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Optimizing Hydrogen Production Capacity of Plasmatron Diesel Reformer

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Abstract. To curb exploding nitrogen oxides emission, Plasmatron converter offers a simple technique to convert diesel fuel into hydrogen rich gas. The H2 rich gas can be used for NOx trap applications, improving lean burn and reducing burn duration. In the present work, a plasmatron device is fabricated using GI Pipe and electrode that produces low current non-thermal plasma. Two design of the device considering fuel inlet process is examined. The diesel reformate obtained is tested for hydrogen content by Gas Chromatography (GC) at four different fuel flow rates. The effectiveness of the designs is tested with respect to H2 content in the reformate and its corresponding fuel flow rate and found that atomized diesel spray using fuel injector is effective in comparison to fuel nozzle. GC results shows hydrogen quantity by volume percentage in the reformate is optimum within the range of 0.18g/s to 0.22g/s of diesel flow rate.

1. Introduction
The world, presently is rightfully implementing stringent emission regulation norms for automobiles and therefore technological advancement in engine emission control is the need of the hour. In 1995, Rabinovich et al. [1] received the patent for a novel plasmatron design for IC engine. The plasmatron can reform diesel into hydrogen rich gas which can be used to reduce toxic emission from IC engine [1, 2]. Andersson [3] claimed that addition of hydrogen into the premixed charge allow one to achieve higher lean air-fuel ratio thus reducing NOx emission. The hydrogen rich gas can also be used for exhaust after-treatment. A reducing agent is usually introduced into the exhaust to regenerate the catalyst. Use of plasmatron reformer generated hydrogen rich gas for catalyst regeneration provides important advantage [4, 5]. Bromberg et al. [4] is an extensive study on exhaust after treatment. The author finds that shorter adsorber/absorber regeneration time and larger range of regeneration temperature is attained by using the reformate. Bromberg et al. [6] reported that Plasmatron reformer addresses the problem of slow startup and onboard mobility; it can eliminate or reduce the use of reformer catalyst along with the advantage of quick fuel reformation. Moreover, fuel reformation using plasmatron requires no catalyst. A dual-leg NOx adsorber system was tested at Arvin Meritor using a Cummins 8.3L diesel engine. NOx trap regeneration was significantly improved compared to that of using diesel fuel directly. Results show significant decrease in fuel penalty, roughly 50% at moderate adsorber temperatures [5]. Hydrogen rich gas can be produced by the plasmatron reformer from normal hydrocarbon fuel such as iso-octane, diesel [7], natural gas [6], gasoline [8] and even biofuels [9]. Gallagher et al. [10] successfully reformed n-tetradecane with plasma in absence of catalyst. They tested the flexibility of gliding arc plasma in reforming wide range of heavy
hydrocarbons and concluded positively. Along with this advantage, the authors also reported fast start time and energy efficient reformation. Khani et al. [11] analysed the effect of non-thermal plasma on lubricating oil and n-hexadecane and found that the reaction results in the formation of hydrogen along with various other hydrocarbon compounds. This paper presents the experimental technique for reformation and the conditions for production of adequate hydrogen rich gas from diesel fuel.

1.1. Plasmatron Technology
One process of hydrogen production is catalytic reformation. This process is sensitive to fuel composition which is absent in plasmatron technology. Plasma is ionized gas which consists of photon, electrons, positive and negative ions, atoms, free radicals and excited or non-excited molecules. A plasmatron can operate either with thermal plasma or with non-thermal plasma. Thermal plasma needs high power and pressurized atmosphere. Non thermal plasma can be generated in atmospheric pressure and uses less power (about 200W) (Green et al., 2000[10]) and has the advantage in onboard applications. In this work non-thermal plasma is being used for reforming diesel fuel into hydrogen rich gas. The kinetics of fuel conversion reactions are known to be influenced by radicals like electronically excited oxygen, hydroxyl ions (OH) or atomic oxygen (O). Non thermal plasma produces highly energized electrons. These electrons can instigate processes like molecular dissociation resulting in formation of active chemical species that act as oxidizing and reducing agents [12]. The plasmatron fuel converter generates continuous plasma discharge which initiates the reforming reactions. In the process – discharge and the exothermic reactions - sufficient amount of energy is generated along with radicals. This energy is used for reformation of the remaining fuel in to hydrogen-rich gas.

