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REVIEW ARTICLE

A Study on the Transient Plasma Ignition (TPI) for ICEs with Bio-Gas Propulsion

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ABSTRACT

The surge in the population growth rate and a manifold increase in the use of vehicles which affects the greenery of the earth, has promulgated the need for innovations in Transient Plasma Ignition (TPI) systems. This study signifies how important that an Internal Combustion Engine (ICE), which is used in automobiles, must use a system that reduces the emission of harmful gases released during the combustion and emission phases. TPI system is concentrated as its high energy producing features can very well ignite biogas which requires a very high temperature to burn. Biogas being a renewable source of energy, also adds to the benefit of using it. This study also emphasizes the need for using biogas for preserving the greenery of the environment. Combating the NO_X emissions has now become so challenging that many research works are being carried out to reduce its emission during fuel exhaust. The ability of TPI incorporated with biogas to reduce NO_X gas emission during the exhaust process of ICE is studied. TPI, on comparison with other non-thermal low efficient transient plasmas was found to be better in igniting the renewable biogas completely.

Keywords: Internal Combustion Engines (ICE), Transient Plasma Ignition (TPI), NO_X, Biogas, Exhaust.

1. INTRODUCTION

Combustion engine works on the principle of generating mechanical power by the combustion of a fuel. Combustion engines are usually classified as, Internal Combustion Engine (ICE) and External Combustion Engine (ECE). ICE is concentrated here. For years, the ICEs are classified depending upon the fuel that is used in them. The most common ICEs, coined as the conventional engines generally use petrol and diesel to ignite the fuel-air mixture during the combustion process that releases energy to propel the whole system [1, 2]. Though, these engines have the sufficiency to burn the fuel, inducing high temperatures within the combustion chamber, is an advantage to faster ignition of ICEs. The disadvantage lies in the fact that they emit gases that are harmful. Thus petrol and diesel engines have flaws of creating damage to the environment. The NO_X emission during the combustion of these fuels can cause various harmful effects to both the environment and the people. Health effects are a serious matter of concern. Trying a fuel that is harmless, but at the same time, that doesn't exhibit a good burning property for combustion is of no use at all. The efficiency that ICEs enjoy when conventional non-renewable fossil fuels are used should never be compensated. So, using a better and efficient ignition technology that ignites a renewable green fuel, that doesn't spare the efficiency of ICEs and controls the exhaust gas during combustion and exhaust is studied here. The ICEs are so important for automobiles to function. We just can't replace them with any other engines. So, a proper ICE must be created that introduces a better ignition technology to improve efficiency and reduce the NO_X emissions during combustion. In the exhaust phase, a better gas must be introduced as a fuel to again control, the NO_X gases that are released during the exhaust phase.

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Plasma Assisted Combustion (PAC) is a technique where its applications in ICEs allow more efficient usage of fossil fuels in the sense that they transform fuels that are of low-quality into high-quality and minimize pollution by means of ultra-lean burn combustion. This PAC technology introduces reverse-vortex flow for their cooling; it also causes widening of the limits of flame creation and also provides wide choices of fuel selection. The study about PAC demonstrated that the direct electron impact dissociation of fuel in the plasma is relatively a minor effect compared to reactions with species generated in the plasma in the presence of oxygen compounds, such as O and OH [3].

Here, the TPI ignition technology which can exhibit a very high burning rate towards combustion by involving species of electrons to ignite the fuel-air mixture with less delay in ignition, no arc formation and without raising the temperature of the gas fuel is studied [4].

Now-a-days TPI is used due to their advantages over traditional spark plug ignitions. TPI exhibits,

- Reduced ignition delay
- Lean-burn capability
- Ability to ignite higher mass flow rates
- Improved efficiency
- Reduced emission
- Lower specific fuel consumption
- Fast burn rates

TPI which involves short ignition pulses typically in the range of 10–50 nanoseconds, has been shown to effectively reduce ignition delays and improve engine performance for a wide range of combustion-driven engines relative to conventional spark ignition systems [5]. TPI can suit the biogas fuel for better ignition so that both together can be used for the combustion of small ICEs meeting automobile needs. This leads to a greener ignition in vehicles which is a part of the study performed.

The processes that take place in the ICEs are intake, suction / compression, power/ ignition and exhaust. All these processes are given lights. These processes directly rely on the vision of reducing exhaust gas emissions and also creating an efficient combustion engine for automobiles. The intake process involves taking the fuel-air mixture where biogas is concentrated as a major fuel so that NO_X emission is reduced. The study greatly proves that ICEs can make use of a renewable gas in future which is harmless. Ignition is also focused, where the non-thermal transient plasma is used to ignite the biogas fuel. The intent of the study is to show that transient plasma being an effective non-thermal plasma can ignite the biogas. The exhaust gas released is also a major focus which shows the impact of harmful gases into the environment. Ecological safeness regarding the engines used in gas turbines to cause low-emission fuel combustion has been studied [6, 7]. Since years various mathematical models have been created to measure the toxic combustors, for gas turbines [8]. This depicts how keen interest was given in early days to reduce exhaust emissions in ICEs. So being people of modern generations, making use of all the best technologies that were found so far to create a new technology that only possesses the best features for a best ICE is a must. Among the two conventional technologies, such as Spark Ignition (SI) and Compression Ignition (CI), the plasma which finds its foundation from spark ignition is focussed and TPI is dealt in this study as a green and efficient evolution in the arena of ignition regarding ICEs. The source of power for TPI is mainly cell type.

Here non-equilibrium plasma which is also called as cold plasma or non-thermal plasma is used as a base in creating TPI technology. Although there is a wide choice of fuel selection for ICEs when using the TPI as an ignition technology, an alternative and renewable fuel i.e. biogas can be used as the fuel, as a replacement to the conventional fossil fuels, since biogas can be highly ignited by TPI.

Even more than a decade back, studies were formulated that pulsed power corona discharges that used plasma technologies in depths that had been utilized for air pollution control [9]. This shows how pollution has been given utter importance for decades. Studies have proved that plasma is used for environmental applications because of their low temperature [10]. This shows that we must create a better technology for achieving pollution control to the maximum. Though the plasma ignition technologies used in the olden days have controlled NO_X emissions [11] that led to clean gaseous emissions [12], when their features are compared with those of TPI, they still fall under a non-thermal low efficient technology as it mainly used conventional fuels that had a low burning temperature. While, the TPI being a non-thermal high efficient ignition technology can exhibit high engine combustion efficiency even if the fuel used is not of a high burning kind like the conventional fossil fuels. This study very well exhibits how TPI exhibits an extraordinary performance with a biogas to be benefitted for ICEs.

