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Design and Development of a Subsonic Ramjet for Experimental Comparison of Biofuel with Jet Fuel

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Abstract

This paper reports the design and development of a ramjet engine with a modified nozzle and flame stabilizer design working under subsonic condition (Mach no = 0. 4). The associated subsystems like liquid fuel injector and ignition system have also been designed, developed and fabricated. The air inlet for the engine is enabled by using the free jet facility. Thermocouple for measuring temperatures at the nozzle inlet and exit has been fabricated. To compare, the ramjet is operated with Biofuel (Biogas + Biodiesel) and Jet fuel (Aviation Turbine Fuel-ATF). Performance graphs comparing ATF and Biofuel are plotted by varying the mass flow rates of the fuel and air. Exhaust gas analysis was carried out to check for the emissions. The experimental results are compared with the literatures, theoretical calculations and CFD analysis. The thrust obtained by ATF is higher than Biofuel only during the air inlet of 18. 56m/s irrespective of the fuel mass flow rate. During all other inlet air conditions the Biofuels performance exceeds the ATFs performance.

Keywords: ramjet; nozzle; flame stabilizer; biofuel; jet fuel; free jet; fuel injector; thermocouple; alternative fuel.

Introduction

The demand for crude oil is rising tremendously day by day. Aviation industry cannot sustain if the availability of crude oil declines. The emissions from the conventionally used fuels are dangerous as they have a high Sulphur and Carbon contents. The world is in need of an alternative fuel that will be eco-friendly and satisfy all the demands of an Aircraft. A fuel which is of low cost and is available plenty in nature can play a vital role to solve this problem [1, 2, 3]. The ramjet engine is the simplest type of the all-jet engines because it has no moving parts. Because of the simplicity of the ramjet design, it can be produced for a very low cost. It is most suitable for high speed operation. Lots of researches has been carried out to enhance the performance of the ramjet engines. Generally Ramjet is not a self-starting engine. It should be accelerated to a particular speed for starting. A ramjet is designed around its inlet. An object moving at high speed through air generates a high pressure region upstream. A ramjet uses this high pressure in front of the engine to force air through the tube, where it is heated by combusting some of it with fuel. It is then passed through a nozzle to accelerate it to supersonic speeds. This acceleration gives the ramjet forward thrust [4]. The body of a subsonic ram jet engine is an open duct composed of a divergent nozzle (called a diffuser), a combustion chamber [5, 6], and a convergent nozzle (usually called the nozzle). In the past, flame holders in subsonic ramjets have been of the so called bluff-body or gutter type [7]. They consist of hollow cones and V shaped gutters. Adequate thermal combustion efficiencies have not been attainable using bluff-body flame holders [8].

Biofuel

A. Biogas

Biogas is a renewable energy resulting from biomass. Biogas typically refers to a mixture of gases produced by the breakdown of organic matter in the absence of oxygen [2]. Biogas can be produced from regionally available raw materials such as recycled waste and is a renewable energy source and in many cases exerts a very small carbon footprint. The major constituents of Biogas consists of 65% CH_4 and of 35% CO_2. The gases such as methane can be combusted or oxidized with oxygen. This energy release allows biogas to be used as a fuel [9]. The various properties like calorific value, flash and fire point of the Biogas are tabulated in Table 1.

TABLE. 1. Biogas Properties

Characteristics	Biogas
Type of source	Renewable
Calorific value(MJ/kg)	50. 01
Flash point (°C)	-187. 8
Fire point(°C)	537. 8
Density (kg/m^3) at 25°C	0. 656
Sulphur content (kg/m^3)	5. 5 * 10^{-6}

B. Biodiesel

Biodiesel has a major advantage over petroleum diesel. It is derived from renewable sources and it is a clean burning fuel that does not contribute to the increase of carbon dioxide, being environmentally friendly [10, 11]. Biodiesel is an oxygenate, sulphur-free and biodegradable fuel, and its content of oxygen helps improve its combustion efficiency.

Therefore, fewer greenhouse gases such as carbon dioxide are released into the atmosphere. Biodiesel has positive performance attributes such as increased cetane, high fuel lubricity, and high oxygen content. The various properties of the Biodiesel are tabulated with respect to their characteristics in Table 2. Since, biodiesel is more lubricating than diesel fuel, it increases engine life and it can be used to replace sulphur, a lubricating agent, that when burned, produces sulphur oxide, the primary component in acid rain [12, 13, 14].

