Performance of Ammonia Fuel for a Commercial Grade Turbofan

Ethan P. Nall[1]
Auburn University, Auburn, Alabama, 36849, United States of America

The ever-growing concern surrounding the environmental impact of greenhouse gas emissions of the airline industry has led to a search for clean fuel alternatives. One possible solution is the use of ammonia as fuel for turbofans. This paper describes an investigation into the use performance aspects of replacing hydrocarbon fuels such as Jet-A with liquid ammonia. An introduction explains the motivation and suitability of ammonia as a fuel that has the potential to power turbofans across an ocean without carbon emission. The analysis setup based on the Numerical Propulsion System Simulation (NPSS) tool originally developed at NASA Glenn Research Center is described in the theory section. The combustion analysis is conducted using equilibrium assumptions and the NASA CEA tool. Results are reported for several city pair flights of typical interest to the airline industry. Some summary comments and next steps for both the engine analysis and the practicality of adapting airliner architectures for ammonia use is included in the summary and conclusion section.

Nomenclature

CEA	=	chemical equilibrium applications
MTOW	=	maximum take-off weight (lb_f)
NPSS	=	numerical propulsion system simulation
TSFC	=	thrust specific fuel consumption (lb_m/hr-lb_f)
TtCombOut	=	total combustor output temperature (Rankine)
W	=	fuel mass flow rate (lb_m/min)

I. Introduction

The aerospace industry growth is outpacing efforts to reduce carbon dioxide (CO_2) emissions. The aerospace industry has been a major contributor to the deteriorating state of the Earth's atmosphere due to the harmful emissions from combustion of the industry standard fuel. Specifically, the commercial aerospace industry has emitted the annual CO_2 emissions at 2.5% of the global total [1]. While this is not a large fraction, ultimately the commercial aerospace reliance on fossil fuels is a weakness that must ultimately be addressed for the future viability of the industry.

Ammonia fuel has garnered attention for being an extremely easy fuel to transport and produce. The infrastructure to produce and handle ammonia is in place in industries such as agriculture where it is the essential component of most fertilizer. Although the form of ammonia used in fertilizer is different than that used in the proposed ammonia fuels, the ability to process the chemical is. A shift to processing liquid ammonia will not be difficult as the liquid ammonia can be made at 20° C with a high-pressure environment. Once the liquid ammonia has been produced, it is easily transportable and storable as it will remain liquid at room temperatures and pressure of about 10 atmospheres. The importance of ammonia's ability to be stored and made readily is the comparison to other hydrocarbon fuel alternatives that require storage and transportation temperatures close to the negative hundred degrees Celsius [2]. These properties, ammonia has become the leading potential alternative for the common aerospace fuel.

[1] Undergraduate, Auburn University-904160086, Member-1744060.

The lack of carbon in ammonia (stoichiometrically ammonia combustion produces nitrogen and water) and a relatively large energy density compared to alternative non-carbon fuels along with the relative ease of use compared to liquid hydrogen has made ammonia a leading theoretical competitor with hydrocarbon fuel for commercial aircraft use. The relevancy in the commercial aerospace sector of the high bypass turbofan engine has rendered the use compatibility of ammonia with the turbofan of utmost relevance. This paper will discuss the methodology of determining the viability of ammonia as a fuel for commercial airliners using a NASA developed program called the numerical propulsion system simulation (NPSS) to analyze the cycles of the engine and combustion equilibrium analysis (CEA) software that analyzes the combustor process only. This software will model a standard commercial airline turbofan engine (CFM 56-5B) at an average design point detailed in the methodology section as well as a varying combustor exit temperature. The ammonia fuel exceeded the fuel weight limitation by a rate of 0.906 %/minute and exceeded the volumetric fuel limitation by a rate of 0.90 %/minute. To maintain current functionality of the commercial jet in a standard Atlanta to Orlando flight, would need 173% more fuel mass. These numbers differ from the average hydrocarbon fuel (Jet-A(L)) by a large margin due to the low energy density of the liquid ammonia fuel. Slight modifications to the engine would allow for greater performance numbers of the ammonia fuel such as an increase in combustion efficiency. Without significant alterations to the airframe and high bypass ratio turbofan of the average commercial airliner, ammonia will not be able to compete with standard hydrocarbon fuel on a performance basis. On an emission basis, the ammonia will be a cleaner fuel, but the amount of ammonia needed to equal the energy of the hydrocarbon fuel will potentially output significant amounts of nitrous oxide gas that can have negative effects on the atmospheric nitrogen cycle [3,4].

