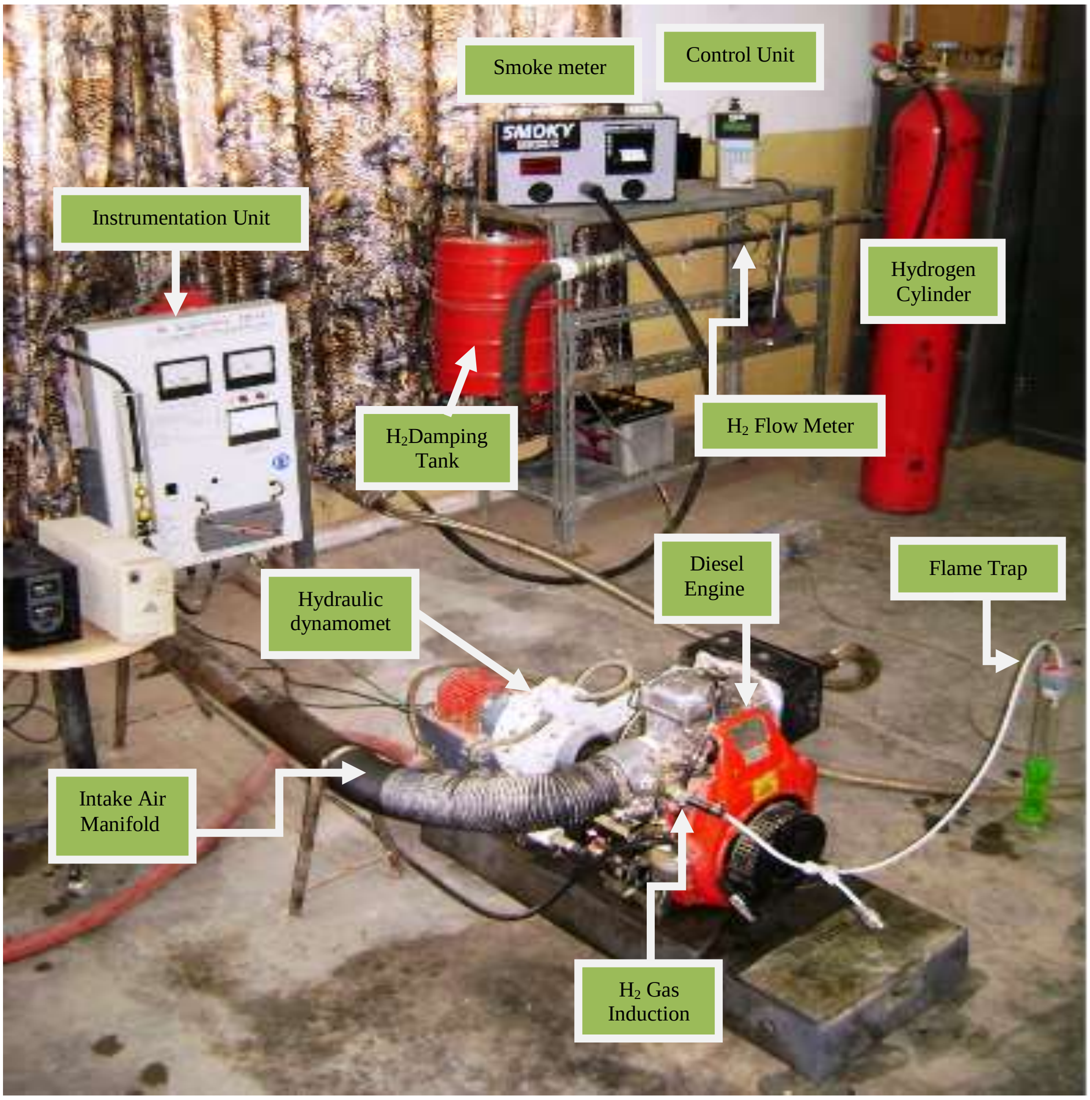



**Figure (1)Photographic view of Experimental Set-up**

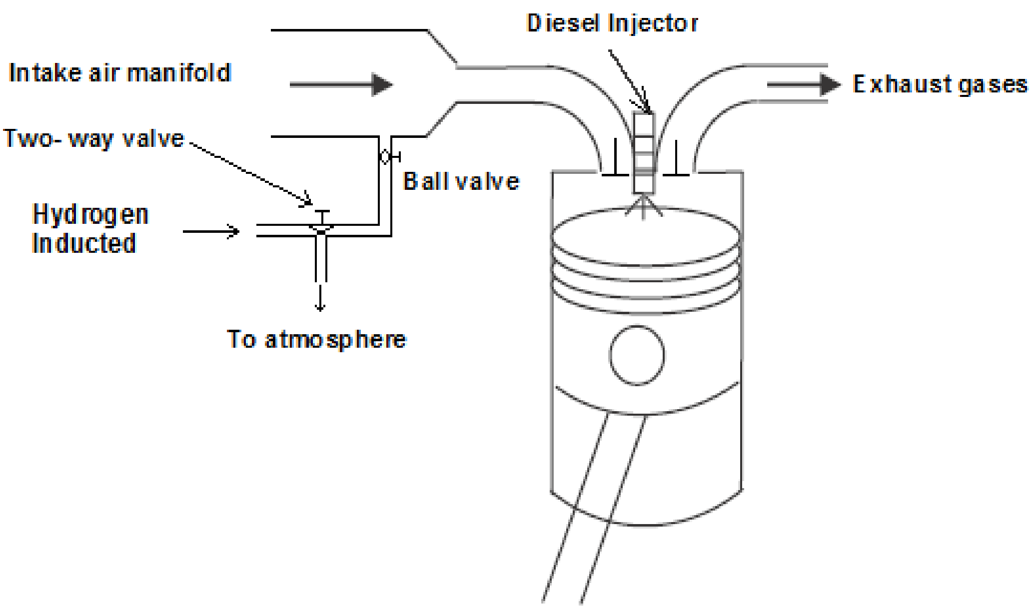
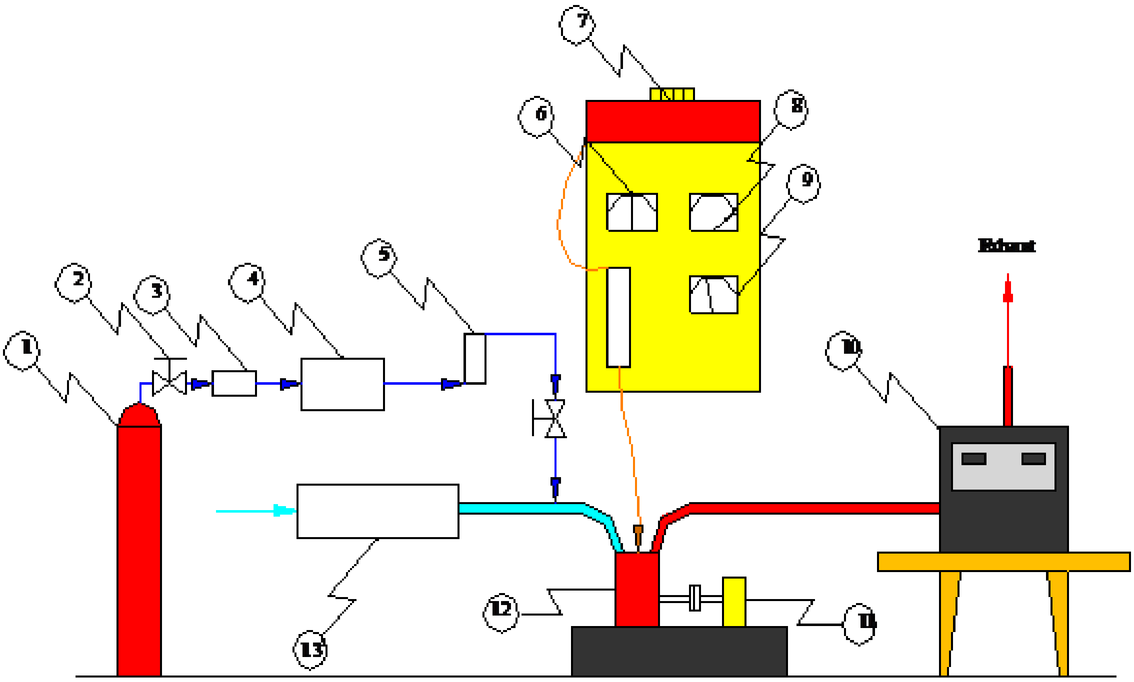



**Figure (2) Schematic diagram of Hydrogen Induction**




***Key:***<u>*</u>*1- Hydrogen source, 2-Ball valve, 3- Flow meter, 4- Hydrogen tank damper, 5- Flame trap, 6- Engine speed indicator, 7- Diesel fuel tank, 8- Engine torque indicator, 9- Exhaust temperature indicator, 10- Opacity indicator, 11- Hydro-dynamo-meter, 13- Intake air damper & flow meter.*