Incorporating TPI, which reduces NO_X discharge and also using gaseous fuel (biogas) that emits less toxic exhaust gas when compared to conventional fuels, form a strong foundation of our study thereby achieving two functions better combustion by TPI and better exhaust emission by biogas.

In this experimental study, first the focus falls on the plasma generation and ignition technologies and then by introducing TPI's features. It can be seen that TPI's feature make it efficient to ignite biogas. For this purpose, light also falls on the fuel properties of biogas that can cope with the TPI for better ICEs.

2. PLASMA TECHNOLOGIES – A FOUNDATION FOR TPI

Plasma is considered to be the fourth state of matter [13-15]. The sources of plasma have been discussed in various studies [16, 17]. The plasma falls under two categories listed below.

- Thermal plasma or hot plasma:

  In the thermal plasma, the energy exhibited by the electrons is of equilibrium. This energy further produces additional ionization influence in the gas together with extraordinary gaseous temperature.
- Non-thermal plasma or cold plasma:

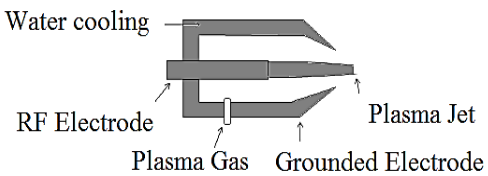
  In non-thermal plasma, the energy that is moved to the electrons from the source advances the reaction without increasing the gaseous temperature. From all the features that the other ordinary plasmas exhibit, TPI is found to be best and the previously used plasmas are said to be low efficient ones. In non-thermal plasma, small mass of electrons can be accelerated easily with the aid of electric charges. These highly energetic electrons produce free radicals, which later decompose the pollutants [18]. Non-thermal plasma has its applications in industrial, environmental, biomedical and agricultural arenas [19, 20].

2.1. Generation techniques of non-thermal plasma

Non-thermal plasma holds improvement over the thermal plasma and other conventional technologies [21]. Here the reactor types, electrode geometry, source of power to ignite, medium of the plasma discharge are important factors for generation of effective and economical plasma generation. Several researchers have engaged with DC source, AC source, high voltage pulse source like Marx generator, Blumlein line stack generator or compressed magnetic pulse source depending on their usages [22, 23].

2.1.1. Atmospheric pressure discharge plasma

The atmospheric pressure discharge is normally created by Atmospheric Pressure Plasma Jet (APPJ). This plasma is non-thermal plasma with a glow discharge that is functioning at atmospheric pressure [24]. Near the atmospheric pressure, regular collisions happen between neutral gas and high energy electrons [25]. This makes the high energy electrons to thermalize the plasmas in a very short period. To ionize the gas source, a mixture of helium, oxygen, argon was used. The discharge is ignited by the ionized gas producing high velocity of reactive chemical species [26]. Figure 1 given below represents an APPJ that can create plasma.



Adapted from [25]

Figure 1.Atmospheric pressure plasma jet

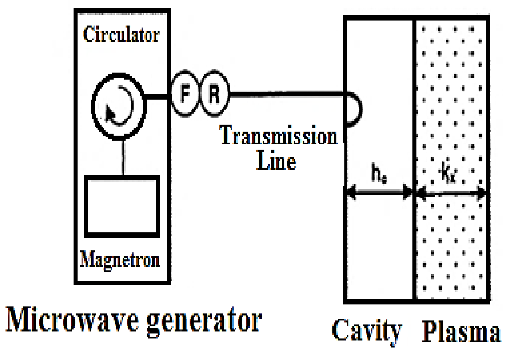
These plasmas have been used in several zones like surface modification of polymers, destruction of microorganisms, sterilization of medicinal equipment, blood coagulation, modulation of cell attachment, material processing and chemical vapour depositions.

2.1.2. Microwave discharge plasma

Microwave discharge is a kind of discharge plasma that shows high frequency where, the electromagnetic radiation happens in ranges of GHz. With the aid of this plasma, high density, large area, good uniformity and low electron temperature of gas pressures are reached [25]. The plasma excited by the microwaves that are non-thermal enjoys benefits like absence of electrode contamination, low gas flow rate and efficient power coupling [27, 28]. Here are some of the microwave discharge reactors [29],

- Multi-slotted planner antenna
- Microwave-induced plasma discharge
- Surface wave discharge
- Microwave electrode discharge

The configuration of the electrode can be parallel plate, cylindrical or hollow cathode, slot, needle, pin type. The microwave electrode discharges that happen here are produced in the place of the powdered electrode. The powdered electrode is an antenna or an exciter vessel. The main difference between the conventional and the microwave plasma discharge is that, here the volume of the plasma is controlled by the discharge vessel. The main feature of this discharge is that, the electrode erosion is absent here. A common microwave system is shown below in figure 2.



Adapted from [25]

Figure 2.A typical microwave plasma reactor system

The application oriented advantages of the microwave discharge plasma are,

- Elemental analysis
- Surface treatment
- Lightning and destruction of contaminated gases
- Sterilization of microorganisms and other applications [30].

2.1.3. Pulsed discharge plasma

An efficient non-thermal pulsed plasma discharge deserves a pulsed power source with voltage showing a fast rise, pulse of short width and of long life period. These necessities act as challenges to pulsed power generator, particularly for switch devices. Normally solid state Marx generator, Blumlein line stack, magnetic pulse compressor are being used as popular pulse source. The classification of the discharge depends upon the transmission as corona or streamer, spark or arc.

- Corona or streamer discharge:

  When the current and voltage are small and filamentary discharge channel are far from ground electrode, the corona or streamer discharge takes place.
- Spark or arc discharge:

  When the discharge channel attains a full development and is able to reach ground electrode, it is termed as spark or arc discharge. Generally the amount of current is very large in arc compared to corona or streamer discharge.

Thus this plasma has an increasing attractiveness than other methods that are used for plasma generation because of its advantages listed below [31].

- Simple nature
- Low cost
- High removal efficiency
- Smaller volume space
- Economic use for many military, industrial and environmental applications [32].

The greener and energy efficient technologies used so far that involve plasma for better ignition is studied in the section 2.2.

2.2. Greener and energy efficient technologies involving plasmas

The technologies discussed here attempts to completely combust the fuel, and also control harmful exhaust gas occurring in the combustion process of ICEs from entering into the environment, thereby creating an environmental friendly ignition. The involvement of plasma is the base to greener ignition. The fuel involved in the ignition must be fully made use of. The effective use of the full fuel involved makes the engine to run more effectively to a long distance. There exist some cases where the fuel used in the engine for combustion is not fully utilized or burnt. This can be overcome by adopting some techniques as discussed below along with using new technologies to increase the energy output to a higher level. Some of the modern technologies that exhibit greener ignition techniques are discussed below.

