Experimental Investigation on Compact Current Non-Thermal Plasma Assisted Hydrocarbon Reforming Hydrogen Rich Gas

P. Rajkumar[1]*, B. Prem Anand[1]

[1] *Department of Mechanical Engineering, FEAT, Annamalai University, Annamalai Nagar, Tamil Nadu, India.*

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On-board vehicle hydrogen-rich gas extraction of gasoline reforming utilizing for fuel cells and GDI-engine lean burn combustion enhancement NOx trap applications. A non-thermal plasma discharge electrode that produces a reduced current, increased voltage 15kV source arc plasma fuel reformer is designed to operate at an arc frequency of 50 Hz. The operating factors gasoline equivalence ratio between 4 and 6.and electronically control by the fuel injector and eliminating ground spark plug plasma arc generation. The plasma arc non-thermal reformer gasoline converted into gas that contains partial oxidation contains combustible gases thermodynamic combustion equation formulas using solve chemical components hydrogen (H_2), CO, non-combustible gases like CO_2, N_2, and a small quantity of H_2O. The non-thermal plasma technology alternative for on-board hydrogen vehicle applications.

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*rajkumarme2014@gmail.com

I. Introduction

Compact plasma enhanced reformers are an effective way to convert various hydrocarbon fuels, such as gasoline, diesel and natural gas, into hydrogen-rich gas. Researchers looked into a new kind of plasma reformers that use a non-thermal plasmatron with a low current and high voltage. When compared to thermal arc plasma reformers, the specific electrical power consumption and electrode wear can be significantly reduced by using a low current nonthermal reformer. This paper details the operation of the new plasmatron setup.

Plasma reformation depends heavily on electrical energy, which is its biggest drawback. To get around this issue and significantly cut down on energy usage, this research describes a novel low current nonthermal reformer.

Hydrogen can be produced on board from hydrocarbons (reforming) for fuel cell feed, although using conventional catalysts can cause issues. Issues with poisoning, a lengthy transitory time, and heavy devices make integration onboard vehicles difficult. Recent years have seen the use of hydrocarbon reforming techniques aided plasmas arc non-thermal for hydrogen extraction in response to these issues. Utilizing a variety of novel methods, this cutting-edge technological assessment elucidates the essential features of plasma reforming.

The GEN 2 low-current plasmatron fuel converter uses a spark plug as the cathode and injects fuels and oxidants close to the electrode gap. The GEN 3 fuel reformer is a wide-area electrode, low-voltage plasmatron device that allows for the injection of species at various inputs through concentric electrodes with an axial gap. While

GEN 1 is a thermal plasma reformer, GEN 2 and GEN 3 are referred to in opposition to it [1–3].

Research is conducted on propane reforming in a plasmatron fuel reformer. The impact of reformation on flow rate dispersion and energy level is examined for a geometry previously researched with methane. As the O/C ratio drops, reforming becomes more plasma power sensitive. At higher O/C levels, plasma is primarily required for startup. At lower values of O/C, startup is power efficient [4].

Investigated gliding arc discharge reactors for methane conversion was facilitated by syngas. A 2.5-liter reactor stainless-steel sheet that was placed on top of the apparatus. Prior to entering the test chamber, power input extending from 3 to 12.11 MJ/kg with partial oxidation reaction warmed to temperatures ranging from 573 to 873 K [5].

Studied methane partial oxidation was carried out using the Gliding arc in Tornado reactor, which utilizes the modern tools of movable circular electrodes. Air was injected in a tangential direction and methane in an axial direction. The reacting components are preheated using an heat exchanger that is attached to the 0.2-liter GAT reactor. The DC power source, which operates at a high voltage, generates about 200 W electricity [6].

Designed an exclusive combined fuel processor to create hydrogen for uses in fuel cells from commercial gasoline and n-octane. The processor autothermal reformer, enhance thermal WGS reactor. A variety of catalysts are used to study the temperature progression at 35% H2 (under the theoretical maximum value) and 1% CO. High temps inactivate catalysts [7].

Experimented with a plasma arc non-thermal model that can reform gasoline at various fuel flow rates using auto-thermal and steam reformulation conditions reliability and adaptability were key design goals for the prototype. The technology of the GA system is crucial to the development of this reactor [8-13].

Studied the PO_X process test gasoline featuring a hydrogen-towards-carbon ratio near 1.93, using a nickel catalyst. Compared to the thermodynamics limitation of 98%, the efficiency was found to be 78.5% with a corresponding source fuel powering 42.64 kWth [14].

Investigated a fuel processor that uses a process involving water gas shift, partial oxidation, and autothermal reforming stages for reforming a fuel containing a conventional formula of $C_{7.494} H_{14.53}$. Operating at 87.16 kWth of input fuel power, the gadget achieved an efficiency of 79%. Full power was said to be reached in 140 seconds, with a startup time of 20 seconds [15].