**Figure (3) Schematic diagram of experimental setup**

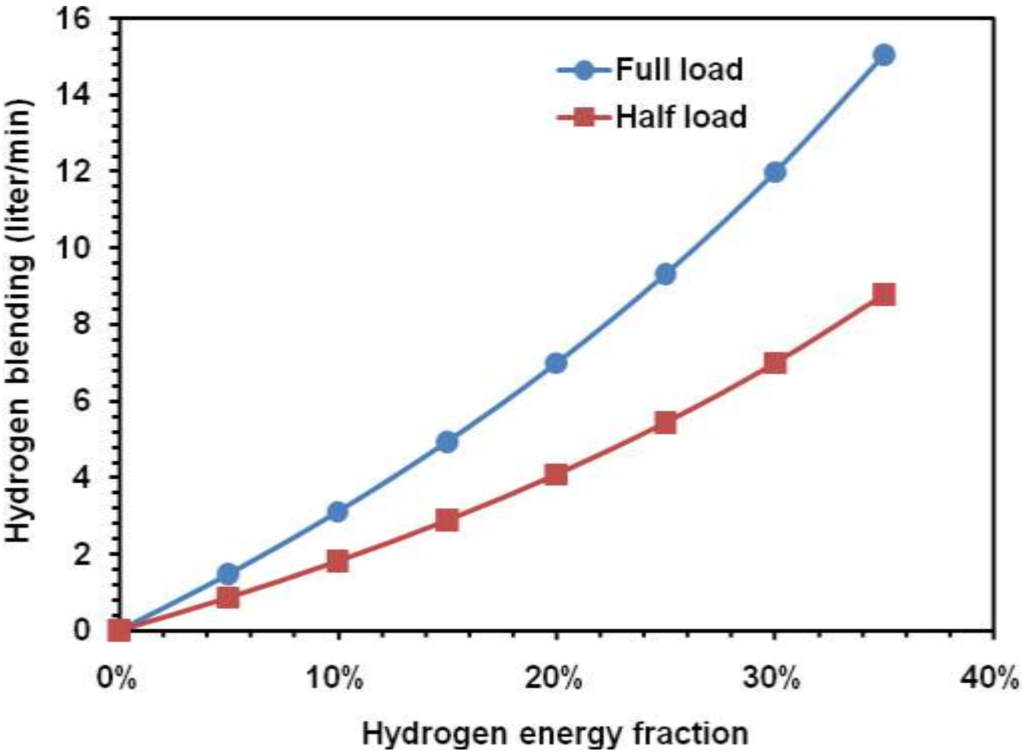



**Figure (4) Variation of hydrogen blending with hydrogen energy fraction**

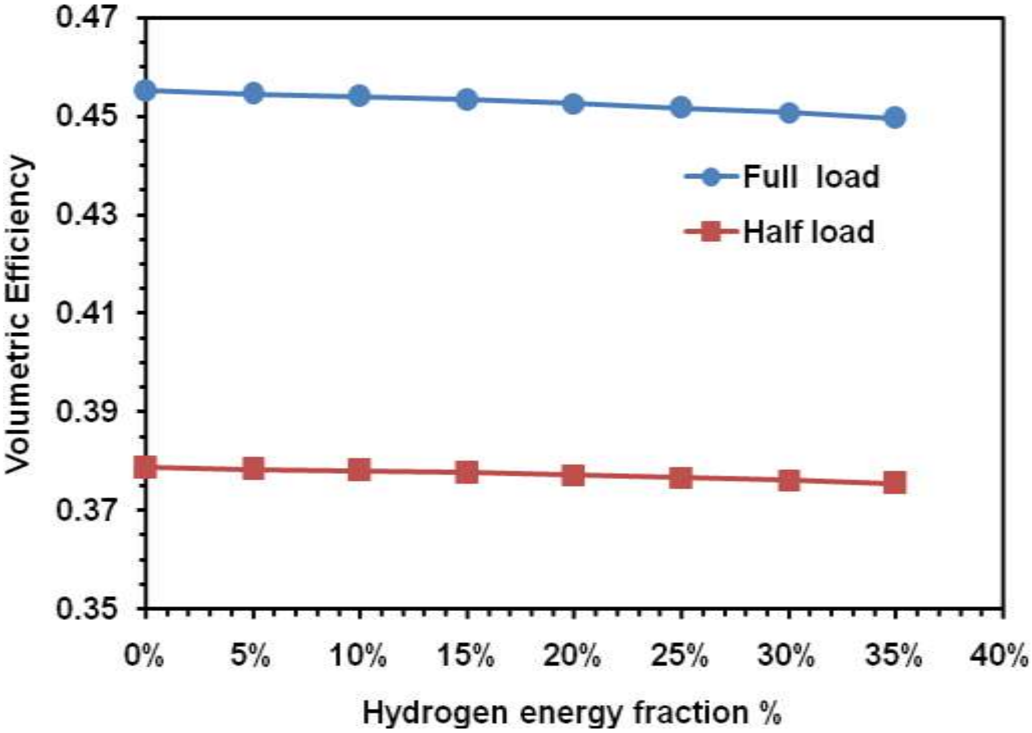



