International Journal of Scientific Engineering and Applied Science (IJSEAS) – Volume-6, Issue-8, August 2020
ISSN: 2395-3470
www.ijseas.com

Modification of a Spark Ignition Engine to a Dual Fuel (Methane/Diesel) System to Achieve Environmental and Economic Benefits

Ayiei Ayiei

School of Engineering, RMIT University

Abstract

Global warming is an existential threat to mankind. Studies show that the resultant effects on climate change are associated with anthropogenic activities. Aviation is one of the major contributors to greenhouse gas emissions, contributing 5% of the global anthropogenic pollutants. As a result, there have been a movement towards engineering designs reduce the use of fossil fuels, via dual fuel engines. This paper investigates the viability of introducing dual fuel operations to facilitate the introduction of non-kerosene base aviation fuel, with specific focus on the modification of a jet A fuel aircraft to operate on methane as a dual fuel. The review examines the utilization of methane in spark-ignition engines, jet aircraft fuel systems, modification of dual fuel engines, and optimization to achieve high fuel efficiency, low maintenance costs, durability, performance and safety.

Keywords: renewable fuels, aircraft fuel systems, dual fuel engines

1. Introduction

Increasing concerns over energy security and the emissions of pollutant gases represents a survival challenge for the global transport industry. This has prompted new studies on the development of technologies that can be used to improve specific fuel consumption and air pollutant emissions. These studies concentrate on essentials of specific fuel consumption, aircraft efficiency, emissions technologies, and the possibility of potential alternative fuels. With respect to alternative fuels, there has been an increase in dual fuel, gas/diesel engines worldwide. This critical literature review investigates the viability of introducing dual fuel operations to facilitate the introduction of non-kerosene base aviation fuel, with specific focus on the modification of a jet A fuel aircraft to operate on methane as a dual fuel.

1.1. Background of the Study

Global air travel has achieved tremendous growth over the past decades. This growth has created concerns over the influence of aviation activities on the environment. Since the 1960s to the turn of the millennium, the demand for air travel has grown at an average of 9% every year. From the 2000s, demand has grown by approximately 4.5% per year. It is estimated that air travel will grow at an average of 5% over the next two decades. However, even though there have been tremendous improvements in energy efficiency of the aviation system, these improvements have not kept pace with the expansion of the industry, and so have exerted minimal positive on decreasing global greenhouse gas emissions (Ross, 2009).

The International Panel on Climate Change (IPCC) carried out an assessment on the state of climate change in the world. The 2007 assessment reported that the surface temperatures increased by 0.76°C from 1875 to 2003. This has led to a simultaneous increase in ocean temperature, global sea levels, and increased the rate at which snow and ice are melting. IPCC also concluded that 90% of the observed temperature increase was due to anthropogenic factors, particularly the rising levels of greenhouse gas concentrations such as carbon dioxide in the atmosphere. From this report, it was also projected that expected increases in temperature to 1.5-3.4°C by the end of this century will have significant impacts on water availability, food production, coastal flooding, and ecosystems. For instance, an increase by 2°C could potentially cause flooding to coastal areas, thereby exposing millions of people to floods and increasing the risk of extinction of species by 30% (IPCC, 2007).

The aviation industry is a small but significant contributor to global climatic change and global warming. David et al (2009) reported that the aviation industry contributed to 5% of the global anthropogenic forcing that is responsible for climate change. Over the years, there have been extensive reviews of the impact of aviation on climate change. The table below is a summary of the emissions that have been associated with this change.

Table 1: Annual emissions from global commercial aviation (2006)

Species	Quantity
CO_2 (Tg C)	162.25
H_2O (Tg H_2O)	232.80
NO_x (Tg NO_2)	2.656
SO_x (Tg S)	0.679
HC (Tg CH_4)	0.111
Organic particulate (Tg)	0.098
Sulfur particulate (Tg)	0.0030
Carbon particulate (Tg)	0.0023

There are predictions that the continued growth in the aviation industry will continue to outpace technological advancements in energy efficiency over the next decades. Changes in aircraft operations and design may be necessary to meet goals for limiting future climate change.