Studied integrated fuel processor for octane and gasoline reformation that stands alone. The efficiency varied between 62% and 70% while requiring relatively little equivalent input fuel power, ranging between 1.44 and 1.56 kWth [16].

Plasma's strong reactivity produces a variety of activated species, radicals, and ions, making the process non-selective. Directly placing the catalyst in the plasma zone or using post-plasma catalysis may improve product production synergistically. Dry reformation of methane (DRM) showed that NTP and the catalyst synergistically increase liquid fuel chemistry yield [17].

The molecules of carbon dioxide and methane are extremely stable, making it impossible to use one-step catalysis to transform them into liquid products. Here, NTP provides a novel approach to enabling low-temperature thermodynamically unfavourable chemical processes, made possible by the non-equilibrium nature of plasma. Gases can be converted into non-thermal plasma by introducing an electric current. Reactive species are created when CH_4 molecules are excited, ionized, and dissociated by electrons heated by an applied electric field. This allows chemical reactions to take place at temperatures and pressures close to ambient conditions. In contrast to its industrial-scale use in trash incineration and ozone manufacture, the activation of CH_4 to produce fuels and chemicals has only been tested in labs so far. The current consensus is that NTP will pave the way for renewable energy to replace fossil fuels in chemical processes in the future, ushering in a more sustainable energy future [18].

The dielectric barrier discharge (DBD) plasma reactor was initially documented by Siemens et al. for ozone generation [19]. A dielectric layer exists between the two electrodes in this reactor. The pronounced preference for hydrocarbons is ascribed to the partial dissociation of CH_4, resulting in substantial quantities of CHx radicals ($x = 1 - 3$), which subsequently recombine to yield C_2H_6 and C_2H_4 [20].

The two electrodes were spaced 5 mm apart and a 0.5 g BZT ferroelectric film was placed in between them. The reactor was powered by 20 kV DC pulses. The range of GHSVs has been 85,000 to 85,000 h-1. In reference [21], a DBD reactor was shown that used mesh electrodes in an annular channel. Electrodes made of stainless steel mesh cover two quartz tubes that run in a coaxial configuration in the reactor. At the core was the high-voltage electrode, while its outermost point was grounded. A discharge gap measuring 3 mm separated the 55 mm long discharge zone. The flow rate ranged from 25 to 100 mL/min, and the mixture used was a 1:1 molar ratio of CH_4 to CO_2. The reactor's operating parameters were a variable frequency of 30–40 kHz and a peak–to–peak voltage of 24 kV. In [57], an alternative design for a coaxial DBD reactor was introduced. An AC high voltage output (40 kV) was attached to the outer electrode in this reactor, while the central electrode was grounded. The area of discharge was 90 mm. The flow rate of the reactant was 50-300 mL/min. Water was used to cool the electrodes. The coaxial DBD reactor in question made use of a cylindrical dielectric tube (10 mm i. d., 40 cm length) lined with aluminum mesh [22].

A BZT ferroelectric film (0.5 g) was placed between two electrodes separated by a distance of 5 mm. The reactor functioned at direct current pulses of 20 kilovolts. A GHSV has fluctuated between 8,500 and 85,000 h–1. A dielectric barrier discharge reactor including an annular channel with mesh electrodes was presented in [23]. The reactor has two coaxial quartz tubes enveloped by stainless steel mesh electrodes. The high-voltage electrode was centrally located, whereas the outer electrode was grounded. The discharge zone was 55 mm in length, with a discharge gap of 3 mm. A CH_4/CO_2 mixture with a molar ratio of 1 was introduced at a flow rate of 25–100 mL/min. The reactor functioned at a peak-to-peak voltage of 24 kV with a variable frequency ranging from 30 to 40 kHz. A distinct design of a coaxial DBD reactor was introduced in [24].

On-board vehicle hydrogen-rich gas extraction of gasoline reformation using for fuel cells and GDI-engine lean burn combustion augmentation NOx trap applications. The fuel reformer is engineered to run at an arc frequency of 50 Hz and uses a non-thermal plasma discharge electrode to generate a reduced current with an increased voltage of 15 kilovolts.

II. Analysis of GC-MS Gasoline Evidence of Hydrogen Rich Gas Components

Gasoline is a complex mixture of several hydrocarbons, which are compounds that include both hydrogen and carbon. The BTEX compounds—benzene, ethylbenzene, toluene, and xylenes—along with butane, pentane, and isopentane are among the approximately 150 hydrocarbons included in a standard gasoline combination. A GC-MS analysis of ordinary gasoline's total ion current chromatogram is displayed in Fig. 1.

Gasoline partial oxidation reformer under extremely fuel-rich circumstances. The exothermic nature of reaction results in a lower heating value (LHV) for the Partial oxidation (POx) gas, which is about fifteen percent lower than the entering gasoline.