2.2.1. Laser ignition

In the laser ignition technology the triggering spark is achieved by the laser [33]. Thus, laser acts as an igniter here. Here the laser produces good source of energy. The deposition rate, and the period of the ignition that has to happen within the combustion chamber, can be easily controlled by laser. The laser ignition that exhibits advantages over conventional techniques is,

- Optimal ignition location:

  The optimal ignition location is found to be impossible in conventional ignition technologies. The spark introduced by the laser is found to have a good performance when compared to the spark that is initiated by the electrical spark from the electrical source.

- Multipoint ignition technology – inducing free plasma positioning:

  The conventional electrical sparks that are normally created by the spark plugs doesn't enjoy the property of the multi-point ignition technology [33].

  The sparks induced by the laser can enjoy the multi-point ignition technology, allowing the possibility of free position of plasma; also the flame travel can be reduced due to multiple ignition points that ignite the flame within the system [34].

The overall advantages due to the involvement of plasma are,

- No electrode erosion.
- Possibility to ignite lean mixtures.
- High correctness of ignition period.
- Combustion duration made low.
- Reduction in the distance of flame travel.

The disadvantage of laser ignition is that the cost of installation makes laser ignition impossible for commercial use.

2.2.2. Microwave assisted spark ignition

Here, the microwave's energy and the conventional spark ignition technology were used together. It relies on the improved combustion that happens through the electro-magnetic interactions in the gases. The non-thermal plasma is created here. In the combustion chamber, the free electrons absorb the microwaves discharged from the spark and create non-thermal plasma. The electron reactive species also improve the reaction rate. These electron impacts can breakdown the gas molecules into highly reactive species. The improvement in the rate of the combustion is because of these species. Electron impacts surge the ionization reaction by expanding the number of free electrons. Microwaves have been found to be better to pass energy to the electronic species to advance the performance of the reaction. Microwaves promote stable properties by regulating the speed of flames by kinetic effects. Microwaves also exhibit greater developments of combustion in leaner mixtures, when compared to the normal procedures, showing the same heat discharge. It is considered to be a high energy ignition system [35].

2.2.3. HCMI (Homogeneous Charge Microwave Ignition)

HCMI is an electromagnetic field ignition technique that uses both the spark ignition and the compression ignition. The source of this ignition is through the electromagnetic field [33]. Petrol and diesel are used as a combustion engine here to improve the efficiency of the fuel. The burning properties of the fuel are a matter of concern. Even if the fuel doesn't show excessive property to combust, the ignition method should progress the burning facility of the fuels. The spark and compression ignition principles of the ICEs that work with the fuels such as petrol and diesel don't ensue towards a successful and a whole combustion process. This in fact leads to surge exhaust emissions and causes the energy used to be very little. This is the reason why these two ignition basics can't help the aim to achieve full efficiency of the gas involved in the combustion process. So, extra processes need to be done during the period of ignition. There are various methodologies to advance the ignition property or ability of the engine, so that the fuel is fully utilized [36]. In HCMI, the volume based and zone based ignition methods are used. HCMI causes increase in the volume of the ignition that has led to high performance, lean-burn. It uses laser and the multi-point ignition procedure, where the number of ignition points increases. The volume of the ignition is increased further by using an improved energy and longer ignition period which is exhibited by the zone based ignition technology.

2.2.3.1. Transient plasma in the ignition phase

The transient plasma is produced during the ignition process. The transient plasma's volume depends on the performance of combustion and the speed of the flame front. HCMI, with increased ignition volume results in improved efficiency and low discharge of unwanted gas.

The drawbacks of HCMI are, it makes use of both petrol and diesel engines, which causes harmful gas emissions though its efficiency is more.

2.2.4. Advanced corona ignition system

The corona discharge is fundamentally a plasma in its transient, formative phase. The ICEs have paved way for the engineers to find a better approach to ignite the fuel-air mixture. To achieve periodical and electronic ignition, spark plugs were used. The drawback of spark plugs are, though they use electrical charge, the power produced by the spark only focuses on a limited area within the combustion chamber, thereby leaving the fuel- air mixture not to be fully ignited or burnt. But now other ignition technologies that makes use of plasma, ignites the ICE's chamber in a grand way so that the fuel is burnt fully and also there is decrease in fuel consumed by the use of a turbocharger. This technology makes the space of the engine very much a compact one [37].

This ignition system uses high-energy plasma to burn the fuel that is present within the combustion cylinder, also enjoying 10% reduction in the fuel that is to be consumed by the turbo charger. Also their high energy plasma that is spread throughout the combustion chamber burns the fuel more and results in a great and powerful explosion. The advanced corona ignition system overcomes electric and laser discharges for the following reasons:

- Better gas coupling by corona discharge.
- Lower energy losses since the radioactivity are low.
- Similar energy content streamers to start combustion.

2.2.5. Low temperature plasma reformer

This system is used in ICEs by utilizing power of about 12v/150w. This system used unleaded gasoline which is atomized with the aid of methanol water as a fuel. Supersonic atomization devices like plasma generator is created and also cooling devices by using low temperatures are utilized. This system produced hydrogen syngas, when the system was operated less than 45° C [38].

The advantage of plasma reformer is that, it works in low temperature and this system proved that the emission of CO and HC decreases while using the low temperature reformer system. But, the disadvantage is that, NO_X emission was increased when the temperature was increased, which spares the emission control.

2.2.6. Applied Plasma Technologies (APT)

This technique augments the reliability of ignition; the properties of instability of flames are avoided and also diminishes the emissions in a large variety of applications.

Adapted from [4]

Figure 3.Plasma igniter in operation

Figure 3 shown above represents the APT supersonic torch based on transient glow to spark discharge. This show a plasma igniter for gas turbines used in the industry. The plasma igniters are mostly based on thermal DC torches, RF initiators and MW initiators for sub flows and supersonic flows. Plasma igniters include their applications in land-based gas turbines. They consume power of about 500W to 1kW and produce plasma flow rate up to 1 g/s and their plasma has a life period of about 4000 operating cycles.

The advantages of applied plasma igniter over conventional spark plug are,

- Very higher plasma volume and velocity.
- Plasma volume causes deeper penetration of plasma plume, which is highly reactive into the combustion chamber for an enhanced ignition.