Although ammonia is easily produced and transported, the thermodynamic properties of the ammonia compound make it non-ideal for combustion. To increase the combustion efficiency, the ammonia must go through a process called “cracking” [5,6]. The cracking process occurs at temperatures between 1750-2100 Rankine. This cracking process means the combustor temperature must be on average higher than that of the standard hydrocarbon fuel. Although combustion efficiency will increase due to cracking, the separation of N_2 and H_2 consumes energy and can, if left at this combustion temperature, be a detriment to the energy of the flow.

Another complication of using cracked ammonia in the combustion process is that at a certain temperature and pressure state, the cracked N_2 and H_2 molecules will mix with the N_2 and H_2 in the atmosphere to make more ammonia. This process is referred to as the Haber-Bosch process [7]. This ammonia is detrimental to the flow and does not contribute to the increase in the flow energy as the nitrogen fixation and Haber-Bosch process consume energy. Both the Haber-Bosch process and ammonia cracking process are important to note in drops of combustion efficiency in certain combustion temperature ranges. Macroscopically, overcoming these problems lead to larger combustor volumes for efficient and complete combustion. This paper addresses the basic performance parameters surrounding the use of ammonia and does not address the practical details of the combustor design.

Other clean fuel alternatives that are popular considerations to replace hydrocarbon fuels are hydrogen and methane. Hydrogen fuel, unlike ammonia, is inaccessible with current infrastructure and is expensive to produce. While hydrogen has a gravimetric energy density of 3 times that of Jet-A(L), The volumetric energy density is more than 4 times lower [8]. Methane is the other popular alternative being considered as a clean fuel. The biggest downside of using methane as a fuel is also the volumetric energy density [9]. Storage of both methane and hydrogen would be very difficult for a commercial jet airliner using the CFM-56 turbofan as the amount of both compounds required would be very difficult to accommodate. Due to the productive capabilities and volumetric energy density of liquid ammonia, ammonia has become the frontrunner for the clean jet fuel alternative.

II. NPSS Model Analysis and Formulation

The viability of ammonia fuel will be investigated based on comparison with hydrocarbon fuel with respect to the thrust output, thrust specific fuel consumption (TSFC), and fuel mass flow rate (W). These values will be used to compare with the hydrocarbon fuel (Jet-A(L)) in those same values as well as overall range of an equal fuel load and the equivalent fuel load for performance of the specified engine at an average design point that is standard for modern commercial aviation. The design conditions of the ammonia fuel will also vary at the exit of the combustion chamber as ammonia has a higher ignition point than hydrocarbon fuel and to remain in components that are possible to burn, must be heated the entire combustion process.

To ensure the validity of the NPSS results, analysis was run at the average conditions of a commercial airline flight in three different cruises corresponding to the length of popular flights. The flights and relevant information are included in Table.1. The popularity and length of these flights means that the results of the NPSS analysis will be applicable to major flight routes that are under the heaviest condition and the data will span three different flight lengths including crossing an ocean. This adds both applicability and relevance to the results. It is important to note that the Seattle-Tokyo flight is the at the maximum travel distance for an A320 so conditions are at an extreme in this case.

Table 1[10] Popular Commercial Airline Flights (Nonstop)

Flight (Airport to Airport)	Time (mins)	Distance (kft)
Atlanta - Orlando (ATL-MCO)	90	2110
New York - Los Angeles (JFK-LAX)	390	13068
Seattle - Tokyo (SEA-HND)	650	25180

The specifications will also be matched to those of the most used commercial jet in the world (Airbus A320) at cruise seen in Table.2. Table.1-2 ensure that the results of the analysis are relevant to the current aerospace industry. The specifications included in Table.1-2 are important for finding the fuel load, range and the other performance parameters previously stated that will show the validity of ammonia as a fuel.