TABLE. 2. Biodiesel Properties

Characteristics	Biodiesel
Type of source	Renewable
Calorific value	41. 3 (MJ/kg)
Gross heat of combustion	40. 135 (KJ/kg)
Cetane level	65
Flash point	174. 0 (°C)
Pour point (°C)	16. 0 (°C)
Cloud point (°C)	16. 0 (°C)

Ramjet Engine Design

A. Overall Design

The ramjet is designed by fixing the inlet air velocity and diffuser inlet diameter [15, 16, 17]. Using the continuity equation and assuming certain conditions for combustion the dimensional calculation is carried out for each section of the ramjet. The overall 2-D design of the ramjet with diffuser, dump combustion chamber and nozzle is shown in Figure 1.

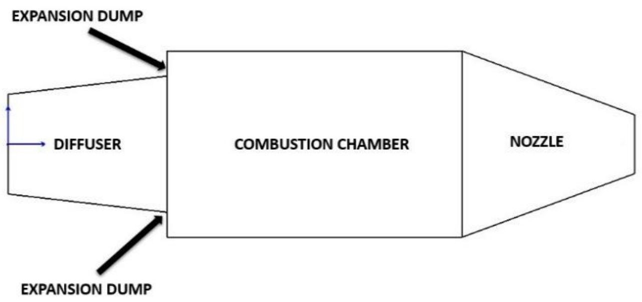

Fig. 1. Ramjet Engine

B. Nozzle Design

The nozzle portion of the ramjet is modified by increasing its length and decreasing its exit diameter [18, 19]. This is done to increase the exhaust velocity.

C. Dump Combustor

The use of dump combustor [20, 21] is one of the oldest method of inducing recirculation in the combustion chamber. The dump combustor is characterized by the presence of sudden expansion between the diffuser and combustion chamber [22]. It is simple in construction, and provides efficient combustion.

D. Flame Stabilizer

The art of combustion is to make the fuel and air stay inside the combustion zone for a particular time to attain complete mixing and burning [23, 24]. The first phase of the flame stabilizing unit consists of 2 sets of stationary radial blade assembly where each set constitutes 6 blades which is bent towards the flow direction to create recirculation. The blade in the sets are positioned in such a way that each blade in the backward set covers the space left by the blades in the forward set as shown in Figure 2.

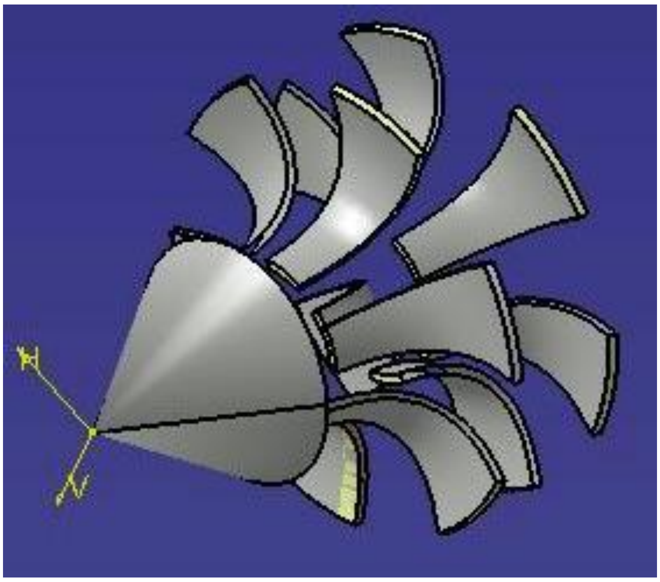

Fig. 2. Flame Stabilizer Assembly

The working of the blade section is based on the flow of the air. If the incoming air is concentrated towards the center the function of blade assembly to recirculate is not possible. Hence a medium which directs the inlet air towards the blade assembly is required to attain the blade assembly function. Therefore, the second phase of the flame stabilizing unit is a cone section which directs the inlet air to flow on the blade assembly irrespective of the inlet air concentration.

E. Fuel Inlet

The use of two fuel inlets [25, 26] increases the rate of mixing when compared to single inlets [27]. For making the fuel stay inside the recirculation zone the two fuel inlets of both biogas and biodiesel are positioned ahead of the flame stabilizing unit at an angle of 45 degree opposing the flow.