2.3. Limitations of plasma systems

Though the plasma sources and plasma ignition techniques studied so far have their own advantages, the above discussed plasma systems are only low transient plasma systems in the sense, they don't enjoy the full benefits of TPI that can fully ignite a high temperature burning renewable gas (biogas) as a fuel without adding conventional fuels to it [39]. The research which focussed on using an effective ignition technology that could ever support combustion in IC engines with biogas as a major fuel nowhere matches and has ever matched with the energy efficiency ignition techniques studied so far. Also this is a new attempt in introducing TPI to do so.

The technologies under 2.2 are termed as greener, only because the harmful gases are controlled in the combustion phase. But no focus was ever given by these techniques regarding the exhaust gas emission in the exhaust phase. Since the harmful exhaust emissions in the exhaust phase are not controlled, they can't be termed as fully greener.

The exhaust gas in the exhaust phase can be controlled only when unharmed gases like biogas are used as a fuel in full.

Section 3 deals with the properties of a biogas that can cause combustion and the engines that make use of biogas as a supplementary fuel (biogas added with conventional gases), for fuel efficiency. But, it is to be noted that, when biogas is added with conventional gases, they cause harmful emissions.

TPI expressed in section 4, which uses nanosecond discharges with the acceleration of electron species enhance the combustion of fuel-air mixture without raising the temperature of the fuel. TPI's property studied under section 4 also describes that it can ignite biogas that needs high temperature to burn without adding petrol or fuel with biogas fuel-air mixture. This makes TPI a real greener ignition technology in all means.

3. BIOGAS AS A FUEL IN INTERNAL COMBUSTION SYSTEMS

Biogas being available from the organic wastes is a good substitute to petroleum fuels. Biogas can be used in the ICEs because they have a better mixing capability with air and they have a clean burning nature. Biogas is created by anaerobic digestion of several organic wastes like kitchen wastes, agricultural waste, municipal wastes, solid wastes, cow dung which happens when oxygen is not present.

This gives low cost and low emissions than any other fuels. It can also be used as a substitute for LPG (Liquefied Petroleum Gas) and CNG (Compressed Natural Gas) [40].

3.1. Production of biogas

India being a largest cattle breeding country, there are a large amount of raw materials that finds itself helpful to produce bio gas. The use of methane (CH_4) in the bio gas is to reduce the harmful emissions by the engines. Biogas consists of approximately 50-70% of methane. Biogas is produced by the concept of Anaerobic Digestion (AD), also called biological gasification. It is a microbial process that happens naturally when organic matters are converted into methane (CH_4) and carbon dioxide (CO_2). The chemical reaction takes with the help of methanogenic bacteria in the absence of oxygen. Table 1 formulated below shows the composition of biogas.

Adapted from [40]

Table 1.Chemical composition of biogas

Components	Amount (%)
Methane (CH_4)	50 – 70
Carbon Dioxide (CO_2)	30 – 40
Hydrogen (H_2)	5 – 10
Nitrogen (N_2)	1 – 2
Water Vapour (H_2O)	0.3
Hydrogen Sulphide (H_2S)	Traces

3.2. Properties of biogas as a fuel

Biogas is cleaned of carbon dioxide and thus the gas becomes a good homogeneous fuel having up to 80% of methane with calorific value over 25mJ/m^3. The most needed component is methane. Methane gas contains a very high octane level of about 120 to 130, which allows it to perform better in producing high output sparks in ignition engines. The octane level in ordinary petrol was measured to be 95 in France. The level of octane expresses the level of resistance to spontaneous ignition, when petrol is compressed and heated. The higher the octane level, the more is the gas utilization. The thermodynamic properties of methane show how it can be a useful compound to create a better fuel property [41, 42]. Table 2 shows the thermodynamic properties of CH_4.

Adapted from [40]

Table 2.Thermodynamic properties of CH_4

Properties	Values
Specific heat (Cp)	2.165 kJ/kgK
Molar mass (M)	16.04 kg/kmol
Density (ρ)	0.72 kg/m^3
Individual gas constant (R)	0.518 kJ/kgK
Lower calorific value (Hu) (Hu, n)	50000 kJ/kg 36000 kJ/m^{3}n

3.3. Biogas for ICE performance

The consumption of fuel using the biogas as a fuel is specified in m³n/h or m³n/kWh. The engine performance using biogas can be altered by using temperature and pressure aspects that happen in the ICE's internal combustion chamber. CH_4 is an ignitable one when added with proper fuel-air ratio in the ICE. The removal of CO_2 from biogas can be done by washing the gas with water. H_2S present in biogas is acidic which when not removed can cause erosion. It can be removed by passing the gas through iron oxide [43].

3.4. Use of biogas as fuel for ICE

There are many notable advantages of using biogas as a fuel because it is a clean fuel. Some of the advantages of using biogas as a fuel are given below.

- It causes clean combustion.
- Recesses contamination of engine oil.

Biogas can't be directly made use in automobiles since it has some other gases like CO_2, H_2S and water vapor. These gases are considered as impurities. For using biogas as a vehicle fuel, the biogas must be first upgraded by eliminating these impurities as expressed in section 3.3. After removing these impurities, it is then compressed in a 3 or 4 stage compressor up to a pressure of about 20 MPa and the biogas is kept in a gas cascade. This biogas in turn is utilized for the purpose to quickly refuel the cylinders. If the biogas is not compressed when it is placed in the cylinder, the volume of biogas will be less and so, the engine will run for a short period of time.

3.4.1. Biogas in diesel engine application

As biogas has high self-ignition temperature, it has to be used with a fuel that has low self-ignition temperature to function properly for the process of combustion in the engine's cylinder. The fuel to be added along with biogas is the diesel fuel, which is adopted to improve the combustion

Not only with diesel engines, but biogas can also act with vegetable oils for dual fuel engine similar to diesel pilot fuel engine. The engine's performance relies on the amount of biogas and petrol fuels that are used. Measures like addition of hydrogen, LPG, removal of CO_2 etc. have shown key improvements in the performance of biogas dual fuel engines. The ignition timing of the pilot fuel engine's ignition increases leading to advanced and improvised period of fuel injections by the fuel injectors. The CO_2% in biogas acts as a diluent to slow down the combustion process in homogenous charged compression ignition engines. Thus a fuel with low self-ignition temperature could be used along with biogas to help its ignition. This kind of engine has shown a superior performance as compared to a dual fuel mode of operation.

3.4.2. Biogas in dual fuel engine application

In this technique diesel fuel is modified into dual fuel engines. The advantages of using biogas in dual fuel engines are listed below.

- Operation on diesel fuel alone is possible when biogas is not available.
- Biogas from 0% to 85% can replace a part of diesel fuel while maintaining diesel's performance to be 100% in fuel operation.
- Even if the biogas is uncontrolled the existence of governor in diesel engine can control it.