Table 2[11] Airbus A320 Cruise Specifications

Specification	Weight (lbf)	Speed (Mach)	Height (ft)
	160000	0.78	35000

A. NPSS Model

NPSS is an advanced object-focused, nonlinear thermodynamic environment that is commonly used in the aerospace industry for modeling, engines, including high bypass turbofans.. NPSS uses extend to most turbomachinery, liquid rocket engines, and air-breathing propulsion systems. The thermodynamic modeling capabilities allow NPSS to model the complexities of the internal thermodynamic processes found in engines and allow users to modify the design conditions the cycles occur allowing for the elimination of incredibly expensive and inefficient testing done with prototyped engines and hand-calculated models. With NPSS, the system being modeled is modeled with no risk of failure and external circumstances interfering with and corrupting testing results as well. NPSS was developed at NASA Glenn Research Center to help develop engine performance models that are viable for integration into pre-existing vehicle systems. Similarly to how NPSS is being used in this study, critical performance information can be modeled and integrated into pre-existing systems using the NPSS framework [12].

NPSS programs consist of three separate files that are run from the command prompt window indexing a directory that includes an executable run file. This run file includes indexing to the model file in which the system is built using a compilation of engine stages referred to as “elements”. The run file also references the case file in which the specifications for the conditions that will change throughout the analysis as well as commands about where to output the results of the test. Along with the actual engine model and case definitions, the run file includes definition of the thermodynamic package that is to be used in analysis. This package changes based on the fuel used and conditions present in the testing scenario. The NPSS models run off an “on-design” case that allows for the model to mathematically satisfy thermodynamic principles and allow for the software to have reference values when making certain calculations. NPSS analysis truly begins with the “off-design” case(s) which allow for the variables defined in the model file to be changed.

This specific model will use the thermo package used is in reference to a compound with the chemical and thermodynamic properties of ammonia mixing with air. When referring to a thermo package in NPSS, all reactants that will be present in the flow upon the combustion of fuel and the chemical reaction must be included so proper chemical equilibrium reactions can be calculated by the CEA software. This means that water, the compound referred to as “Air” in NPSS, and the ammonia compound. The NPSS model for the hydrocarbon fuel uses the same specifications as the ammonia model but with a different themo package. This package includes “Air”, water and Jet-

A in both gas and liquid forms. The NPSS software has an included directory for the thermodynamic properties of common fuel options, including Jet-A. It is also necessary to outline the components of the flow going through the modeled engine.

B. Turbofan Model and CFM 56-5B Components

The turbofan selected is the CFM 56-5B because it is the most common powerplant for the jet being examined and the industry standard for commercial jet airliners. As seen in Table.3, the engine specifications needed to properly define the components in the NPSS model are included and Fig.3 shows a cross-sectional view of the stages of a high bypass ratio turbofan engine and the airflow through said engine [2,13].

Table 3[2,11,12,13] CFM 56-5B Engine Specifications for NPSS Model

Engine Component	Engine Specification	Value
Inlet(1)	Ram Pressure Recovery	0.995
Splitter(2)	Bypass Ratio	6
Fan Compressor Bypass(1.1 and 4.1)	Design Efficiency	0.86
	Design Pressure Ratio	1.8
	Fan Map	2
	Design Correct Speed	1
Duct Bypass(7 thru 9.1)	Duct Pressure Loss	0.025
Low Pressure Compressor(3)	Design Efficiency	0.88
	Design Pressure Ratio	2.5
	Fan Map	2
	Design Correct Speed	1
High Pressure Compressor(4)	Design Efficiency	0.86
	Design Pressure Ratio	8.8
	Fan Map	2
	Design Correct Speed	1
Fuel Start Combustor	Lower Heating Value	18577
Burner(5F to 6)	Adiabatic Burner Efficiency	0.98
	Duct Friction Pressure Drop	0.05
	Fuel Loop Max Counter	250
	TtCombOut	3000
High Pressure Turbine(7)	Design Efficiency	0.89
Low Pressure Turbine(8)	Design Efficiency	0.88
High Shaft(4 to 7)	Mechanical Speed of Shaft	9000
Low Shaft(2 to 8)	Mechanical Speed of Shaft	3500

The NPSS model uses the engine specifications shown in Table.3 to model the tendencies of the flow with the thermodynamic information provided from the CEA portion of the software. The components listed above are indexed by corresponding numbers in Table.3 to the components shown in the complete turbofan seen in Fig.1.