CFD Analysis

For validating the overall design and combustion performance of the ramjet, CFD analysis [28, 29] is carried out using ANSYS 13. The section where recirculation is achieved maximum is selected as the zone for injecting the fuel [30]. The design is made in such a way that the mixing of air and fuel is achieved completely at the end of the blade assembly. Hence to start combustion the igniter is positioned behind this mixing zone. The region behind the mixing zone in Figure 3 where the velocity is very low is selected for positioning the igniter [31]. The sections where recirculation is achieved maximum is selected as the zone for injecting the fuel.

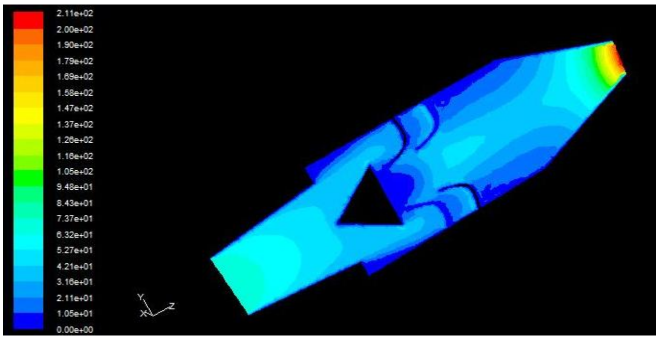

Fig. 3. Velocity Contour

Another important function of the flame stabilizing unit is to increase pressure at the combustion zone. It is found from the simulation in Figure 4 that the complete flame stabilizing assembly increases the pressure from 101325 pascal to 104000 pascal.

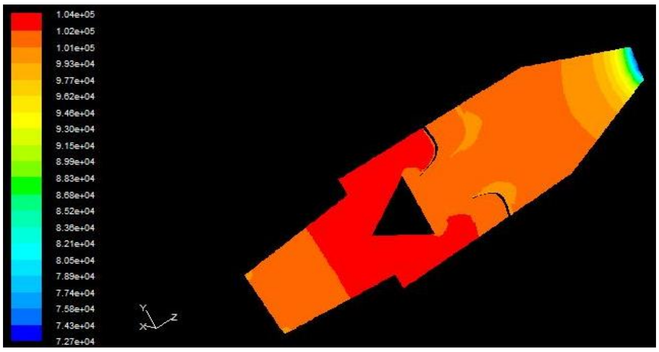

Fig. 4. Total Pressure Contour

The recirculation zones are clearly visible through the velocity vector contour shown in Figure 5.

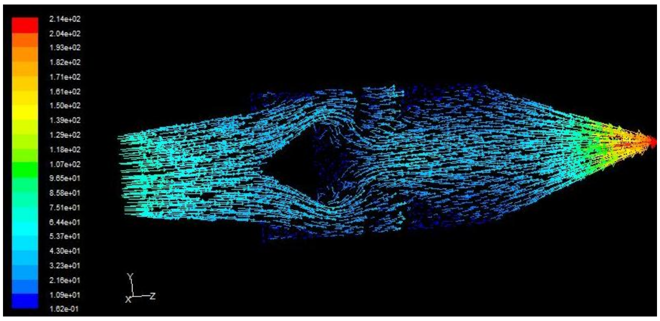

Fig. 5. Velocity Vector Contour

The Combustion model boundary conditions are as follows,
Double precision in ON condition.

Model	K-epsilon
Turbulence Intensity	10%
Hydraulic Diameter	0. 1494m
Materials	Biofuel, Oxygen, Carbon dioxide, Water
Condition	Fuel 1 & 2 at 0. 000019033 kg/s
Fuel Turbulence	10% Intensity

The results obtained from the combustion model simulation are,

Inlet Velocity	13. 13 m/s
Exit Velocity	75. 10 m/s

A plane at the ramjets exit is created for finding out the mass fraction of exhaust products after the combustion reaction [32]. The biofuel mass fraction contour in Figure 6 shows that the fuels are burnt completely hence there is no unburnt fuel in the exit of the ramjet. Complete combustion is characterized by the presence of carbon dioxide and water vapor in the exhaust [30]. This is achieved in this ramjet design. The mass fraction contour of the carbon dioxide and water vapor from the combustion model in Figure 7 shows that the exhaust gases contains maximum percent of carbon dioxide and water vapor.