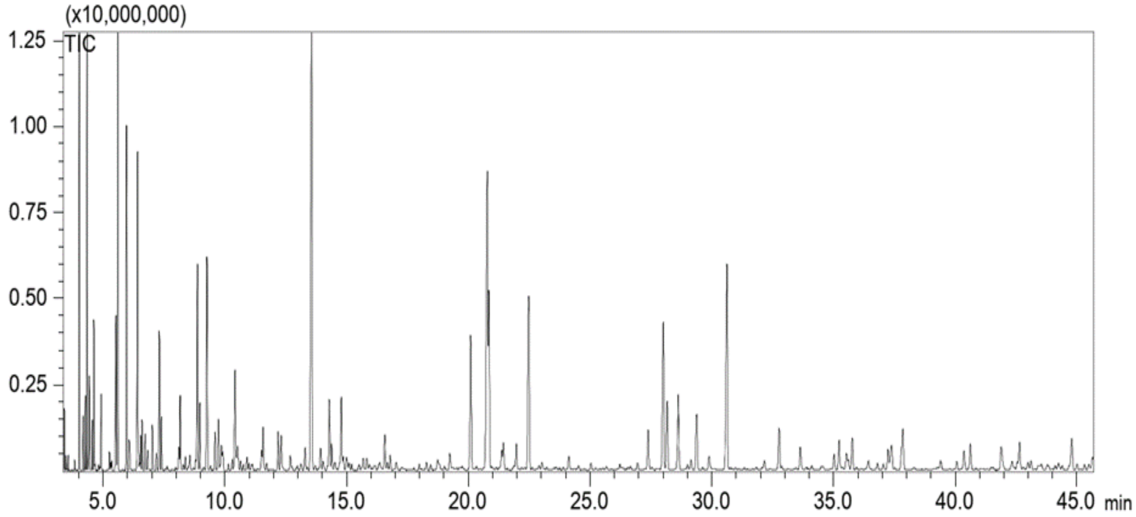

Fig 1: Analysis of GC-MS gasoline total ion current chromatogram

Retention Time	Compound Name	Retention Time	Compound Name
3.240	Isobutane	20.084	m-xylene
4.020	Isopentane	22.487	o-xylene
5.259	Cyclopentene	24.130	n-nonane
6.101	1-hexene	28.641	1,3,5- trimethylbenzene
7.024	Trans -3- methyl-2-pentene	32.167	n-decane
7.193	2,2-dimethylpentane	33.640	Indan
7.988	2,4-dimethyl-1-pentene	35.768	1,3-dimethyl-5-ethylbenzene
8.160	Benzene	37.034	Methyldecane
9.129	Cyclohexane	37.244	1,4-dimethyl-2-ethylbenzene
10.410	n-heptane	40.354	1,2,4,5-tetramethylbenzene
14.387	4-methylheptane	41.875	5-Methylindan
16.560	n-octane	44.788	Naphthalene

Table 1: Gasoline GC-MS compounds Identification

III. Design and fabrication of Non-Thermal Plasma Arc Fuel Reformer

The main body of plasma fuel reformer has plasma arc produce - zone for the reaction of gasoline, Fig. 2 depicts the location of the fuel injection zone as well as the heat exchanger zone. The plasma generation-reaction zone developed a collector and a chamber for reactions. The spark plug's ground electrode was removed to create the anode, and a steel cylindrical chamber makes up the cathode. the electrodes are carefully polished with emery sheets to eliminate any burs or protrusion that may have been present. In order to generate a plasma arc between the electrodes, the spark plug is positioned vertically atop the cylindrical chamber. During the partial oxidation procedure, a plasma arc is kept at a temperature of around 870℃. In order for the incoming air fuel combination to be transformed into reformat gas, the cathode assembly directs it to go through the plasma arc. The plasma fuel converter takes the homogenous charge from the surge hub and turns it into hydrogen-rich gas, other combustible gases, and gases that are not combustible.