**Figure (5) Variation of volumetric efficiency with hydrogen energy fraction**

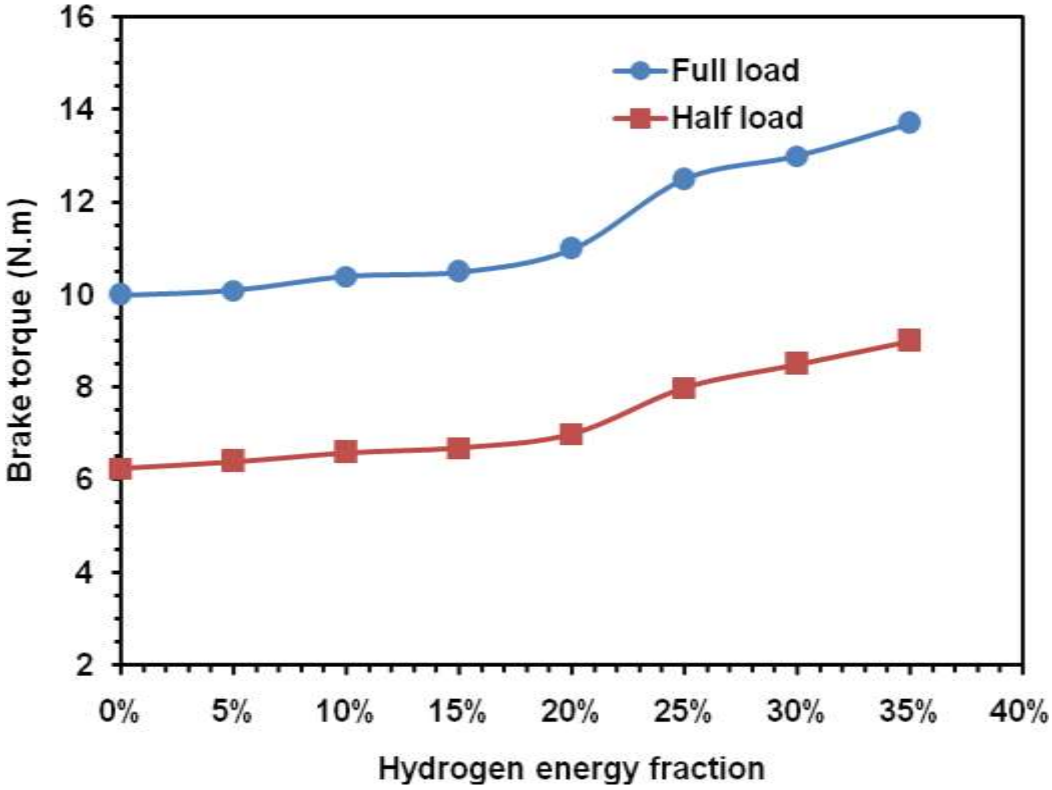



**Figure (6) Variation of brake torque with hydrogen energy fraction**

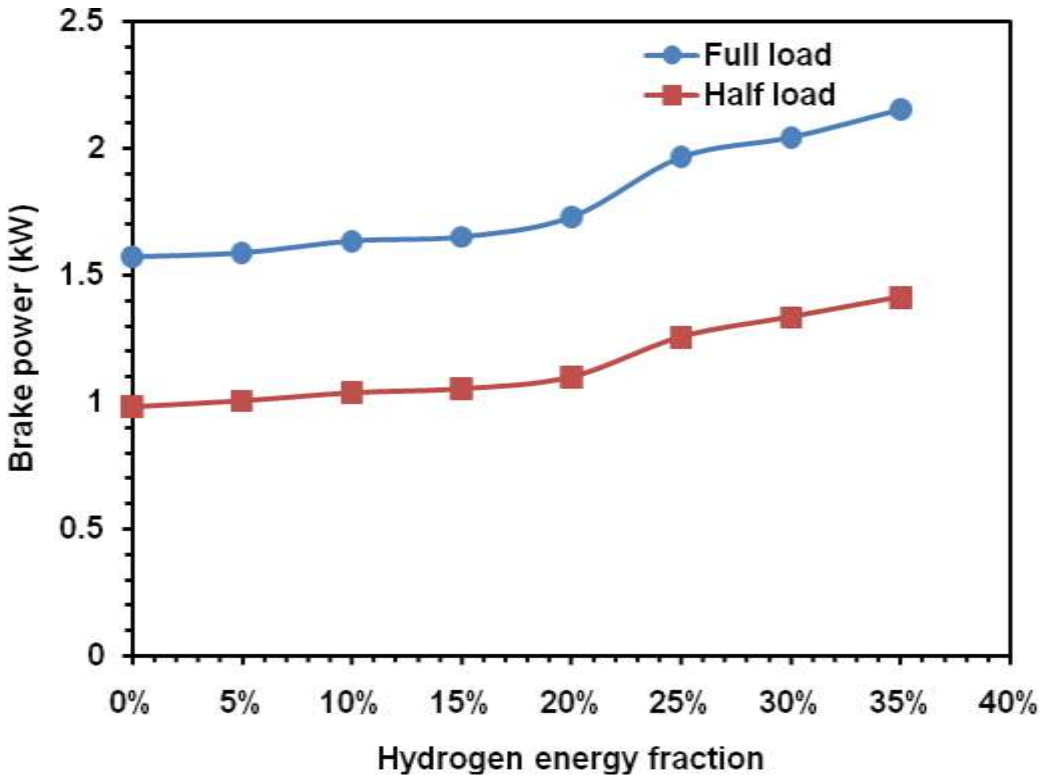