1.1.1. Aviation and Greenhouse Gas Emissions

With the current expansion in the global aviation industry, it is expected that the proportion of GHG emissions will also increase. In fact, there has been an increase in aviation fuel use over the past decade. It is important to note that analyses of the historical fuel use show that aviation fuel use growth has significantly surpassed that of other industries. This can be shown by examining the proportion of carbon dioxide fraction.

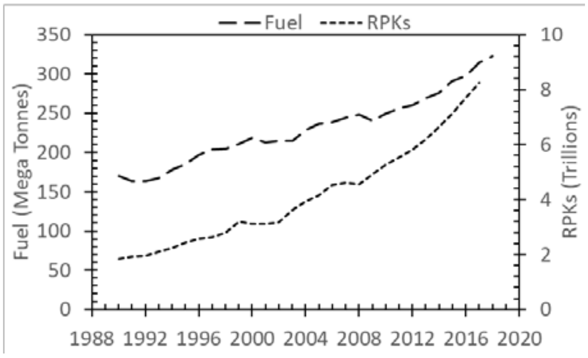


Figure 1: Shows the historical aviation fuel use and traffic.

It is important to note that aviation induced climate change does not originate singularly from carbon dioxide emissions, but also from nitrogen oxides, water vapour, and particles. The effect of these emissions on the climate is often determined by determining the radiative forcing index. This index takes into account the carbon dioxide as well as the NOx compounds, ozone, methane, water, contrails and particles emitted from aircraft exhausts with CO_2. When these compounds are released into the atmosphere, their anthropogenic radiative forcing is much greater than that caused by fossil fuel production. This is because of the longer residence times that the aircraft emissions require. This difference is taken into account when developing the radiative forcing index (RFI), which offers a reliable method for comparing the total radiative forcing effect caused by different emissions. The equation for the RFI can be expressed as:

$$\mathrm{RFI} = \frac{\mathrm{RF(CO_2)} + \mathrm{RF(O_3)} + \mathrm{FR(CH_4)} + \mathrm{RF(H_2O)} + \mathrm{RF(contrails)} + \mathrm{RF(particles)}}{\mathrm{RF(CO_2)}}$$

Radiative Forcing Index was used to measure the effect of aircraft and the results showed 2.7, with an uncertainty of at least ±1.5 (Commission for Integrated Transport, 2003). RFI has been used to develop projected future aviation operations by NASA's Atmospheric Effects of Aviation Project (AEAP), Emissions Inventory Database Group (EIDG), European Civil Aviation Conference's ANCAT and EC, as well German Aerospace Centre (DLR) to make projections up to 2050. The projections show that RFI will increase to 3.0 by 2050; however, when the aviation industry adopts alternative technologies, the RFI will be reduced to 2.6 by 2050. Projections by all these institutions show that the index can range from 2.2-3.4 within the same time frame if subsonic aviation is considered.

According to the UK Royal Commission of Environmental Pollution and the Commission of Integrated Transport, even though debates on the value of RFI continues, the current scientific evidence suggests that RFI is an important instrument for measuring total greenhouse emissions originating from the aviation industry (Dallara, 2011). Radioactive forcing can be defined as the instantaneous effect of accumulated emissions over a given period in time. In aviation, radiative forcing represents the prior and current aviation activity originating accumulated CO_2 emissions, in addition to the current effects such as the short-lived contrails. However, it should be noted that since different climate effects have different time scales, using RFI as the standard for measuring the effects may be misleading when comparing short term and long-term effects (Dallara, 2011). Foster et al (2006) reviewed studies on RFI and suggested that the current methodology fails to account for the resident time scales of emissions. As such, it exaggerates the impact caused by non-carbon dioxide emissions from aviation.