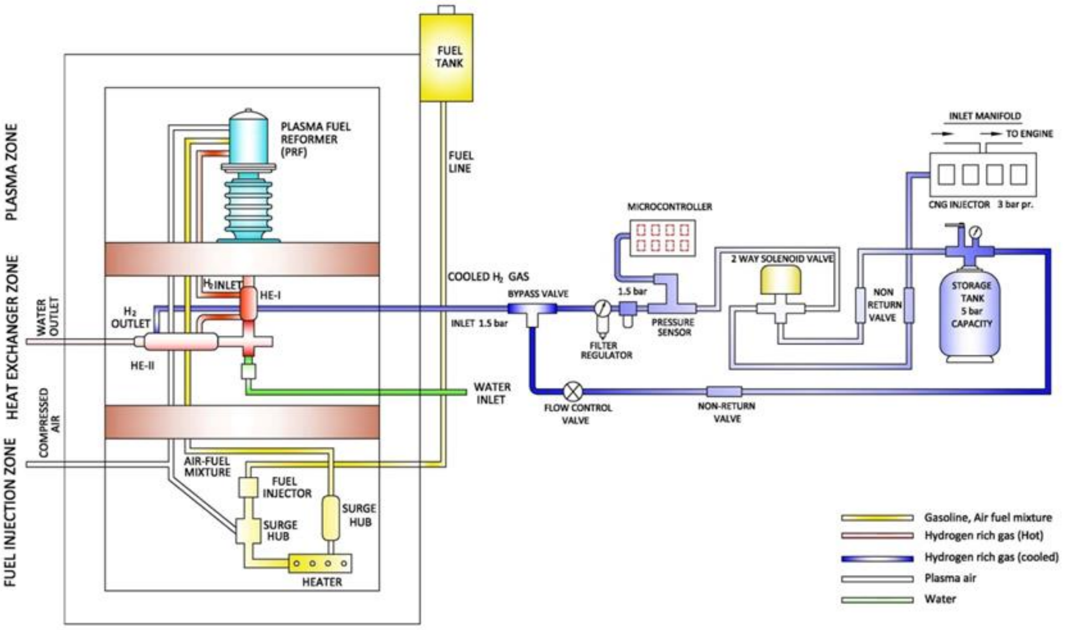

Fig. 2: Schematic view of Plasma Arc Non-Thermal Fuel Reformer

Plasma Arc Non Thermal Reformer	Specification
Plasma Arc Input	12 Volts
Anode Dia.	1.82mm
Injection Fuel	0.41 to 0.61 kg/h
Plasma Arc Output	15 kV
Plasma Arc Length	26-36 mm
Plasma Arc Frequency	50 Hertz
Oxygen/Carbon ratio (A)	0.6 – 0.87

Table 2: Particulars of the specification of Plasma Arc Non-Thermal Fuel Reformer

The process continues with the plasma's gas being routed via two counter flow heat exchangers that are positioned at right angles to each other. A substantial reduction in temperature occurs in the transformed gas within the heat exchanger zone. In order for the PFR to function (Tab. 2), the plasma arc output is 15 kV and the plasma arc frequency 50 Hz. The operating factors gasoline equivalence ratio between 4 and 6.and electronically control by the fuel injector and spark plug plasma arc generation. The plasma arc non-thermal reformer gasoline converted into HRG under partial oxidation conditions.

IV. Thermodynamic Analysis of Partial Oxidation Gasoline Plasma Arc Non Thermal Reactions

The non-thermal plasma arc reformer efficiency defined as the amount of plasma arc that is current in H_2 at the result from the reactor in comparison to the amount of plasma arc that is input at the beginning from the fuel. We are operating under the assumption that a multi-H_2O shift stage will result in the release of hydrogen from carbon monoxide.

Following that, the effectiveness of the reformer is determined by using the following relationship:

$$\eta_{\mathrm{ref}} = \frac{(\mathrm{n_{CO}}+\mathrm{n_{H2}})\Delta \mathrm{H_{H_2}}}{\mathrm{n_{fuel}}\Delta \mathrm{H_{fuel}}+\mathrm{NP_{ele}}} \quad (1)$$

With n_{H2} plasma arc non thermal reactor releases as a molar flow of hydrogen, n_{CO} the level of carbon monoxide released by the plasma reaction, n_{fuel} gasoline flow rate as input, ΔH_{H_2} combustion at a lower temperature for hydrogen, ΔH_{fuel} The lower combustion temperature of isooctane (44 × 10^6 J/kg) and NP_{ele} Energy transferred to the gas through plasma discharge.

The plasma arc non-thermal can only operate with a plasma arc frequency of 50 Hz and an output voltage of 15 kilovolts conversion rate to converted into gaseous hydrogen, CO_2 and light HC in the plasma arc reactor. The following equation is used to evaluate it:

$$\mathrm{U_{Gasoline}} = \frac{\mathrm{n_{CO,dry}}}{\mathrm{n_{C,in}}} = $$
$$= \frac{\mathrm{n_{CO,dry}} + \mathrm{n_{CO_{2.dry}}} + \mathrm{n_{CH_4,dry}}}{7\mathrm{n_{C_{8.26}H_{15.5}}}} \quad (2)$$

In order to determine the amount of air that is injected into the reactor, the air proportion α is utilized here. There is a relationship between the quantity of oxygen that is injected air and the quantity of oxygen that is required the complete burning of fuel. This relationship is referred to as the air ratio.

1 mole of gasoline burned stoichiometrically $C_{8.26}H_{15.5}$

$$\mathrm{C_{8.26}H_{15.5}} + 12.1(\mathrm{O_2} + 3.761\mathrm{N_2}) \rightarrow 8.26\,\mathrm{CO_2} + 7.75\,\mathrm{H_2O} + 45.5\mathrm{N_2} \quad (3)$$

1 mole of gasoline burned partially oxidized $C_{8.26}H_{15.5}$

$$\mathrm{C_{8.26}H_{15.5}} + 4.1(\mathrm{O_2} + 3.761\mathrm{N_2}) \rightarrow 12.39\,\mathrm{CO} + 11.62\,\mathrm{H_2O} + 22.75\mathrm{N_2} \quad (4)$$

The chemical energy of the gasoline utilized to make the hydrogen rich gas will be greater than that of the plasma reformed gas since the PO_X exothermic chemical reaction. The PFR efficiency measures these losses and is calculated by dividing the Lower Heating Value (LHV) of the gas turned out by plasma reforming it by the LHV of the gasoline that was used to produce.