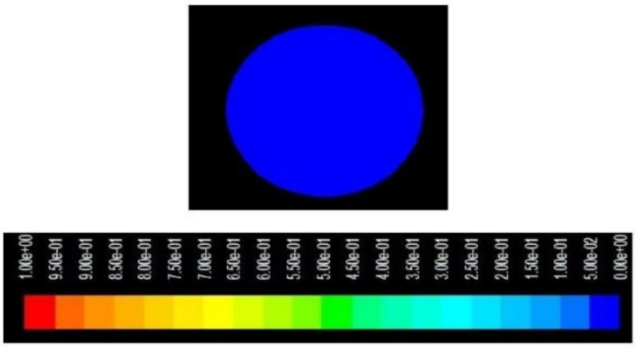

Fig. 6. Biofuel Mass Fraction Contour

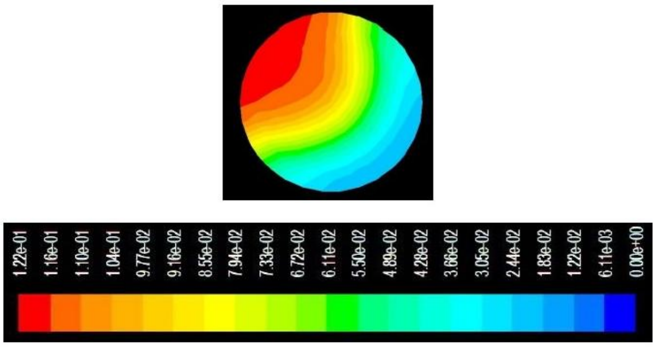

Fig. 7. Water vapor and Carbon dioxide Mass Fraction Contour

Results and Discussions

The Ramjet with the entire setup is placed in front of the Free jet facility [33] (Air Inlet) as shown in Figure 8 for experimentation. The experiment is carried out by testing the engine for various mass flow rates of biogas to determine the engine performance [34, 35].

For calculating thrust and exhaust velocity the thermocouples are placed at the nozzle inlet and nozzle exit to measure the temperatures from which other parameters for comparing the two fuels are calculated.

Fig. 8. Experimental Setup

Initially cold flow analysis is experimented for various inlet air velocity [36, 37].

TABLE. 3. Cold Flow Analysis

V_{Inlet} (m/s)	V_{Exit} (m/s)
13. 13	33. 8
18. 56	56. 48
22. 73	61. 24
32. 15	83. 59
41. 5	112. 5
55. 69	139. 23
61. 56	160. 56
69. 95	182. 5
112	261
140	364

From Table 3 and Figure 9 It is seen that even without the combustion process occurring the engine was able to accelerate the exit flow to a higher value than the inlet. This implies that the design of the ramjet meet the standard requirements.

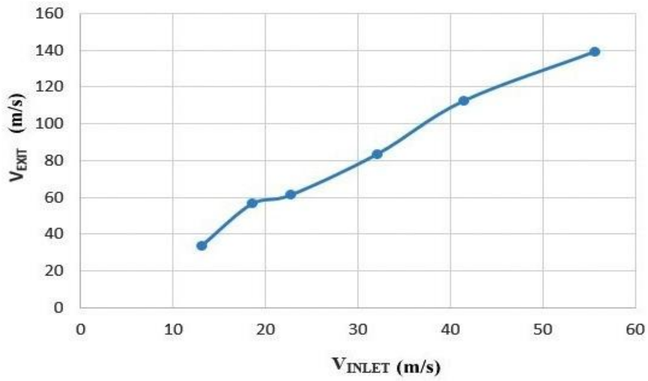

Fig. 9. Cold Flow Analysis Velocity Plot

Another important factor in designing is that the flame should not propagate out of the nozzle [38]. The flame should stay inside the recirculation zone and the exhaust gases with high velocity and temperature should flow out. This is achieved in this design as shown in Fig 10 and 11.

Fig. 10. Engine operating with lean mixture of fuel

Fig. 11. Sustained combustion with rich mixture of fuel

From the performance graphs plotted, During the combustion with 1lpm, 1. 5 lpm, 2 lpm, 2. 5 lpm and 3 lpm mass flow rate of biogas, the blow out takes place at 26. 25 m/s, 26. 25 m/s, 29. 25 m/s, 34. 72 m/s and 34. 72 m/s respectively.