The limitations of using biogas as a fuel are,

- The dual fuel engine can't operate without the supply of diesel fuel for ignition.
- The fuel injection jets may overheat when the diesel fuel flow is reduced to 10% or 15% of its normal flow.
- A check of the injector nozzle after 500 hours of operation in dual fuel is recommended.

3.4.3. Homogeneous Charge Compression Ignition (HCCI) engine application

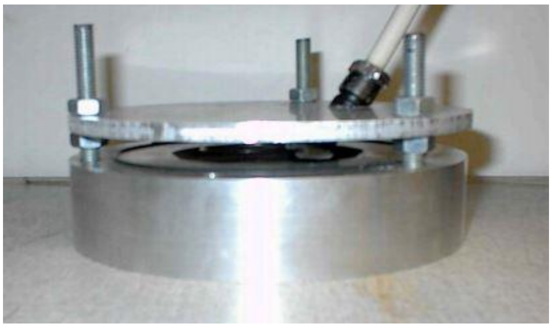
The HCCI concept is a potential for achieving a high thermal efficiency and low Nitrogen Oxide (NO) emission [40]. The HCCI engine with 50 % biogas as a primary fuel and 50% diesel as pilot fuel giving a maximum no of 20ppm is a major advantage over biogas diesel dual fuel mode. In biogas diesel dual fuel mode the presence of CO_2 in biogas lowers the thermal efficiency. However, in Biogas Diesel HCCI (BDHCCI) mode CO_2 reduces high heat release rate. The break mean effective pressure (BMEP) in BDHCCI mode is in the range of 2.5 bar to 4 bar. The smoke and Hydro Carbon (HC) level were also low when the biogas is used as a primary fuel for BDHCCI mode. For HCCI operation, the inducted charge temperature is required to be maintained at 80-135°C, which can be obtained from the exhaust heat. Thus biogas with HCCI engine gives high efficiency and low emission.

All these engines only used biogas added with other conventional fuels. This study deals with using biogas as a solo and major fuel for ignition purpose. Thus there is an emergency to use biogas as a primary fuel fully to ignite the ICEs to avoid emission of harmful gases.

4. TRANSIENT PLASMA IGNITION (TPI)

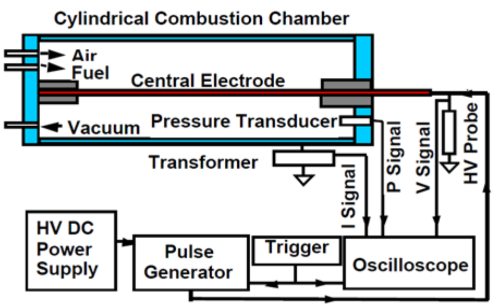
This section deals with explaining the features of TPI. Here, the performance of TPI is studied by using natural gas alone as the fuel and nowhere over here; are the conventional fuels like petrol and diesel used. As studied under section 3, from the components of biogas, methane is found to be a major constituent, which is also present in natural gas. So, it is clear that biogas can replace natural gas which forms a strong basement for our study. The features mentioned below can rightly make out a conclusion that, biogas being a simple fuel can still ignite completely with the best ignition technology, without its temperature being raised. And so, TPI can be made use in ICEs in future [44].

Plasma, being the fourth state of matter, is focussed here as it is the foundation for TPI. Transient plasma igniter, an enhanced plasma igniter that is far better than other plasma igniters is involved in this study. There are various sources of sparks like, sparks induced by electricity, use of the spark plugs, sparks induced by laser, plasma sparks etc. The sparks induced by the plasma is proved to be the best than the conventional spark systems. The traditional spark ignition causes corrosion while the sparks are lasted for a longer period, while the TPI doesn't thus making TPI better than SI (Spark Ignition). The engine cylinder for visualizing corona discharges is shown in figure 4.



Adapted from [53]

Figure 4.Engine cylinder for visualizing corona discharges



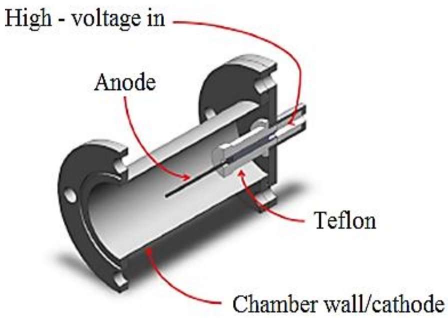
Adapted from [53]

Figure 5.Experimental setup for flame ignition

Figure 5 shows the experimental setup for investigation of flame ignition by pulsed corona discharge, which is the other name for TPI [53]. Figure 6 shows the experimental apparatus of transient plasma system [54].

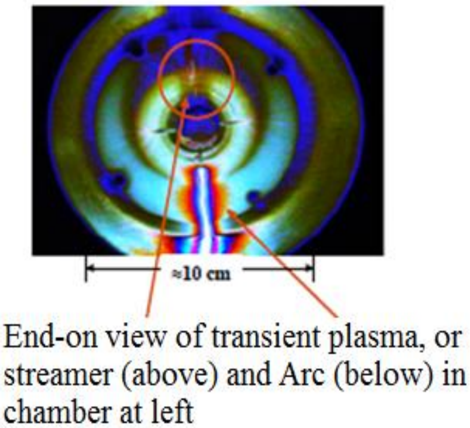
Figure 7 shows the streamers and arc formation which depicts that the arcs are not formed fully for the case of TPI and it is avoided by using nanosecond pulsed power.

[54] This Nano pulsed power shuts of the power before the arc forms.



Adapted from [54]

Figure 6.Transient plasma research experimental apparatus



Adapted from [54]

Figure 7.The streamers and arc formation

TPI is also called as pulsed corona discharge. This technique has a wide variety of application, one of them being the ability to start the combustion in low-turbulence ICE where the mixture for ignition is pre mixed. This is used to get back the burning rate that is lost by reduction of turbulent levels.

4.1. Features of TPI that support better ignition

4.1.1. Fuel efficiency

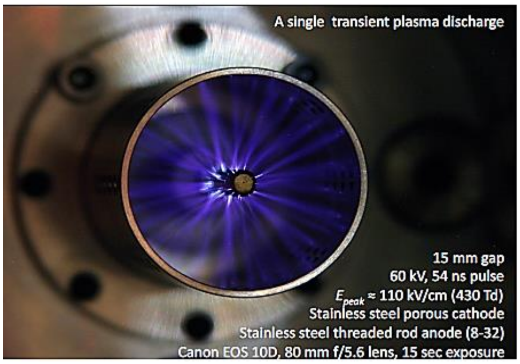
The most important physical matter is that it can very easily conduct electrical charge in the sense that it can perform high voltage ignition systems. This makes an explosion inside the combustion chamber, burning the fuel-air mixture completely, thereby allowing the ignition to be a leaner one and also increases the exhaust air that may contain burning properties to recirculate again in the combustion chamber so that they can be fully sucked up by the ICE for their burning capability and thereby producing very low emission.