However, for a plasmatron to work according to the theoretical assessment one need to make an error free design which can operate in a large range of parameters. The plasmatron have to be able to run for long hours together and be small in size so as to fit it onboard a vehicle. Design and operation plays a major role in the proper working of the plasmatron. Plasmatron designed by Bromberg et al. [4] showed higher reforming efficiency. About 15% of hydrocarbon fuel energy is released according to - partial oxidation reaction [4] inside the plasmatron. In this device the cross sectional area is filled with non-thermal plasma through which diesel-air mixture is passed. The experiment is conducted with different diesel flow rate. The details of the design process are explained in the later sections.

1.2. Development of Plasmatron Device
The Plasmatron device is designed considering maximum conversion of diesel fuel into hydrogen rich gas. Two different designs have been proposed with regards to the fuel inlet process. The first design involves use of a mechanical nozzle and the second involves use of electronic controlled fuel injector to spray atomized diesel into the reformer chamber. At the foremost, a 3D model of the device is prepared using modelling software package Pro-E Wildfire 12 Fig. 1(a) and (b). The model consists of two co-axial vertical cylinders having a clearance of 1.5 cm that serves as a water jacket for cooling purpose. They are fastened together by six hexagonal nuts at the bottom having the provision of incorporating the apparatus to the engine’s inlet manifold. The upper face is completely en-closed with two flanges with the help of four hexagonal nuts while the lower face is left open for passing out the reformate. An inlet and an outlet passage are provided in the water jacket to facilitate water flow thorough the reformate chamber.

Based on the 3D model, the plasmatron device is fabricated. The material selected for fabricating the device is Galvanized Iron (G.I). Galvanized iron being strong, tough, light in weight, cheap with low maintenance cost is considered to be in ideal candidate for fabricating the device. In between the two flanges, steel reinforced asbestos sheet is provided for insulation. The plasma produced in the device is non-thermal plasma, which are formed in atmospheric pressure and ambient temperature [13]. For the generation of plasma, a Bosch spark plug is used. The ground electrode of the plug is cut and removed. Instead the entire body of the apparatus is ground and thereby it acts as negative electrode (cathode). The central electrode of the spark plug thus acts as anode and a uniformly distributed intense spark length is obtained throughout the inner space of the apparatus. This turns the
atmospheric air to change into plasma state. Two nozzles with inlet diameter 3 mm and outlet diameter 2 mm are provided to serve the purpose of fuel and air inlet Fig 1 (c).

Fig. 1(a) and 1(b): Isometric and bottom view of the Pro-E model of the plasmatron respectively. Fig. 1(c): Fabricated model of the plasmatron.

2. Test Set up

The test set up consists of three basic units: the fuel supply unit, the plasma producing unit and the reformate chamber. The fuel supply unit consists of a fuel tank, fuel pump, an air compressor and a fuel nozzle which was later replaced by a 3-hole electronic fuel injector controlled by an electronic timer circuit Fig. 2 (a and b). The plasma producing unit consists of a spark plug connected to an ignition coil which acts as the electrode, a combination circuit of condenser and electromagnetic relay connected to the ignition coil that acts as a source of continuous generation of electric pulse. A 12 volt battery serves as an electrical power source Fig.2 (c). The reformate chamber, as mentioned earlier consists of the plasmatron embodiment.

Fig. 2(a): Plasmatron fitted with a fuel injector nozzle. Fig.2 (b): Timer circuit for operating the fuel injector. Fig.2 (c): Battery with the ignition coil and relay circuit.