Sausen et al. (2005) provided estimates of radiative forcing from aviation that updated those provided by the Intergovernmental Panel on Climate Change (IPCC, 1999). The researcher estimated that The RF from other aviation-induced cirrus clouds might be as large as the present estimate of the total RF (without cirrus). The researcher also noted that the current knowledge of the effects of aircraft induced cirrus clouds has received little investigation making it difficult to establish reliable estimates of the climatic impact. The radiative forcing of these sources of aviation was presented by Sausen et al., (2005) as:

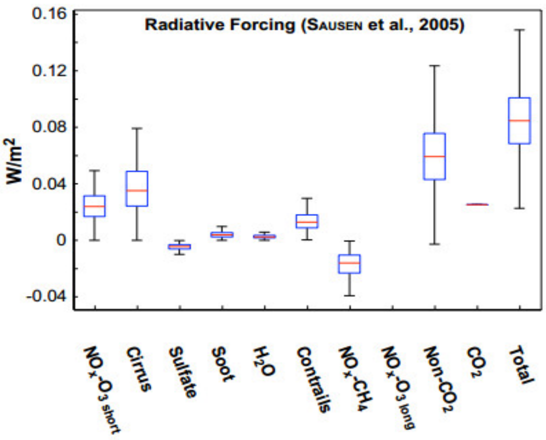


Figure 2: A comparison of CO2 and non-CO2 radiative forcing

The table also clarifies that aviation induced climate change results not only from the release of carbon dioxide, but also from emissions of nitrogen oxides, water vapor, and particles.

1.2. Problem Statement

As the aviation industry expands, concerns over the environmental impacts of aircrafts have become more pronounced. The major concerns have been the impacts of community noise exposure, degradation of air quality around airports, and climate change arising from greenhouses gases and altered cloud properties. Concerns over noise exposure have existed since the beginning of the industry; however, recent attention has mainly been on the role of aviation in climate change and how various technologies can be adopted to limit this impact. To this end, there have been increasingly stringent international standards that have been established to provide environmental restraints in aircraft design and operation. Thus, since the 1980s, all aircrafts have had to comply with the environmental standards stipulated by the International Civil Aviation Organization (ICAO). These standards directly affect the design of the aircraft as it influences the aircraft operating costs, community noise as well as emissions. The design is therefore a balance between performance and environmental objectives. The best strategy has been to implement a combination of wing, engine and mission design parameters that have the capacity of minimizing aircraft operating cost configurations while at the same time improving environmental performance. Thus, the need for research into different alternatives that can reduce costs and achieve high environmental standards is persistent.

The analyses provided in the background of the study shows the sources of aircraft climate impact. One key understanding is that the impacts resulting from greenhouse gas emissions are directly proportional to fuel consumption. The consumption depends on the ambient and engine operating conditions. From this, we can infer that technologies and operational strategies that reduce aircraft fuel consumption also reduce the climate impact. At the same time, the choice of one strategy is influenced by the economic competitiveness and the overall environmental performance that will be gained. The use of alternative fuels is one strategy that reduces operational costs due to reduced fuel expenditure and improves the aircraft climate performance. However, the use of alternative fuel in aircrafts can only be achieved through a modification of the engine to operate on dual fuel. This study is therefore concerned with not only the climate impacts of the aviation industry but also the choice of an appropriate alternative fuel and the subsequent modification of engine to achieve both economic and environmental benefits. Of particular interest will be the two ways in which diesel engines can be modified to operate on methane: dual operation with ignition by pilot fuel injection and operation on gas alone with spark ignition.

2. Alternative Aviation Fuels

Commercial aviation has attained rapid growth over the past several decades. While this growth has positively impacted on global economic growth and expansion of the transportation of people and goods, it has also led to an increase in aviation emissions despite technological improvements in fuel efficiency. Emissions are of importance to this study because they influence the radiative balance of the earth system. Commercial aviation is a significant contributor to global anthropogenic forcing associated with climate change and global warming (Dallara, 2011). Changes in aircraft operations and design therefore constitute a necessary intervention for limiting future deleterious effects of greenhouse gas emissions.

Major developments in recent times have concentrated on internal combustion technologies focusing on engine efficiency improvements and emissions reduction. The concern has been on the damaging effects of fossil fuels, hence the need for alternative fuels (Wu et al., 2011). The use of natural gas in diesel engines has been associated with both economic and environmental benefits. The economic advantage is linked to the abundant availability of natural gas in many parts of the world and it also gives high resistance to knocks when utilized as fuel in internal combustion engines. The environmental advantage is linked to a reduction in particulate matter in exhausts, as well as reduced impurities when compared to petroleum fuels (Selim, 2003; Selim, 2005).