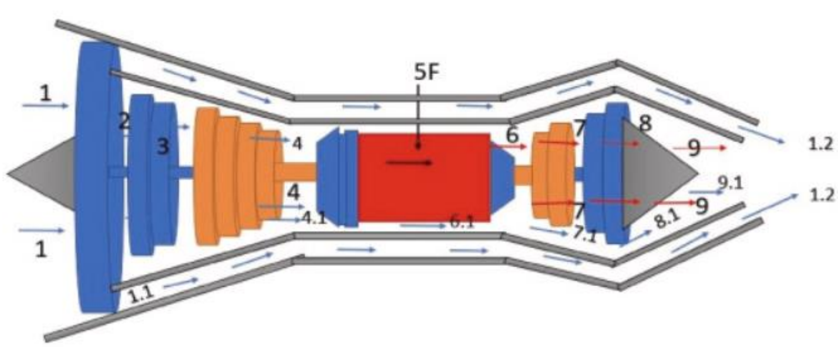

Figure 1 [2]: Component based diagram of modeled turbofan in NPSS environment

Due to the strong chemical bonds of hydrogen and nitrogen found in ammonia, higher temperatures are needed to crack the substance into a viable fuel solution. The combustion of ammonia requires a higher temperature in the combustion chamber and this value will be altered throughout the NPSS testing over a range of values between 1500 and 3050° Rankine. The specifications for all compressor/fan/turbine components are described in terms of the design efficiency, design pressure ratio, and the design correct speed. These values allow for calculation of losses to the energy of the flow from the beginning of the component to the end. The other components in the turbofan model are also characterized generally by pressure loss or adiabatic efficiency. Those values are outlined for the burner/bleed/nozzle components.

III. NPSS Results and Applications

The NPSS analysis was done for both the hydrocarbon and ammonia fuels on the previously defined specifications to ensure the results would be valid for comparison and the fuels are the only variables left to change. The only value that was changed between the NPSS models was the lower heating value which changes due to the fuel in use. The results from NPSS were inputted into a mathematical graphing software called MATLAB that output the figures included in the results section.

A. Ammonia Fuel Analysis

The results of the ammonia analysis are included below in the MATLAB figures with relations representing how well the engine is performing. The data shown was calculated over a range of combustor exit temperature (TtCombOut), so the energy produced corresponding to the specific combustor temperature is the focus of the analysis. The ammonia performance is shown specifically in the relationship between the TSFC and produced thrust which is significant of the fuel efficiency of the fuel in the engine. This relationship is shown in Fig.2 with a higher general TSFC value but a similar trend as other fuels in high bypass ratio turbofan.

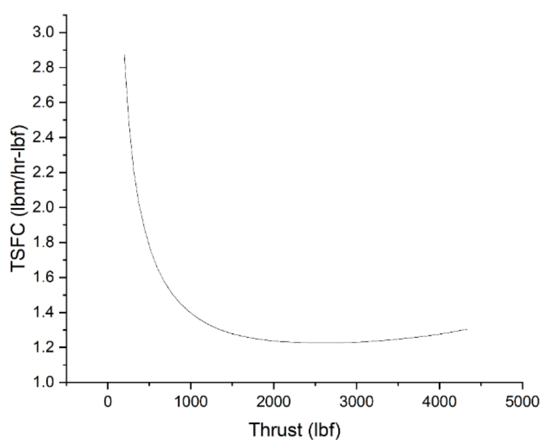

Figure 2: TSFC vs. Thrust relationship over a range of combustor exit temperatures

The second relationship examined is that between the fuel mass flow rate and the thrust produced over this range of combustion temperatures. The thrust produced will always increase for a greater fuel flow rate value but the rate at which this increase occurs shows how efficient in the combustor temperature range that the fuel/engine relationship is at converting the chemical energy in the fuel to thrust produced. Fig.3 shows this relationship and an average trend. The relationship in Fig.3 is a significant contributor to the TSFC value seen in Fig.2.