**Figure (7) Variation of brake power with hydrogen energy fraction**

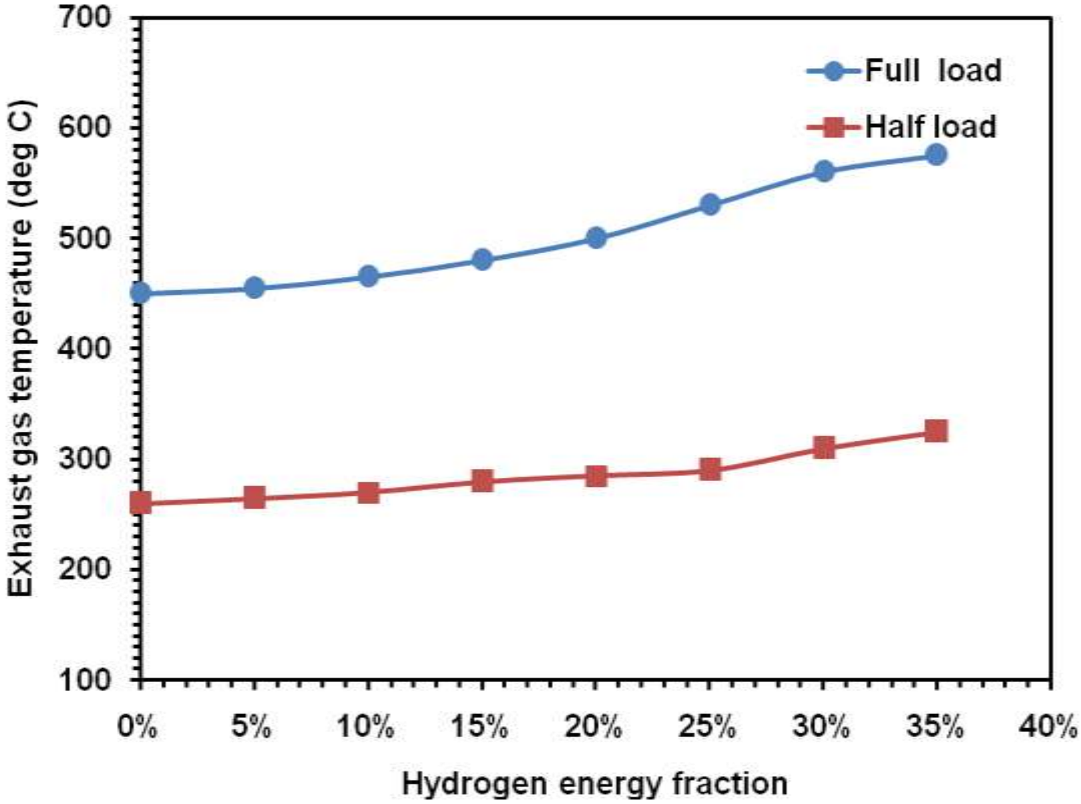



**Figure (8) Variation of exhaust temperature with hydrogen energyfraction**

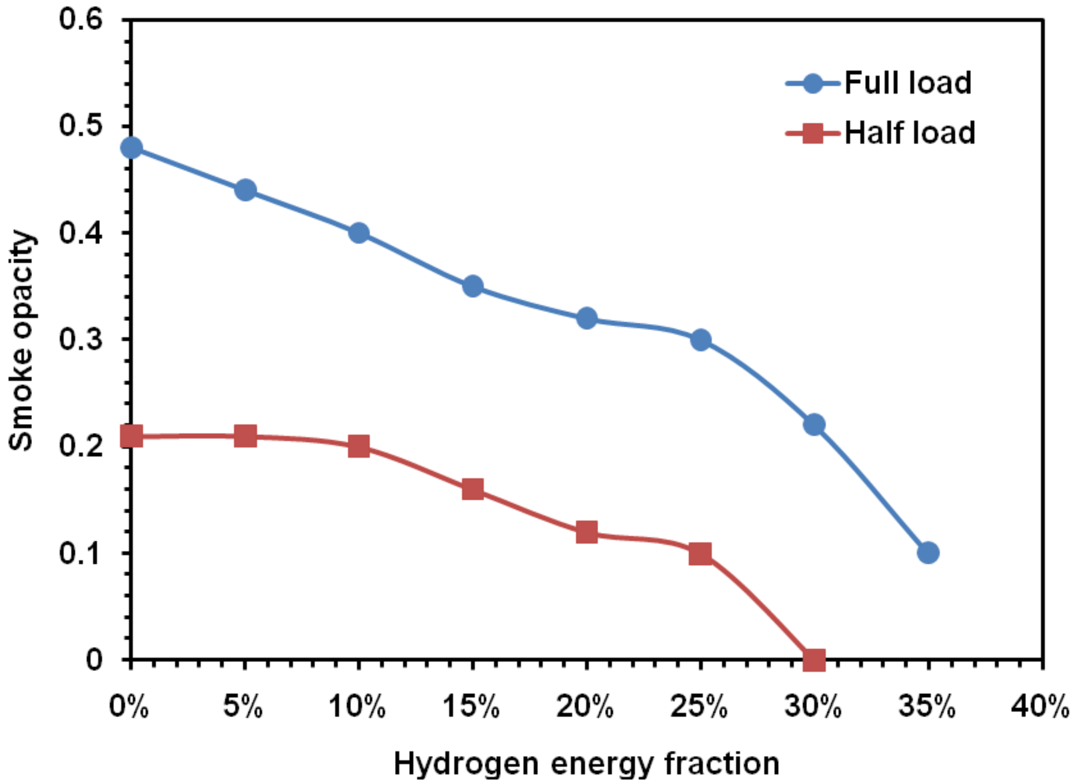