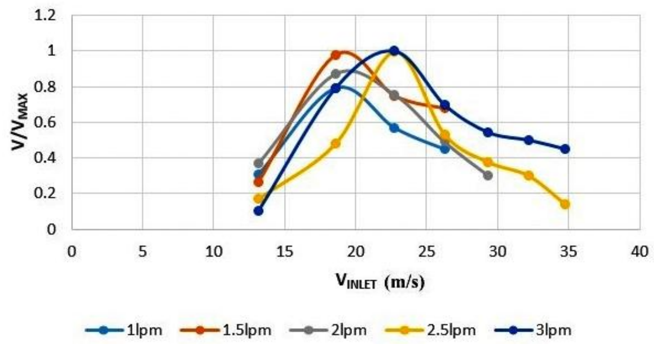

Fig. 12. Velocity Plot

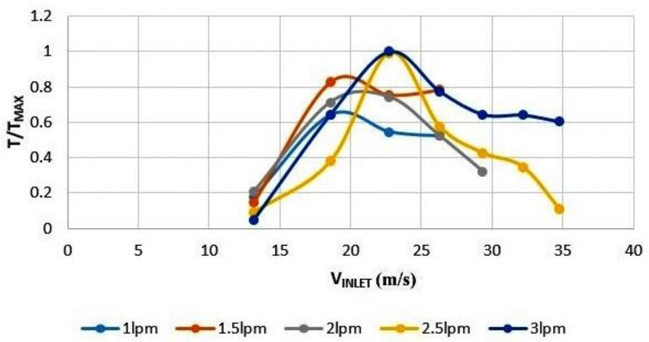

Fig. 13. Thrust Plot

From the Velocity and Thrust plots in Figures 12 and 13 the maximum performance is achieved at 18. 56 m/s of air inlet at 1 lpm, 1. 5 lpm and 2 lpm of biogas. For 2. 5 lpm and 3 lpm of biogas the maximum performance is achieved at 22. 73 m/s of air inlet. During 1 lpm, 1. 5 lpm, 2 lpm, 2. 5 lpm and 3 lpm of biogas complete combustion is attained at the air inlet of 22. 73 m/s, 26. 25 m/s, 26. 25 m/s, 29. 35 m/s and 32. 15 m/s respectively which is inferred by the appearance of blue flame inside the chamber.

From the experimental results of combustion, it is noted that the ramjet is performing well as referred from literatures. The blow out velocity of the ramjet is found to be 34. 72 m/s of air inlet at 3 lpm of biogas. The operation of the ramjet can be widened by further increasing the mass flow rate of the fuel to higher fuel rates to obtain the design Mach number. The ramjet is operated by varying the mass flow rate of biogas but the mass flow rate of biodiesel and ATF are kept constant to record the performance of biofuel and ATF with Biogas The battery of sensor nodes in the wireless sensor network become rechargeable, the network design changes fundamentally. Designing the network that reduces the cost for power recharging is an important one.