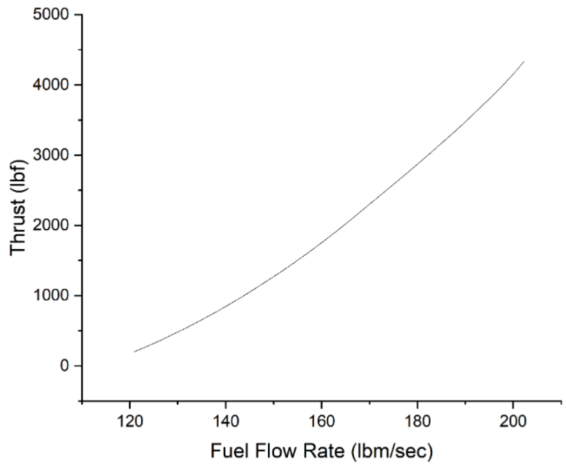

Figure 3: Fuel Flow Rate vs. Thrust produced relationship over a range of combustor exit temperature

The third relationship of importance is the relationship with combustor temperature and the thrust produced. This relationship is significant for ammonia fuel as the temperature at which combustion of ammonia occurs dictates the efficiency of combustion. This is because of the cracking and Haber Bosch processes that greatly affect combustion efficiency and thus the thrust produced. The relationship shown in Fig.4 is significant of this combustion efficiency as the combustion temperature changes. Due to the processes in ammonia combustion, Fig.4 could show whether the thermodynamic properties of ammonia will prevent it from becoming the staple fuel in the aerospace commercial industry.

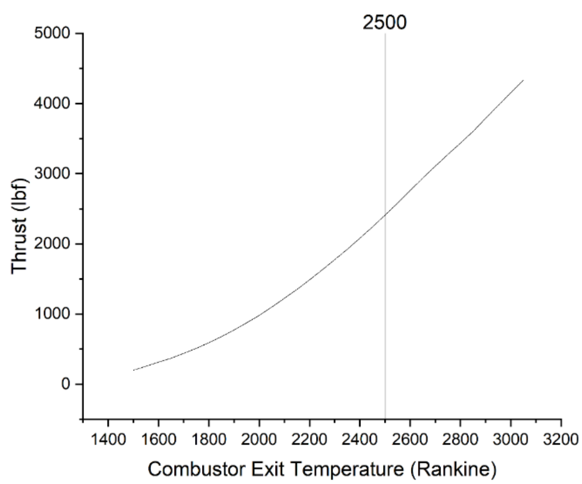

Figure 4: Combustion Exit Temp vs. Thrust produced relationship over a range of combustion exit temperature

B. Hydrocarbon and Ammonia Fuel NPSS Comparison

Figures 2-4 allow for a comprehensive view of the ammonia-turbofan system performance over the combustor temperature ranges. This shows that ammonia is at least a functional fuel solution, but the purpose of this study is to compare the performance of the hydrocarbon and ammonia fuel. The addition of hydrocarbon fuel allows for direct comparison for engine-fuel system performance.

The first comparison of note is that of the thrust specific fuel consumption and the thrust produced. This comparison will allow for observations to be made about which fuel type allows for the best fuel efficiency. As seen in Fig.5, ammonia has a greater TSFC value over the same range of combustion temperatures meaning that the ammonia fuel efficiency is worse than that of hydrocarbon jet fuel. Although the general trends are similar, as the combustion temperature increases (signified by the increasing thrust) the gap between fuel efficiency of the fuel types becomes greater. At the first and lowest combustion temperature (1500 Rankine) the percent difference in TSFC is 45.01% in favor of Jet-A(L). At the greatest difference or the highest combustion temperature (3050 Rankine) the TSFC is 65.26% in favor of Jet-A(L). The MATLAB code was also used to find the average percentage difference of the TSFC to be 59.10% between the fuel types. This difference is not ideal, but the fuel is in fact viable in a fuel efficiency sense.

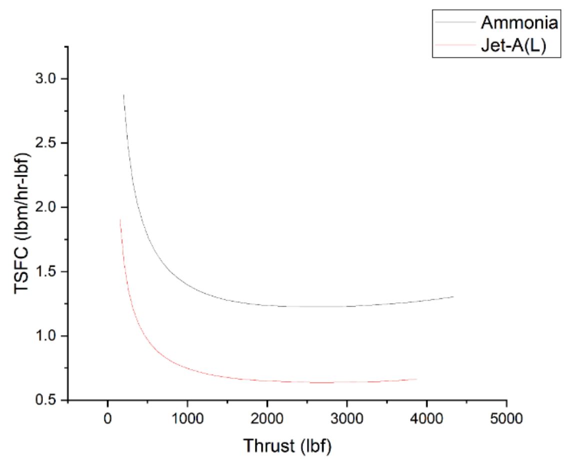

Figure 5: TSFC vs. Thrust produced for both Jet-A(L) and ammonia for comparison of the fuel efficiency