**Figure (9) Variation of smoke opacity with hydrogen energy fraction**

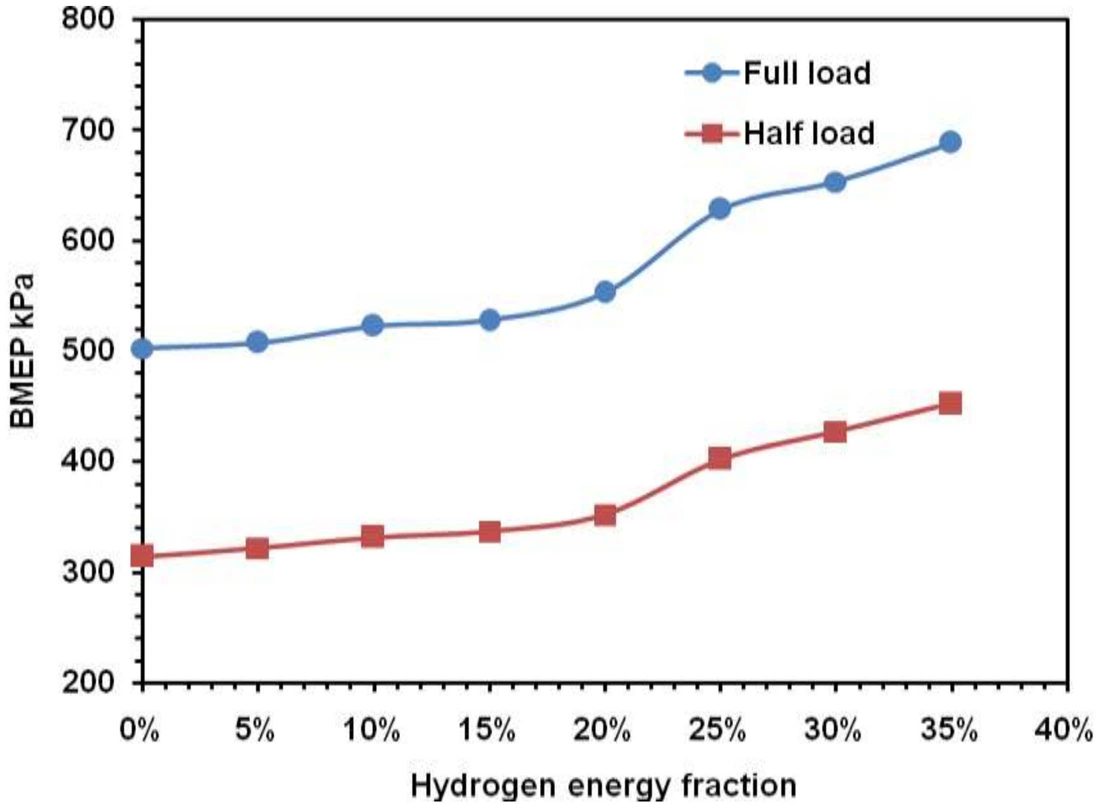



**Figure (10) Variation of brake BMEP with hydrogen energy fraction**

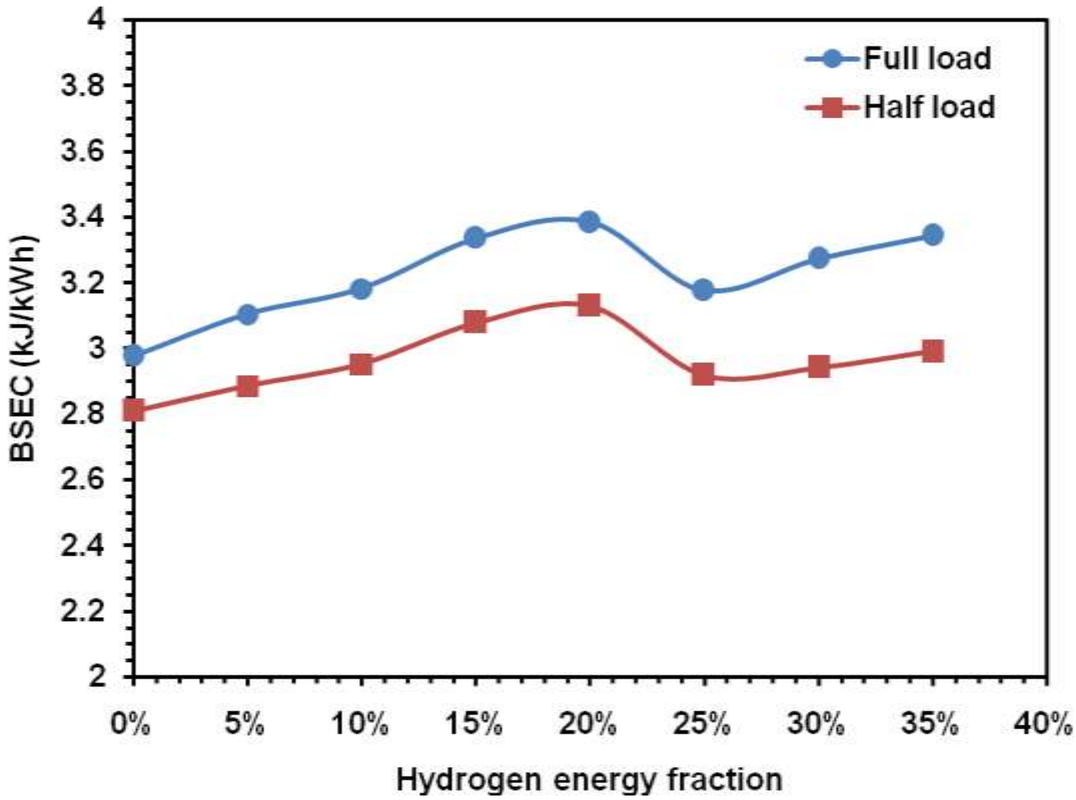