The plasma arc non thermal partial oxidation of hydrocarbons is the predominant process, and because to the increased CO_2 level, a high conversion of gasoline is accomplished with a low efficiency. When compared to the energy efficiency, which remains from forty to fifty percent, The range of conversion rates is rather significant, increasing from seventy-five to over ninety percent. An oxygen to carbon ratio of 1 brought about the maximum energy efficiency, which was equal to forty-eight percent This should be compared to the 67% that was produced from calculations based on thermodynamics equations.

Table 3. Partially oxidizing heptane and gasoline, and then thermodynamically burning HRG, are the three topics under consideration here. The standard equation of combustion for hydrogen rich gas is taken from [25-30].

Equivalence ratio ϕ	H_2	CO	N_2	CO_2	H_2O
4	16.87	15.71	63.81	0.81	2.89
5	18.77	16.12	59.21	1.22	4.71
6	19.92	16.37	56.27	1.47	6.12

Table 3: The stoichiometric theoretical equation for hydrogen-rich gas combustion.

V. Results and Discussion

V.a) Plasma Arc Regimes

Fig. 3 illustrates the time-dependent dry molar percentage of the reformate gas production under plasma arc non-thermal reforming circumstances (oxygen/carbon) 0.81 and water/Carbon) 0.44, with a net input electric power of 15 kilovolts.

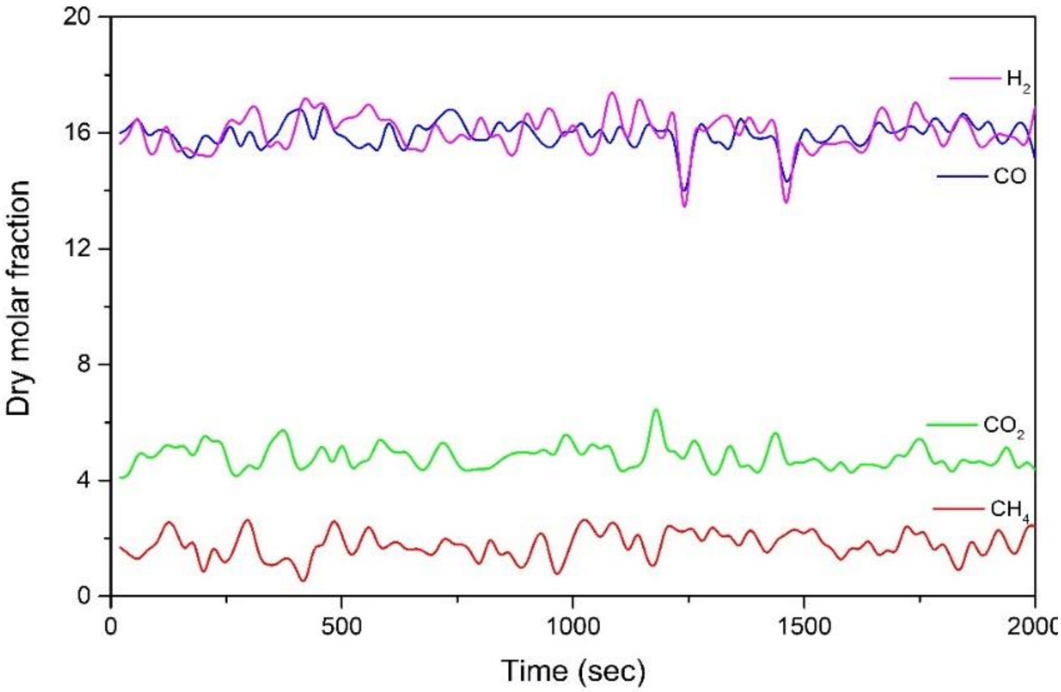

Figure 3: The dry reformate molar fraction that is produced over time with an oxygen to carbon ratio of 0.81 and water to carbon ratio of 0.44 under conditions of a 15kV net input power supply.

Mean dry volume fractions were very stable, fluctuating by less than 1%, as shown in the figure. The average molecular concentrations of CH_4 = 1.2, CO_2 = 4.9, CO = 16.4, H_2 = 16.7 correspondingly. Results from the experiments demonstrated that the electric discharge regime had a significant impact on the reformatted composition.