4.1.2. Short, intense, low energy electrical pulses

The TPI produces short, intense and electrical energy of low energy which measures about 10-15 nanoseconds [45]. The short pulses have been proved to improve the engine performance in an effective manner for the internal combustion engines that deal with thermal ignition. This has also lead to the usage of the transient plasma in small combustion engines utilized in aerospace research activity such as unmanned aerial system. This shows that the TPI usage can make the big ICE so compact in its size.

4.1.3. Transient plasma spark

Sparks are the discharge of electrons. The electrons can be discharged fully or depending upon the need to spark the fuel-air mixture. Arc is formed by a spark, which depicts the continuous stream of electrons that bridges the distance between the two conductive surfaces kept closer together. The intensity of spark and the intensity of the arcs rely on the resistance exhibited between the discharge points. When the voltage from the power source is very high, the air will ionize creating a conductive path for the electricity created to flow. The amount of electricity indicates the temperature of the arc. As the current goes high, the temperature of the arc too goes high. Even arcs with lower current can cause a greater ignition. Figure 8 given below shows the transient plasma discharge.



Adapted from [45]

Figure 8.A single transient plasma discharge

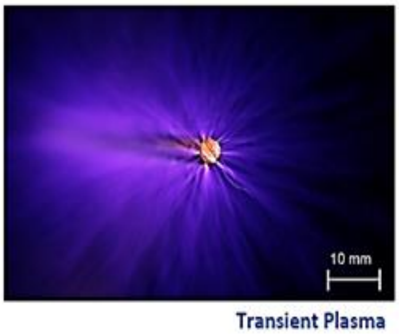
4.1.4. Non-thermal plasma discharge

Non-thermal plasma holds numerous advantageous over thermal plasma and other conventional technology such as low cost, low temperature, low heating losses, high removal efficiency, and smaller volume space.

4.1.5. Nanosecond discharge

The transient plasma exhibits a pulsed, high voltage nanosecond discharge. This happens in a plasmatrons series [46]. The discharge is given in figure 9. It shows three modes of development while relying on the frequency, voltage and the mass flow rate. They are,

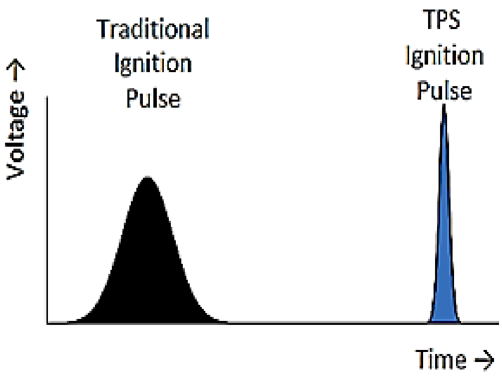
- Surface streamer
- A localized spark
- Distributed non-equilibrium transient spark



Adapted from [45]

Figure 9.Transient plasma discharge

Figure 10 shows the comparison between the traditional ignition pulse and the Transient Plasma System (TPS) ignition pulse with respect to time and voltage.

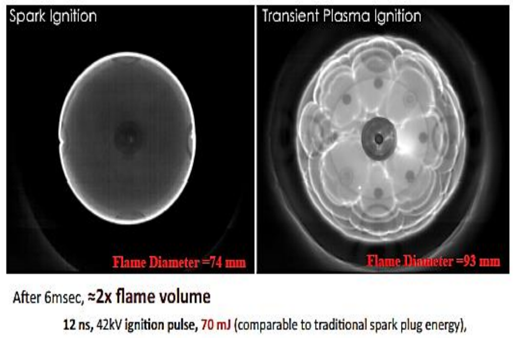


Adapted from [45]

Figure 10.TPI's ultra-short nanosecond electrical pulses in comparison to traditional ignition pulse

4.1.6. Flame speed

The flame speed of TPI and spark ignition is shown in the figure 11. It depicts the diameter of the flame in traditional spark ignition and transient plasma ignition. It is clearly understood that after 6 milli seconds, the flame rate of the TPI gets doubled.



Adapted from [54]

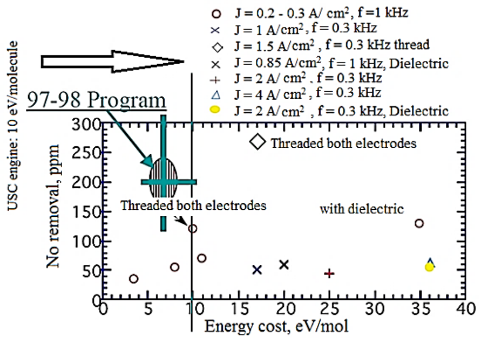
Figure 11.Figure showing flame speed

4.1.7. Less erosion

The electrolyte used in the TPI system is not eroded easily because the TPI uses very less heating when compared to the conventional system that produces the arc phase discharge of ignition.

4.1.8. Low emission of NO_X

Study shows that the IC engine having a distributed spark has a fuel economy of about 40 per cent and also the tendency to function in ultra-lean condition of about less than 0.15, which exhibits a low exhaust temperature and results in a very low NO_X emission.



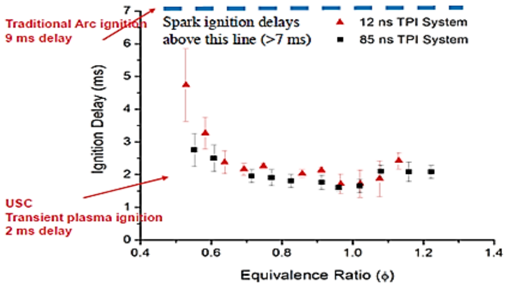
Adapted from [55]

Figure 12.Removal of NO_X by TPI

Figure 12 shows the removal of NO_X by TPI, which minimizes the energy used for critical applications [55]. The energy cost is taken as a function of V, short pulse polarity, repetition rate, electrode configuration, dielectric and current density. An achievement of less than 10Ev/mol shows less than 5 per cent of energy requirement.

4.1.9. Low ignition delay

The TPI produces low ignition delay in PDE (Pulse Denotation Engines). This is shown in figure 13 given below.