The second comparison examined is shown in Fig.6 displaying the thrust produced as the fuel mass flow rate increases over the combustor temperature range. The fuel flow rate and thrust relationship is significant of the efficiency at which the fuel can be converted into thrust. This means that regardless of fuel efficiency, the ammonia fuel allows for a greater amount of fuel to be combusted and converted into thrust than the Jet-A(L) fuel. The greatest percentage difference in the relationship is again at the coldest combustion temperature (1500 Rankine) at .00296% in the favor of ammonia. The greatest percentage difference occurs at a combustion temperature of 3050 Rankine at 1.33% in the favor of ammonia. The average percentage difference is calculated to be 0.73% in favor of ammonia. At these values, the difference in the engine ability to consume the specific fuel is virtually the same and should not be a concern to the analysis of ammonia fuel performance.

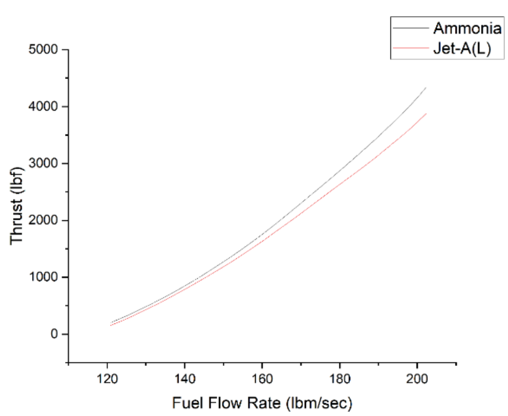

Figure 6: Fuel Flow Rate vs. Thrust produced for both ammonia and Jet-A(L) fuels for comparison of fuel flow efficiency

The third comparison of note is that of the combustion temperature and the thrust produced. Although the relationship shown in Fig.5 is important, the relationship shown in Fig.7 between the combustion temperature and thrust produced will show whether the Haber-Bosch and ammonia cracking processes render the ammonia impossible to rely on as a commercial aerospace fuel solution. The relationship between thrust and the combustion temperature is monotomic, as with any other fuel. The area of interest is the rate at which this increase occurs. If ammonia were unable to produce at least the same thrust at the same temperatures as Jet-A(L) then ammonia would not be a viable fuel solution. It is also important to note that thrust production did not suffer significant losses at the Haber-Bosch or ammonia cracking temperature ranges. Other concerns have to do with practicality whereas the concern with the thermochemical reactions that are special for ammonia could have uttered ammonia completely useless as a jet fuel. As seen in Fig.7, neither concern materialized when we assume equilibrium combustion as ammonia slightly outperforms Jet-A(L) in thrust production over this combustion temperature range. The smallest percentage difference in thrust produced occurs at 2100 Rankine at 6.97% in the favor of ammonia. It is worth noting that at this temperature the Haber Bosch reaction is taking place so the energy not represented in thrust may be used in the chemical reactions happening in this temperature range. The greatest percentage difference in thrust produced occurs at 1550 Rankine at 25.17% in favor of ammonia. The average percentage difference is 10.16% in favor of ammonia. These values show that although the chemical reactions that take place in the use of ammonia as jet fuel may use up some of the energy, ammonia has a greater combustion efficiency than Jet-A(L). Much further study is needed to determine what size and design the combustor for ammonia would need to take on in order to achieve these results.