V.b) Effect of Oxygen to Carbon and Water to Carbon Ratios

The ratios of oxygen to carbon and water to carbon are used depict composition of reactant mixture, which consists of steam, gasoline, and air. Full partial oxidation occurs when the water-to-carbon ratio is zero and the oxygen-to-carbon ratio is one. It is preferred to raise the water/carbon ratio in order to achieve better hydrogen yields. The essential to balance with partial oxidation due to the endothermic reforming activity, though. The oxygen/carbon ratio, as opposed to the water/carbon ratio, is generally more important for reforming. As a result, we will conduct a more accurate water/carbon analysis when we have determined the influence of the oxygen/carbon ratio.

Fig. 4, observe the relationship between the oxygen/carbon ratio and the dry molar proportion of the reformate composition. These outcomes were achieved using a water/carbon ratio of 0.44 and an electrical plasma power of 21% based on the lower thermal value of the mass flow rate of the gasoline entering the system. The main cause of error bars is variations in the content of the reformate. This figure shows that as the oxygen/carbon ratio grows from 0.92 to 1.27, the molar fractions of hydrogen and carbon monoxide drop 22% to 16% and 21% to 16%, respectively. In the same oxygen/carbon range, carbon dioxide concentrations rise by 3% to 4% but the volume of the methane molar fraction stays relatively stable at around 1%. An increase in plasma energy and the number of byproducts from combustion H_2O, CO_2 are both caused by an enhancement in the oxygen to carbon ratio. The first thermocouple shows a rise starting at 1143.15 K. The outcome is a reduction in the molar percentage of hydrogen and oxidation of its content in reformate gas.

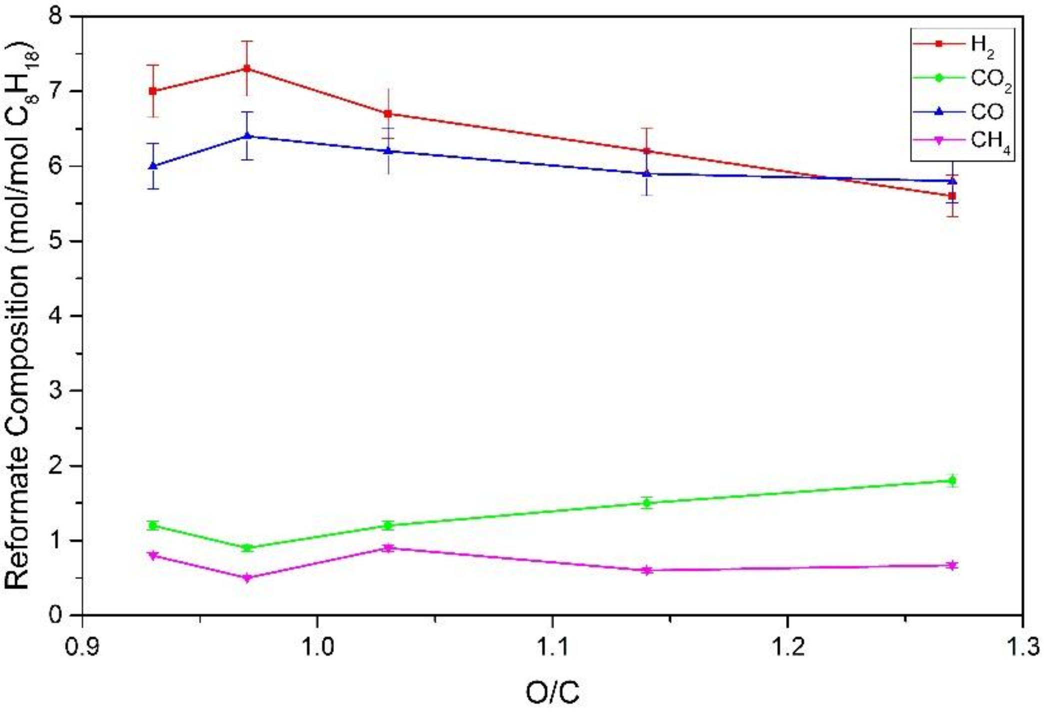

Figure 4: The resultant reformate molar fraction is plotted against the oxygen/carbon ratio using a water/carbon ratio of 0.44 and a plasma power source that is 21% of input low heating value gasoline.

In Fig. 5, observe the energy effectiveness and conversions rate of gasoline for the components shown in Fig. 4. When the oxygen/carbon ratio rises, the two parameters are impacted in the opposite way. Higher gasoline converting at low effectiveness because of the enhanced CO_2 level is a result of hydrocarbon oxidation dominating the process.