In the current business environment, new technologies are being developed and fossil fuel is the major source of energy production. Just like in other industries, growth in the aviation industry is also increasing fossil fuel consumption and therefore exacerbating the climate change impact discussed in the previous chapter.

To put the growth in energy use in perspective, it is important to note that total energy consumption in the world has grown by 36% over the past 15 years. This increase is expected as human population and industries expand. Increased use will also increase production and subsequently draining of the existing reserves at a higher rate. Currently, 60% of all the oil in the world comes from countries that experience frequent political turmoil. This has been the main driver of fluctuations in oil prices and disruptions in oil supply across the world.

The rapidly depleting reserves as well as the impact of fossil fuels on air quality, climate change, and global warming have created new concerns. All over the world, there are awareness groups that continue to fight for more measures to protect the environment as well as promote investments in alternative fuels. A number of alternative fuels have been cited as potential replacements for petroleum. Some of these fuels are natural gas (NG), which is predominantly methane, liquefied petroleum gas (LPG), as well as ethanol, methanol, and di-methyl ether, among others.

Natural gas (NG) consists of 95% methane, 3% ethane, and 2% propane and butane. In automotive, NG is used as liquefied LNG or compressed natural gas (CNG) in cylinders. Rarely is LNG used in practice due to its difficulty to handle. Compressed NG is preferable because higher compression ratio can be utilized to increase combustion rate. One disadvantage of using compressed NG is reduced engine volumetric efficiency. The fact that NG has to be stored in a high-pressure tank means that it is heavy and reduce payload and luggage space, for example, an engine with a 75-litre talk is about 150 kg heavier than its gasoline counterpart. Further, thermal stability and heat transfer issues demand use of high-purity methane instead of NG. My present analysis is emphasizing on properties of methane as an alternative fuel (Wu, 2011).

There have also been studies that have also looked into ways in which hydrogen can be used as the future fuel for internal combustion services. Most of these alternative fuels are derived from other sources that are different from petroleum and emit lesser pollutants when compared with gasoline. Most of these alternatives are also more economically viable when compared with gasoline. The most preferred of these alternative sources of energy is methane, especially for aircraft engines.

2.1. Natural Gas

Natural gas (CNG) is considered favourable as an alternative fuel owing to economic and environmental benefits. Methane is the major component of CNG. It’s a clean fuel and considered appropriate for most fuel engines, particularly spark-ignition engines. This does not mean that CNG does not have disadvantages. For example, due to the slow burning velocity of natural gas combined to the fact that it has poor lean-burn capability, the CNG spark-ignition engine has some disadvantages arising from low thermal efficiency, large cycle-by-cycle variation, and poor lean-burn capability. These disadvantages decrease power output and increase fuel consumption.

Nonetheless, CNG is considered a better fuel that petroleum because it has unique combustion and can be utilized to form a suitable mixture formation. Further, due to the high octane number of CNG, the engine can operate smoothly and efficiently at high compression ratios without knocking. It is the high octane number of 130 that ensures that the engine operates at high compression ratios with little knocking. Since CNG has a lower flame speed, it promotes a very high level of engine durability. The cost of producing CNG is lower compared to crude oil production. While a large proportion of CNG is composed of methane, there are also traces of other gases such as of ethane, propane, nitrogen, helium, carbon dioxide, hydrogen sulfide, and water vapour. Nonetheless, methane (CH4) is the principal component.

Another advantage of using methane as fuel is that the current gasoline and diesel engines can easily be converted to CNG engines with little structural changes. CNG engines are known to have good thermal efficiency and high power, as well a broad combustion range. CNG engines strive to achieve lean combustion. These results in low fuel consumption and reduced production of NOx. These engines also yield lower levels of emissions when compared to conventional diesel or gasoline engines. There are various studies that have been carried out and have supported these advantages of CNG engines, with particular regard to emission characteristics. In light of these advantages, there is an incentive to convert gasoline or diesel engines to CNG engines (OECD, 2012).