The experiments are conducted in two phases (for two different test setups) and for four different values of mass flow rate of diesel (0.18, 0.22, 0.25 and 0.29 gm/s), keeping the air flow rate and pressure as constant. In the first phase of experiments, the mass flow rate of diesel is calculated by measuring the mass of diesel collected in a measuring flask and the corresponding time taken. The nozzle is fitted into the plasmatron apparatus and the Air Compressor is switched on. After the compressor is filled with sufficient volume of air, the outlet valve is slowly opened and the air pressure is maintained to a constant value of 1.5 bar. The mass flow rate of diesel is maintained at a constant value and the plasma circuit is switched on. Diesel passing through the plasma region reforms into hydrogen rich gas. The reformate collected are basically fumes which are pale white in colour. However it is found that light drops of diesel starts dripping from the plasmatron apparatus which indicates that only 20% of the total amount of the diesel in being reformed. To encounter the problem, the nozzles are replaced by a petrol engine fuel injector which is operated by a timer circuit. Diesel is supplied by a submersible fuel pump.
This is the second phase of the experiment, where similar experimental procedures are conducted using the fuel injector instead of the nozzles. The experiments are conducted for the same values of diesel flow rates. The reformate successfully collected in all the four experiments are found to be dense and no diesel is found leaking from the device. The reformate mass collected are stored in separate sample collection container and are labelled as S1, S2, S3 and S4. All the four gas samples are tested for hydrogen content by Gas Chromatography analysis using a Perkinelmer, Clarus 600 GC-MS Analyzer.

![Experimental set-up before and after modifications](image)

**Fig. 3(a) and (b): Experimental set-up before and after modifications respectively.**

### 3. Results and Discussion

The results obtained by Gas Chromatography analysis of the four samples are plotted in Fig. 5(a) – 5(d). The plot displays formation of adequate percentage of hydrogen gas with some unevaporated compounds of diesel fuel; C10: n-decane, C11: n-undecane, C12: n-dodecane, C13: n-tridecane, C14: n-tetradecane, and C15: n-pentadecane, carbon compounds and nitrogen gas. The hydrogen percentage is comparable to (Bromberg et al., 2003[5]). The percentages of hydrogen by volume in four different samples are tabulated in Table. 1.

![Graph showing hydrogen percentage](image)

(a) $H_2 \% = 29.90$

(b) $H_2 \% = 34.10$
Fig. 4(a, b, c and d): GC plot of plasmatron reformate samples (S1, S2, S3 and S4) at constant diesel flow rate (0.18, 0.22, 0.25 and 0.29 gm/s) respectively.

Table 1. Diesel reformate and hydrogen content percentage for four different samples.

| Sl No. | Sample No. | Diesel flow rate (g/s) | Hydrogen content in the reformate (%) |
|--------|------------|------------------------|--------------------------------------|
| 1      | S1         | 0.18                   | 29.90                                |
| 2      | S2         | 0.22                   | 34.10                                |
| 3      | S3         | 0.26                   | 36.30                                |
| 4      | S4         | 0.29                   | 38.60                                |

Figure 5. Variation of Hydrogen content with respect to diesel flow rate.

It can be observed from Table 1. that the rate of hydrogen production by volume increases with increase in diesel flow rate and is maximum for the tested diesel flow rate of 0.29 g/s. Figure 5 shows the variation of hydrogen content with diesel flow rate considered. It can be visualized from figure 5 that as we gradually increase the flow rate from 0.18 to 0.29 g/s the quantity of hydrogen produced...
increases. The trend clearly indicates that the hydrogen production is related to the diesel flow rate. On close observation, we see that the increase in hydrogen percentage corresponding to increase in diesel flow rate is maximum in the range of 0.18g/s to 0.22g/s which is 4.2%. However with further increase in diesel flow rate the increase in hydrogen production is less (2.2% increase for 0.04 g/s increase in diesel flow rate and 2.3% for that of 0.03 g/s). Therefore we can conclude that the optimum working condition for the designed plasmatron is in the range of 0.18 g/s to 0.22 g/s of diesel flow rate.

4. Conclusion
In the present research work, an attempt has been made to optimize diesel flow rate into the novel Plasmatron device in order to obtain maximum percentage volume of hydrogen in the reformate. The Plasmatron device is designed and fabricated in such a fashion that an array of non-thermal plasma can be generated. Diesel fuel has been considered for the testing purpose. The reformate produced from the Plasmatron is tested for hydrogen percentage by GC analysis. The following inferences can be drawn from the plots of the GC results:
   a. The optimum range of diesel flow rate for this plasmatron is between 0.18g/s to 0.22g/s.
   b. Increasing diesel flow rate above 0.22g/s is not advisable because it may lead to decrease in reformation efficiency.

Further modification to generate stronger plasma in the plasmatron can create higher hydrogen production capacities. This can be achieved by designing a higher voltage plasma circuit.

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