**Figure (11) Variation of brake BSEC with hydrogen energy fraction**

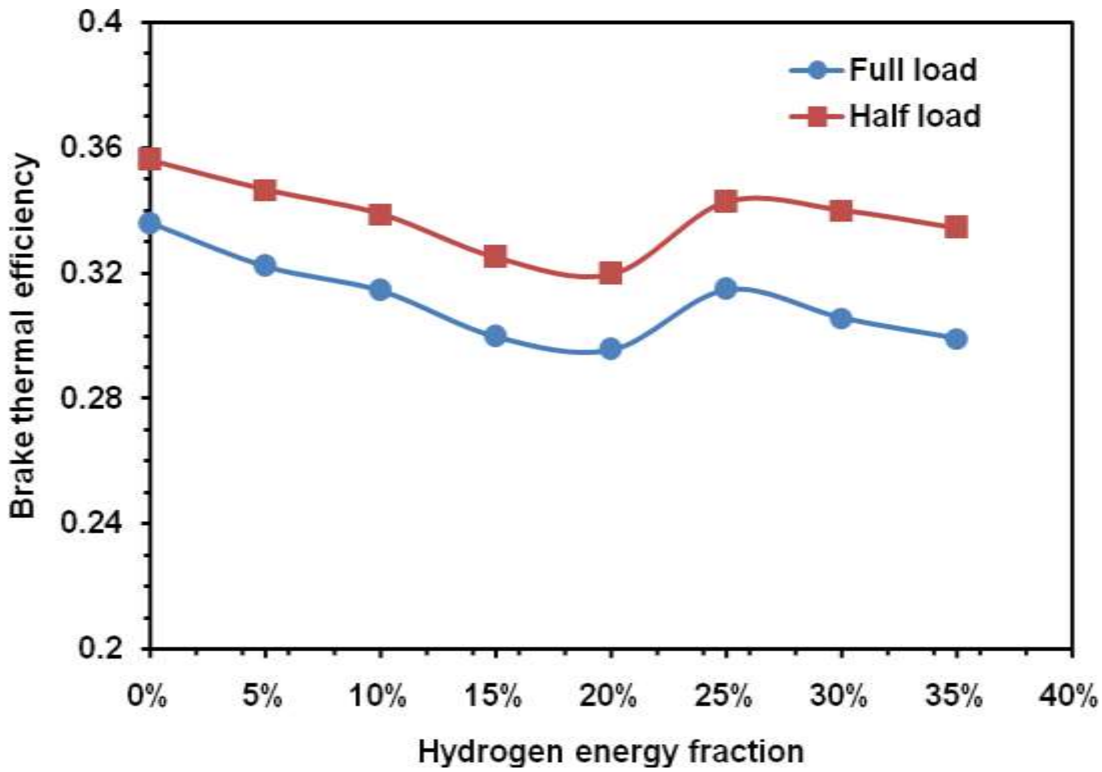



**Figure (12) Variation of dual efficiency with hydrogen energy fraction**

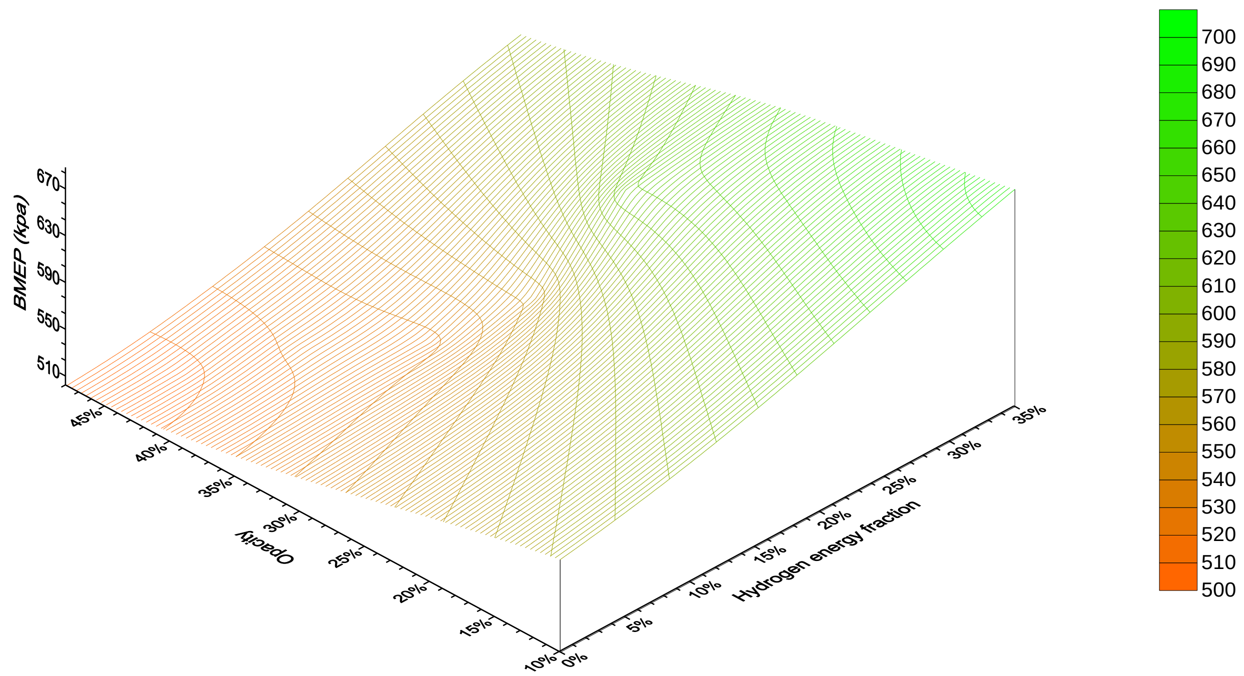