2.2. The Utilization of Methane in Spark-Ignition Engines

There are several alternatives that have been studied to current internal combustion (IC) engines, particularly natural gas (NG), which is predominantly methane, liquefied petroleum gas (LPG), hydrogen, as well as ethanol and methanol. These studies have tested their use either as replacement or supplement fuel to gasoline or diesel in spark engines. In compression ignition engines, dual operations provide the pilot with the ignition source. LPG has also been tested because of its relatively high density and octane rating as well as low pollutant. One major advantage of LPG is that it can be stored as a liquid in moderate temperature unlike most of alternative fuels. Methanol has also been tested and it has a very high octane rating. However, it has low heating value and low stoichiometric air fuel ratio (AFR). This means that volumetric fuel consumption is higher for methanol comparative to gasoline. In sense, natural gas is more advantageous than all the other alternative fuels. Apart from all the other benefits discussed, it also has the advantage of energy diversification and the total reserves have been estimated in the same order as petroleum but with only 60% of its production rate (Vuorenkoski, 2004).

Methane (CH4): a radiatively active gas. It is approximately 25 times more effective on a per-molecule level than CO2 in terms of its integrated greenhouse effect at hundred-year time scales. For this reason, there are studies that have been done on the effects of CH4 as a favourable alternative fuel. In a study done by Santoni et al (2011), fuel-based emission indices for CH4and N2 were quantified from CFM562C1 engines aboard the NASA DC-8 aircraft during the first Alternative Aviation Fuel Experiment (AAFEX-I) in 2009.

There have been several studies on the utilization of methane in spark ignition engines. (Wu et al., 2011) investigated dual-fuel injection strategies in spark-ignition engines and showed that dual injection allows in-cylinder blending of two fuels, at any fuel ratio, when port fuel injection (PFI) and direct-injection (DI) are simultaneously combined. In this case, both fuels can be the main fuel and the choice depends on engine demand and availability of fuel. As such, a bi-fuel concept that utilizes a single cylinder spark-engine is one of the ways through which methane can be used alongside diesel in aircraft engines (Paragiannakis & Hountalas, 2003).

In another study Duc & Wattanavichien (2007) established that biogas–diesel dual fuelling of stationary engines has revealed no deterioration in engine performance. However, cases of lower energy conversion efficiency were offset by the reduced fuel cost of biogas over diesel. Selim (2001) also demonstrated that combustion noise increases in dual fuel engines compared to diesel engines. Nonetheless, biogas–diesel dual fuelling is feasible alternative.

According to Langton, Clark, Hewitt, & Richards (2009), there are specific fuel system drivers that must be taken into account as they directly affect key performance, operational, and cost parameters. These drivers are; the intended aircraft mission, dispatch reliability and system operational availability, fuel tank boundaries and location issues, measurement and management system with functional requirements, and the electrical power technology and management system architecture. These factors must necessarily inform development of dual fuel systems, specifically the modification of a jet A fuel airline to operate on methane as a dual fuel that this thesis will focus on.

According to the International Association for Natural Gas Vehicles (IANGV, 2009), there are about 11.2 million natural gas vehicles in the world and the interest is increasing because natural gas combustion has significantly less emissions of CO_2, NOx and other emissions from diesel and gasoline engines. Natural gas vehicles can either be fully converted, dual operation or dedicated engines. The conversion of port injection gasoline engine to natural gas engines often leads to reduced power and limited upper speed. This is linked to the reduced volumetric efficiency and low turbulent flame speed. However, these limitations can be eliminated by direct injection which will increase volumetric efficiency while also improving the mixing as a result of turbulence induced by high pressure injection. The development of direct fuel injection is however complicated and costly because the cylinder heads must be redesigned and retrofitted to accommodate the direct fuel injector (Martz, 2012).

2.3. Direct Injection Concepts

There are two main characteristics of direct injection. These are internal mixture formation and closed valve injection. In direct injection, the mixture is important because the time for air-fuel mixing is relatively short when this compared with carburetion or indirect port injection. In spark ignition engines, the mixing of fuel and air takes place in the cylinder. But a premixing process can occur depending on the type of fuel delivery required in the modified engine. In an indirect port injection, the fuel vaporizes and mixed in the air stream before it enters the combustion chamber.