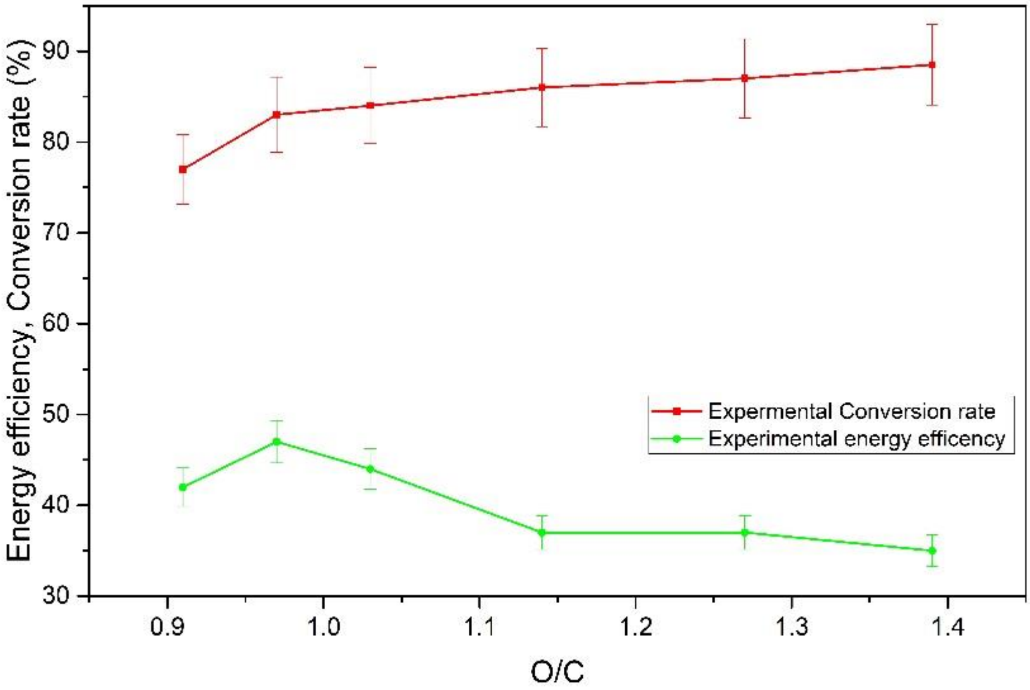

Figure 5: The efficiency and rate of conversion are influenced by the oxygen/carbon ratio, with a water/carbon ratio of 0.44. The net electrical plasma is equal to 21% of the incoming gasoline's low heating value.

Observe that conversion rates rise from 77% to almost 90%, with energy efficiency staying put at 40% to 55%. Energy efficiency reached a peak of 48% at an oxygen/carbon ratio of about 1, which is comparable to the 69% achieved through thermodynamic calculations.

Fig. 6 illustrations the reformate component as a reaction of the water/carbon ratio. The research results were achieved using an oxygen/carbon ratio of 1 and plasma power equal to 12% of the lesser thermal value of the gasoline used for input.

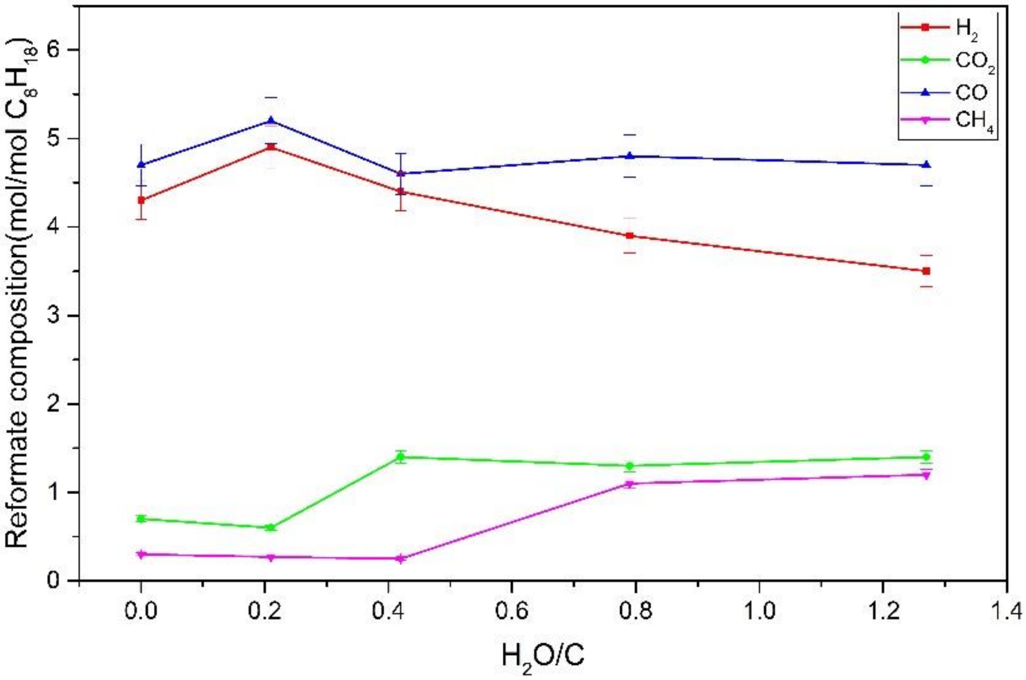

Figure 6: Analyzing the resulting reformate component in relation to the water/carbon ratio, assuming an oxygen/carbon ratio of 1 and an overall electrical plasma power that is equal to 12% of the low thermal value of the inward gasoline.