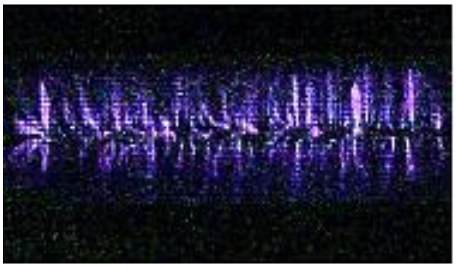
Adapted from [54]

Figure 13.Low ignition delay

A comparison is shown between TPI and traditional arc in terms of delay in ignitions. With the TPI, greatly shortened denotation time is achieved. The Deflagration-to-Detonation Transition (DDT) time is improved and the peak pressure is increased with the TPI. The PDE offers higher reposition rate. High flow rate of about 1/3 kg/sec has been recorded. Shortened DDT by factors greater than 4 is achieved in 9 to 2 msec. The repetition rate and thrust are significantly increased.

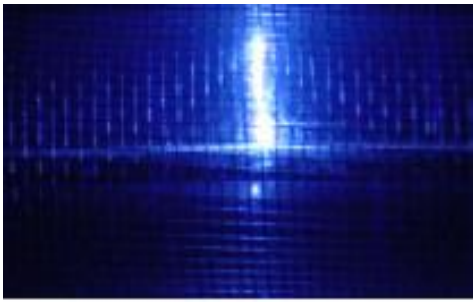
4.1.10. Fuel utilization and enhanced flame ignition

The transient plasma based ignition system also makes use of the power to be increased in a larger amount and also the fuel to be consumed in a smaller amount. The plasma ignition technologies never use hybrid prototypic structures that make the system very complex and expensive as well [47, 53]. This clearly shows that the flame ignition is enhanced a lot. Figure 14, 15 and 16 given below shows the different stages of ignition in TPS.



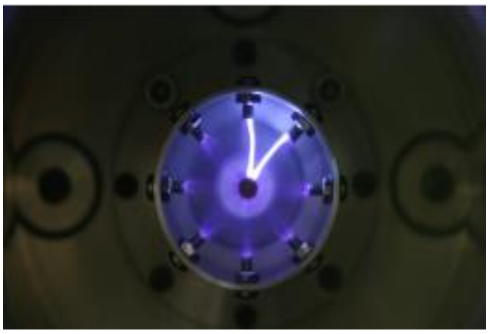
Adapted from [53]

Figure 14.TPI occurring in less than 100 ns



Adapted from [53]

Figure 15.TPI transition into an arc



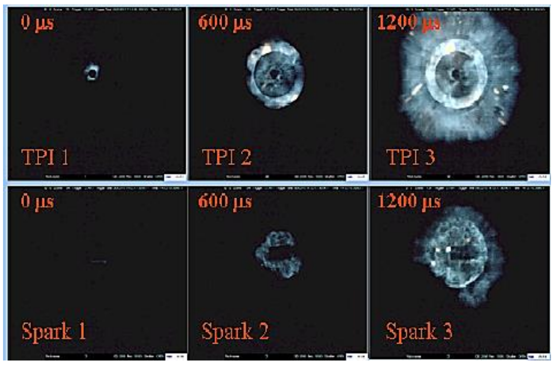
Adapted from [53]

Figure 16.Plasma streamers

Figure 16 shows the volume distributed plasma streamers prior to arc formation with a period less than 100 ns

4.1.11. Burn rate and faster flame propagation

The TPI's increase in the burn rate causes the transient plasma generators to produce more efficient energy when compared to other ignition systems that produce ignition in arc discharge. Figure 17 given below shows faster flame propagation in TPI [48]. The figure below which shows a graph is a data taken by Nissan research centre, which is implemented by TPI in internal combustion engines.

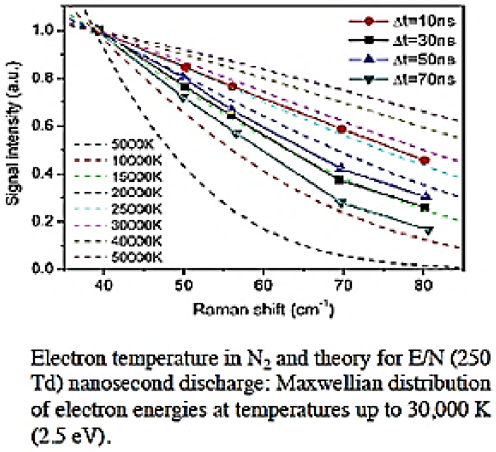


Adapted from [45]

Figure 17.TPI's faster flame propagation

4.1.12. Excitation of electrons in the chamber

The transient plasma discharge ignition causes highly reactive electronic species.



Adapted from [56]

Figure 18.Maxwellian distribution of electron charges

These electron species create only the transient plasma phase of the discharge. The arc discharge that happens in the latter stage is very less efficient to transfer energy into ionization, electronic excitation and dissociation. So less energy is needed for a given plasma ignition. The TPI generates higher energy electrons. This is shown in figure 18.

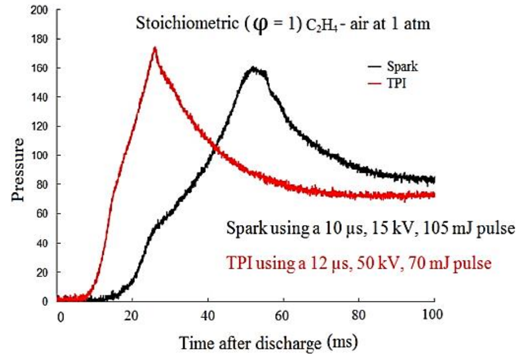
Figure 18 depicts the following details. Electron temperature in N_2 and theoretical Energy Distribution Function (EEDF) follows Maxwellian distribution with initially higher electron temperature. Significant populations of higher energy electrons up to $10^{11}/cm^3$ is with the energy of 10eV or more. 10eV is the threshold energy for the excited state and radical production: O^-, H^-, $N_2(C)$ and other active species. Better active species are generated to aid combustion [56].

4.1.13. Lean-burn technology

The process of combustion that happens in the combustion chamber is considered to be lean. The burning process is said to be lean when air in excess is introduced into the engine with the fuel [49].

4.1.14. Fast combustion rate

The TPI performs an enhanced burn rate when compared to the traditional spark ignition technologies. Figure 19 shows the graph depicting fast combustion rates happening in traditional spark and in TPI. The plasma enhanced combustion expects a greater than 10 per cent value in the combustion rates when compared to the traditional spark.