**Figure (13) wirefram variation of smoke opacity with BMEP and hydrogen energy fraction at full load**

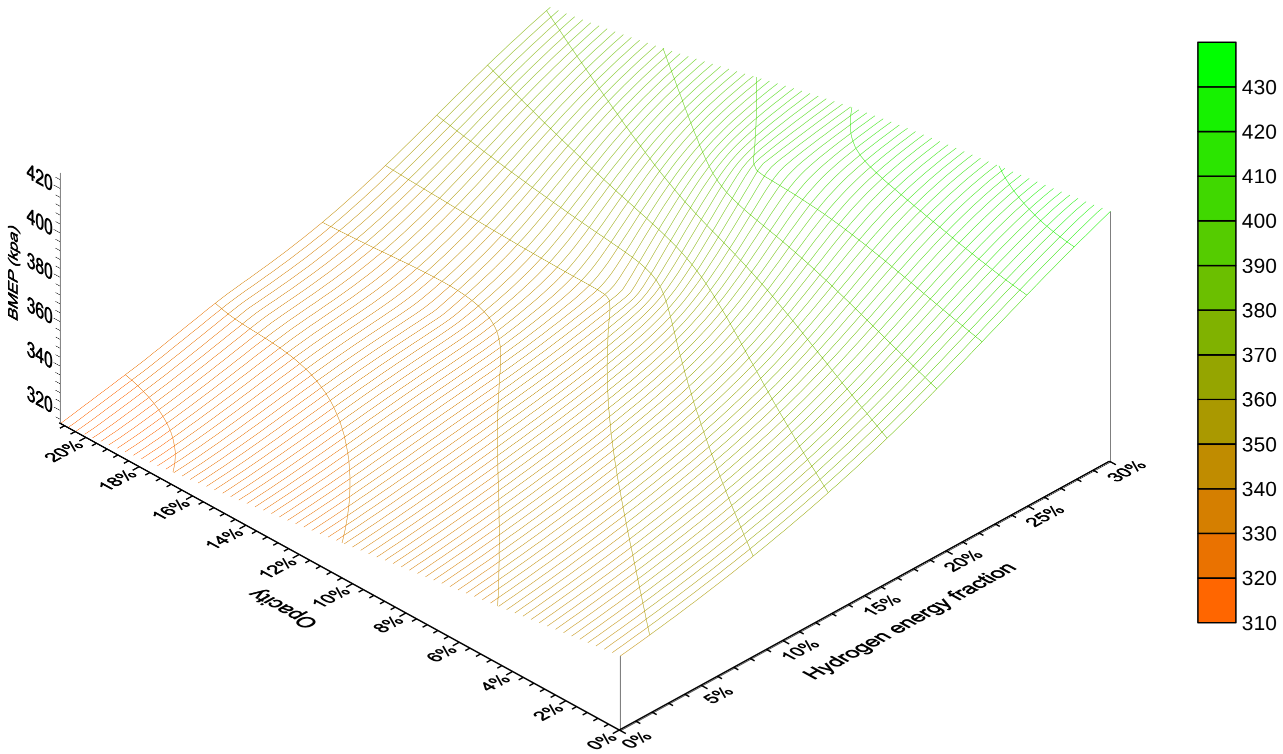



**Figure (14) wirefram variation of smoke opacity with BMEP and hydrogen energy fractionat half load**