Initially with a minimal water/carbon ratio, the generation of HRG increases smoothly within the range of 0 to 0.2 partial oxidation. Then, as the water/carbon ratio rises, it produces a steady rise in CO_2 and CH_4 and a slight drop in hydrogen and carbon monoxide.

Fig. 7 illustrates the bond between the water/carbon ratio and the energy effectiveness and gasoline rate of conversion. At a water/carbon ratio of 0.2, the results shown in Fig. 5 indicate the optimum achievable efficiency. An increase in the water/carbon ratio lowers the conversion rate and energy efficiency within the subsequent range. This drop is accounted for by the reformate the chemical compounds, that contains a lower concentration of carbon monoxide and hydrogen. On this range, the energy efficiency at thermodynamic equilibrium is around 69.7%.

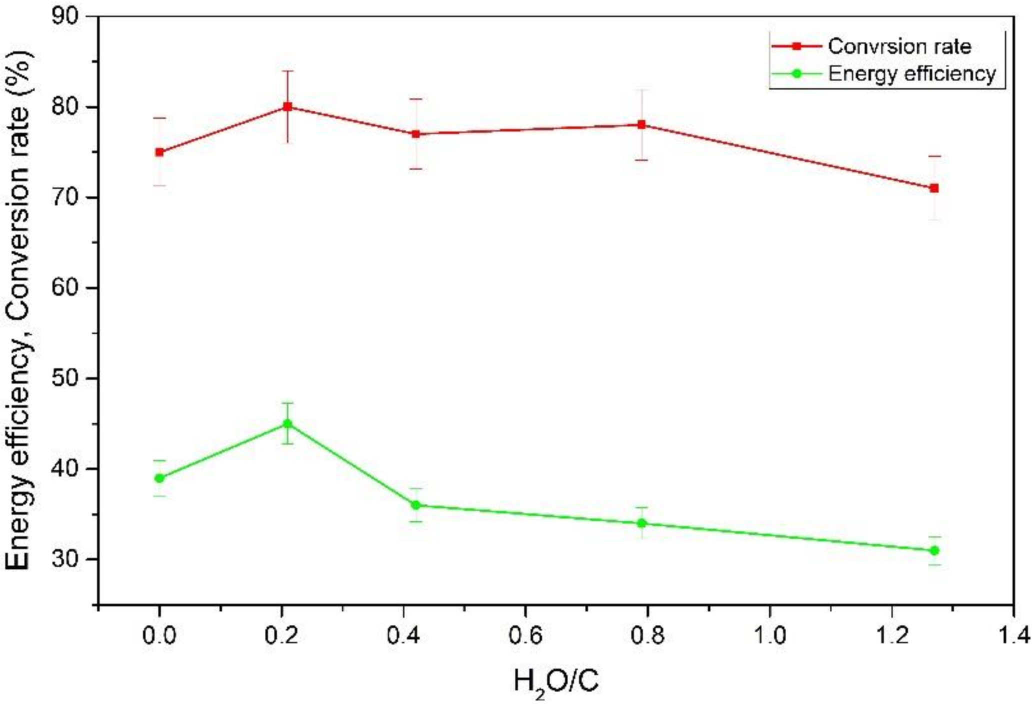

Figure 7: Efficiency and rate of conversion Vs water-to-carbon ratio with oxygen-to-carbon =1 coupled with an electrical plasma power net equal to 12% of the low-heat-value input gasoline.

Researching the parameters of the initial composition (the ratio of oxygen to carbon and water to carbon) reveals that the optimal performance is reached at an oxygen/carbon ratio = 1 and a water/carbon ratio = 0.2. the energy needed to accomplish the non-thermal plasma reforming reaction has been balanced out by the heat losses caused by the plasma arc exothermic reaction.

VI. Conclusion

The utilization of a non-thermal plasma high voltage, low current plasma arc for reforming commercial gasoline investigated. The electrical power produced spark plug 15kV generate the plasma arc of about 870◦C is maintained for the partial oxidation reaction. Thermodynamic optimization of the non-thermal plasma reformer upgrades should lead to more hydrogen rich gas output. Exothermic reactions (partial oxidation reforming) counteract the significant heat losses in the current system, making it unsuitable for endothermic steam reforming.

This research demonstrates that the plasma reformer can produce hydrogen rich gas. Furthermore, in comparison to other plasma reformers, excellent energy efficiency and gasoline conversion rates were achieved the investigated oxygen to carbon ratio range. The best results were observed at oxygen to carbon = 1 and water to carbon = 0.21, with τ = 80% and η = 41%, respectively.

The non-thermal plasma technology can become a clean NOx trap into heightening the technology for on-board vehicle technique.

VII. Acknowledgements

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