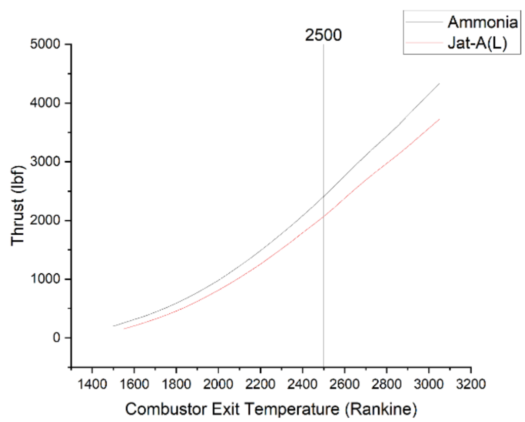

Figure 7: Combustor Exit Temp vs. Thrust produced for comparison of the combustion efficiency of the fuel solutions

C. Popular Commercial Flight Application

The comparison of fuel types is necessary for verifying the validity of ammonia as a jet fuel, but it is still necessary to compare the system performance to popular commercial flights to analyze both the capability of performing the flights and whether the fuel load or amount of ammonia needed is practical. As seen in Table.1 and 2, the specifications for the cruise of the flights are set to the average values for the CFM 56-5B high bypass turbofan. The fuel load will be calculated using the following Eq.1.

$$Fuel\ Mass\ Load = W \times Duration\ of\ Flight \quad (1)$$

Finding the fuel load allows for calculation of whether an A320 can complete the flight with ammonia as a fuel and fuel load. The fuel volume an A320 is prepared to carry is limited to 27200 liters of fuel [14]. The volumetric limit must be considered alongside the fuel weight limitation that is found in Eq.2 below.

$$Max\ Fuel\ Weight = MTOW - (Max\ Zero\ Fuel\ Weight) \approx 34171.65\ lb_f \quad (2)$$

This fuel weight limit must be compared to the weight of liquid ammonia corresponding to the maximum volumetric limit. Table.4 below shows the calculated values for the steps listed in the equations and the difference between the maximum and the amount needed for the most fuel strenuous flight. The maximum fuel weight of the ammonia will be calculated using Eq.3 below with the liquid ammonia density value of 1.503 lb_f/liter.

$$Ammonia\ Fuel\ Weight\ Load(Volumetric\ Limit) = 27200 \times 1.503 = 40891.06\ lb_f \quad (3)$$

Immediately comparing the results of Eq.2 and 3 show that the aircraft will be unable to fill the fuel tanks with the liquid ammonia fuel because the fuel weight would cause the aircraft to exceed the MTOW. Although the current A320 configuration is unable to carry full fuel tanks of the liquid ammonia, an alternative configuration could be a possible solution. Utilizing Eq.1 and 3 above, the fuel load for liquid ammonia fuel was calculated for all three flights in Table.1 and the final values for the fuel load are shown in Table.4 below. The fuel flow rate used for calculation will be 161.03 lb_m/min as this was the fuel flow rate in the NPSS simulation. A conversion between pound mass and pound force will also be used and that conversion factor is shown in Eq.4 below.

$$1lb_f = 32.174\ \frac{lb_m * ft}{sec^2} \quad (4)$$

Table 4[3,10] Required Ammonia Fuel Load for Popular Commerical Flight

Flight (Airport to Airport)	Fuel Mass (lb_m)	Fuel Weight (lb_f)	Fuel Volume (liters)
Atlanta - Orlando (ATL-MCO)	14490	4.66E+05	3.10E+05
New York - Los Angeles (JFK-LAX) (Nonstop)	62790	2.02E+06	1.34E+06
New York - Pheonix (JFK-PHX) Pheonix - Los Angeles (PHX-LAX)	56189 + 16261 = 72450	1.81E+06 + 5.23E+05 = 2.33E+06	1.20E+06 + 3.48E+05 = 1.55E+06
Seattle - Tokyo (SEA-HND)	104650	3.37E+06	2.24E+06

It is also possible to find the weight of fuel required using the Breguet Range Equation included below in Eq.5. The equation relies on the thrust specific fuel consumption of the engine, cruise velocity, lift-to-drag ratio, and the range to find the ratio of the fuel weight to the maximum weight of the aircraft. Using Eq.5 and the assumed maximum weight, the fuel weight can be found. Equations 1-4 are important to use in order to find the fuel volume for consideration of whether or not the aircraft can hold the required amount of fuel.

$$R = \frac{V}{c_t}\left(\frac{L}{D}\right)\ln\left(\frac{W_{i-1}}{W_i}\right) \quad (5)$$

As Table.4 shows, the fuel load of pure liquid ammonia jet fuel is too much for the current capabilities of the A320 and the general competitors in the market. The analysis made concessions by adding a connecting flight for a possible refuel into the New York to Los Angeles flight but no feasible route would allow for the limits to be met. The limiting factors for the ammonia fuel load was a fuel weight limit of 34171.65 lb_f of fuel and volumetric limit of 27200 liters. In the pure state considered for the analysis, the ammonia fuel is much too heavy, and the flight would require far too much for the ammonia to be a viable fuel solution. All three missions fail the parameters given by the percentages in Table.5 below.