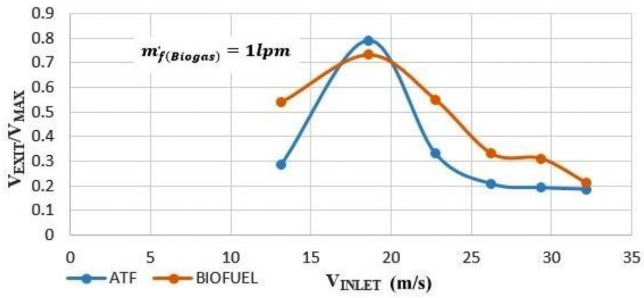

Fig. 14. Velocity Plot comparing Biofuel and ATF at 1 lpm of Biogas

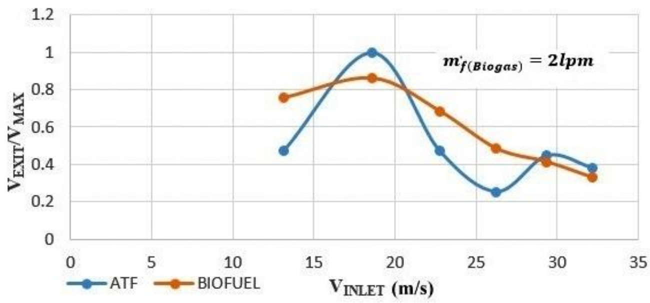

Fig. 15. Velocity Plot comparing Biofuel and ATF at 2 lpm of Biogas

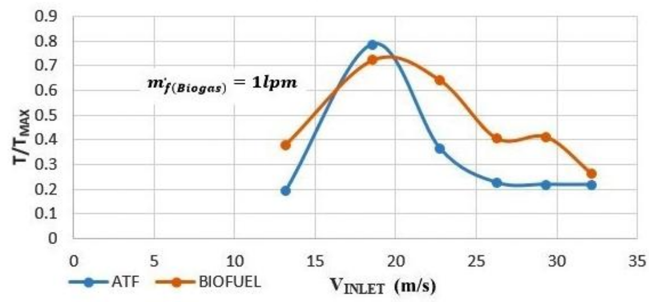

Fig. 16. Thrust Plot comparing Biofuel and ATF at 1 lpm of Biogas

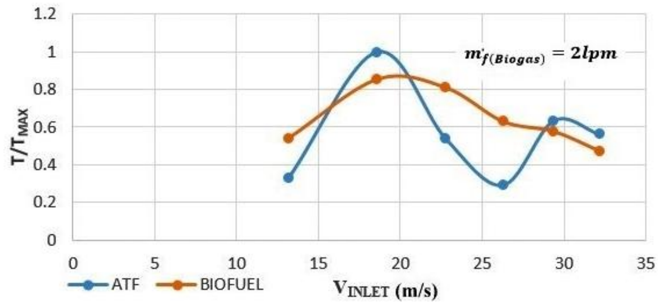

Fig. 17. Thrust Plot comparing Biofuel and ATF at 2 lpm of Biogas

From the comparison plots of Figures 14, 15, 16 and 17 the following criteria of performance are inferred,

- The exhaust velocity and thrust of the ramjet while operating with ATF drastically increase at an inlet velocity of 18. 56 m/s and then drastically decreases with increase in air inlet irrespective of the fuel mass flow rate. In case of Biofuel the exhaust velocity and thrust is found to vary at a constant rate with respect to the air inlet and irrespective of the fuel rate.
- While operating with ATF maximum cycle temperature of 837 degree Celsius is obtained but the maximum temperature obtained while operating with Biofuel is 713 degree Celsius. Hence, thermal and circumferential expansions will be very low if operated with Biofuel. Amount of cooling required is also very low.
- The thrust obtained by ATF is higher than Biofuel only during the air inlet of 18. 56 m/s irrespective of the fuel mass flow rate. During all other inlet air conditions the Biofuels performance exceeds the ATFs performance.

Emission Test

Exhaust gas analysis is used to determine complete combustion and Emissions. In case of complete combustion the exhaust gases will contain only the water vapor and carbon dioxide as the exhaust products [39].

TABLE. 4. Emission Test Results at Minimum Fuel Rates

Content	Atf	Biofuel	Percentage
CO	0. 04	0. 03	% Volume
HC	55	29	ppm Volume Hex
CO_2	3. 10	3. 90	% Volume
NO	1	0	ppm Volume

CO Carbon Monoxide **CO_2** Carbon Dioxide
HC Hydro Carbons **NO** Nitrous Oxide

The results from Table 4 shows that at minimum flow rate of fuel, emissions from ATF are very high compared to Biofuel. The complete combustion is achieved here with both the fuels.

TABLE. 5. Emission Test Results at Maximum Fuel Rates

Content	Atf	Biofuel	Percentage
CO	0. 09	0. 05	% Volume
HC	22	18	ppm Volume Hex
CO_2	8. 70	2. 70	% Volume
NO	7	7	ppm Volume

CO Carbon Monoxide **CO_2** Carbon Dioxide
HC Hydro Carbons **NO** Nitrous Oxide

The emission test results from Table 5 shows that emissions are very less from biodiesel and is ecofriendly for operation. Similar to the literatures the nitrous oxide emissions from Biofuel are very high compared to the ATF. Except the nitrous oxide other emissions from Biofuel are very low comparing to ATF.

Conclusion

The paper experimented the performance of the ramjet engine with different flow conditions using biogas. Important engine performance criteria like thrust, exhaust velocity, blow-out velocity and emissions for a given fuel flow ratio have been recorded. The ultimate aim of comparing the Biofuel and ATF was also achieved.

- The blow out velocity of the ramjet is found to be 34. 72 m/s of air inlet at 3 lpm of biogas. The operation of the ramjet can be widened by further increasing the mass flow rate of the fuel to higher fuel rates to obtain the design Mach number.
- The thrust obtained by ATF is higher than Biofuel only during the air inlet of 18. 56 m/s irrespective of the fuel mass flow rate. During all other inlet air conditions the Biofuels performance exceeds the ATFs performance
- Similar to the literatures the nitrous oxide emissions from Biofuel are very high compared to the ATF. Except the nitrous oxide other emissions from Biofuel are very low comparing to ATF.
- This design can be used to manufacture a low cost subsonic air to air missile Powered by Biogas and Biodiesel.
- Finally the paper validates that Biofuel (Biogas + Biodiesel) can be used as an alternative for ATF in conventional aircraft engines.

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