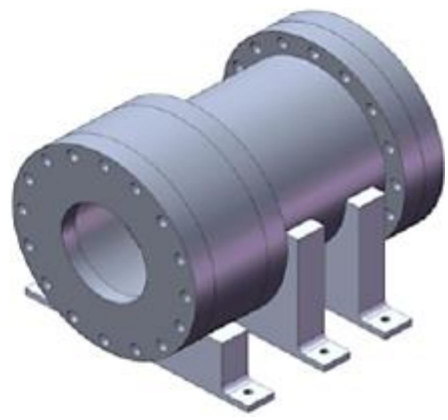


Adapted from [4]

Figure 19.Fast combustion rate- A comparison between TPI and traditional spark

4.1.15. High pressure combustion chamber

The combustion efficiency can be measured by the following features such as lean burn and low emission from the engine output. As these properties produce a good combustion, TPI can be used to design a high pressure combustion chamber that can exhibit a maximum pressure of about 200bar and injection pressure of about 1800bar. The TPI system has the following ports like, TPI electrode, pressure transducer, vacuum/exhaust valve and fuel injector. Figure 20 given below shows the high pressure combustion chamber.

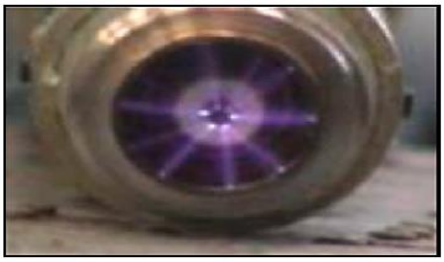


Adapted from [54]

Figure 20.High pressure combustion chamber

4.2. TPI application in an ICE at Nissan Research Centre (NRC)

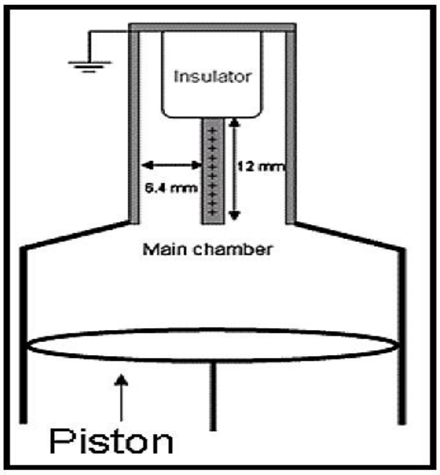
Nissan research centre has performed a system with which they used TPI for internal combustion engines using natural gas as a fuel. Figure 21 given below shows the TPI discharge.



Adapted from [45]

Figure 21.TPI discharge

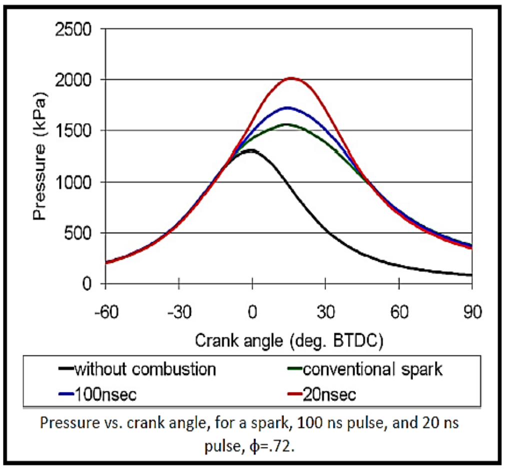
Figure 22 given below very well shows the experimental setup at Nissan. The important parts of the system are an insulator, piston and a combustion chamber for combustion to take place.



Adapted from [45]

Figure 22.Experimental setup at Nissan

This Nissan research centre has showed how the TPI increases pressure when compared to traditional sparks, which is shown in the graph expressed as shown in figure 23.



Adapted from [45]

Figure 23.Pressure increase - a comparison

4.3. Overall benefits of TPS

- 10-30 per cent increase in the engine's efficiency that runs using natural gas, diesel and gasoline.
- Reduction in NO_X emission up to 95 per cent.
- Reduction in ignition delay.
- Exhibition of lean burn capability and fast burn.
- Quicker fuel igntion and faster moving mixtures.
- More power from the fuel showing better fuel utility.

4.4. TPI meets our needs

The above given Nissan is a practical proof that TPI can run on natural gases because of the high burning nature of TPI [45]. From the biogas fuel properties, and from the TPI technology, we can come to a conclusion that both TPI and the biogas can be successfully installed in ICEs [50].

5. CONCLUSION

5.1. Why biogas must be made a major and single fuel for ICEs?

It is reported that 80% of the energy needed for transportation purpose, is got from the combustion of the conventional fossil fuels (diesel and petrol). This fact must be seen in with two dimensions. The first view is Mother Nature's blood (fossil fuel) is taken from the fossil buried trillions of trillions of years ago. As we know that these fossil fuels are non-renewable ones, and if they are depleted faster, it takes lots and lots of decades to synthesize them again. Already we are in fossil fuel crisis and utilizing more than a half per cent of fossil fuels for transportation alone is not fair because there are many other appliances that are in need of these conventional fossil fuels alone to function. The most popular renewable fuel is the biogas. This can be used as an alternate to propel ICEs used in vehicles.

The second view is that the fossil fuels create emission of harmful gases. When trillions of vehicles run on earth, they release loads and loads of harmful gases mainly NO_X, which can cause a great disaster to the living things that exist on the earth and also destroy or damage the living things [50].

So, the oil that is extracted from the fossil fuels to propel ICEs, only uses the blood of the earth and gives back harmful gases. If this oil that is sucked, gives back us green and safe gases, it is not a problem to worry. But harmful reactions only take place when petrol and diesel are used in ICE, killing human lives indirectly and generations to come causing global warming and also several health issues. These two views have formed the base for this study.

5.2. Real greener ignition with TPI and biogas

The term greener ignition can be given only for the ICEs that use TPI in conjunction with biogas. Greener ignition refers to a pollution free ignition in two processes of ICEs. The first place is in the combustion process where the plasma techniques studied under section 2 could control NO_X emission. But, in the second place which is the emission process, the plasma techniques studied could not control the emissions because they contained engines which used biogas fuel as a supplementary to conventional fossil fuels, and not completely using bio-gas [51, 52]. The reason why they couldn't use biogas as the only fuel is that the ordinary plasma techniques discovered could not ignite a gas like biogas fully because biogas needs high temperature to be ignited. Thus when comparing with TPI which uses biogas, other plasma techniques are deemed inefficient ones. With all the reports studied above, this study thus proves that TPI can enhance the efficiency and throughput of ignition technology for ICEs, when used with biogas.

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