Table 5[4,10] Required Ammonia Fuel Load Percentage Failure

Flight (Airport to Airport)	Fuel Mass (lb_m)	Fuel Weight (lb_f)	Fuel Volume (liters)
Atlanta - Orlando (ATL-MCO)	173%	173%	168%
New York - Los Angeles (JFK-LAX) (Nonstop)	193%	193%	192%
New York - Pheonix (JFK-PHX) Pheonix - Los Angeles (PHX-LAX)	193% + 175% = 194%	193% + 175% = 194%	191% + 171% = 193%
Seattle - Tokyo (SEA-HND)	196%	196%	195%

The data in Table.5 shows that the ammonia fuel greatly exceeds the constraints of the aircraft. The energy density of ammonia would have to increase greatly for ammonia to become a viable fuel solution in the commercial aerospace industry. The relationship between the percentage difference per duration of the flight is not proportional as the percentage difference increase tapers exponentially as the amount of time increases. The average fuel mass percentage difference varies at a rate of 0.906 %/minute. The average fuel weight percentage difference also varies at a rate of 0.906 %/minute. The average fuel volume percentage difference varies at a rate of 0.90 %/minute. These rates are clearly far too high for this state of the ammonia fuel to be a useful fuel solution in this application case.

IV. Conclusion

Considering the issues analyzed in the results, some deductions can be ascertained. All comparisons are made using the most common commercial aerospace industry standards. The turbofan engine used was the CFM 56-5B, the aircraft chosen was the A320, and the hydrocarbon fuel chosen was Jet-A(L). The flights considered are three different flight durations and include a flight that would cross the sea. The ability of an ammonia fuel to power a commercial aircraft across the ocean is an extremely important milestone that dictates the extent to which ammonia can be adopted into the commercial industry.

The NPSS analysis showed that the engine/fuel performance properties of the turbofan and ammonia were similar if not slightly better in terms of combustion efficiency and rate of fuel flow. The TSFC value of ammonia was significantly worse than Jet-A(L), meaning the production of thrust per unit of fuel is much less than the ammonia fuel but the ammonia is able to mix with the flow well and combust most of the material when temperatures allowed for high cracking efficiency and a limited amount of Haber Bosch reactions.

Another important conclusion was made using the NPSS data and implementation in the calculation of practicality among three different yet common flight routes in the commercial aerospace industry. When the NPSS results were utilized in reference to finding the required volume of ammonia fuel and the corresponding fuel weight required, the requirements were compared to the limits set by the model aircraft (A320). Both the volume and weight of the ammonia fuel were significantly greater than the limitations set by the aircraft. The total percentage difference in both categories was great enough that configurations made to the aircraft or engine to assist the required fuel values would not be able to make the ammonia fuel solution viable. The process that could be beneficial to observe would be the behavior of the flow in the combustion chamber because of the cracking of the ammonia and the Haber Bosch reaction. To ensure the greatest combustion efficiency with the ammonia fuel, the greatest ammonia cracking efficiency must be achieved. This requires a lot of heat and constant application of this heat because unintended chemical reactions will take place that take energy from the flow and will degrade the thermodynamics of the combustion process. In a certain temperature range, cracked ammonia molecules will mix with the N_2 and H_2 molecules in the atmosphere to create ammonia. This creation of ammonia will also take energy from the flow and be detrimental to the energy and thermodynamic efficiency of the engine. If these processes are analyzed properly and engine performance is still subpar, manipulating the ammonia fuel state to increase the energy density of the fuel for greater fuel efficiency performance will lead to the increase in thrust output necessary for Ammonia to be a viable fuel replacement. A hybrid fuel solution that allows for the ammonia fuel to engage outside of the Haber Bosch temperature range is also a plausible solution as this would still result in less greenhouse gas emission and better thermodynamic efficiency in these stages of flight.

Acknowledgments

The author would like to thank Dr.Roy Hartfield for his guidance and recommendation.

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