On the contrary, in a port injection system, the fuel is injected and the velocity of fuel jet determines atomization and evaporation of fuel in air. However, in the direct injection method, the fuel is directly injected into the combustion chamber when the intake valve is closing. The gas jet produces turbulence in the combustion chamber and this determines the degree at which the fuel and air will mix. Mixing in the direct injection therefore occurs over a very short time. Unlike in carburetion, where the fuel-air mix is achieved before entering the combustion chamber, in indirect injection the mixing has to happen in confined cylinder geometry. Understanding these concepts is therefore necessary because direct injection in spark engines is the basis of dual fuel engine modification, increasing thermal efficiency and subsequent reduction in pollutant emissions. Further, it is important to understand that the degree of fuel-air mixture as well as the mixture uniformity is an indicator for reliable combustion.

3. Aircraft Fuel Systems

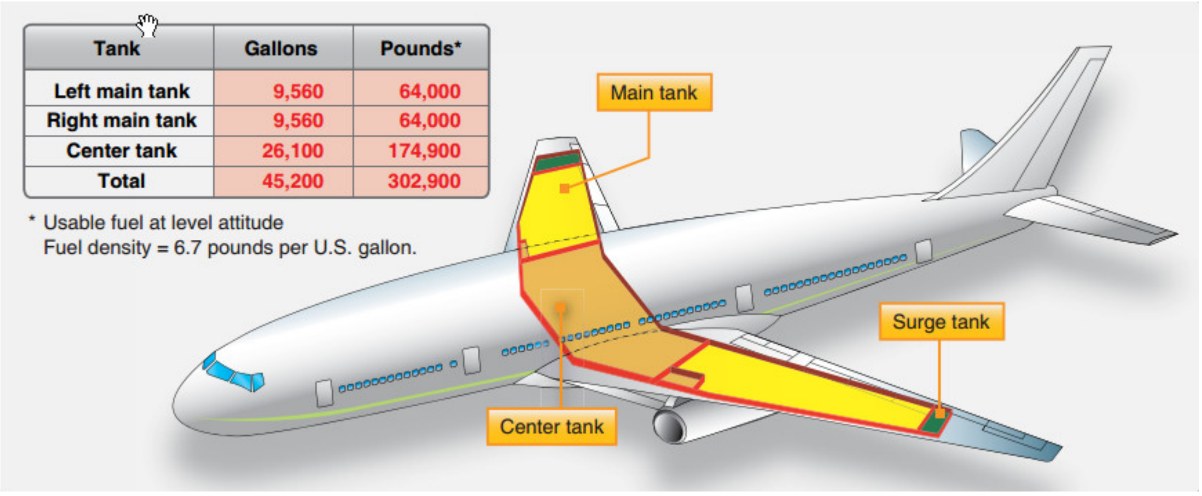
The analysis presented below covers the aircraft fuel systems, with specificity to jet aircraft fuel systems. A fuel system consists of storage tanks, pumps, filters, valves, fuel lines, metering devices, and monitoring devices. The conversion must ensure that the system has the ability to provide uninterrupted flow of contaminant-free fuel regardless of the altitude of the aircraft. Again, since fuel load occupies a significant portion of the aircrafts weight, considerations for airframe are also discussed. Again, variations in fuel loads and shifts in weight during manoeuvres should not have a negative effect on controlling the aircraft in flight (Wu, 2011).

3.1. Jet Aircraft Fuel Systems

There are different fuel systems designed and produced by aircraft manufacturers. However, all these systems have the basic requirements. The most important of which is that each system must have the ability of storing and delivering fuel to the engine at a pressure and flow rate that can sustain normal operations irrespective of the operating conditions of the aircraft. Of interest to this study are jet transport aircraft fuel systems.

Fuel systems on large aircrafts are necessarily complex and contain components that are not in small-single engine, small multi engine, large reciprocating-engine, or even helicopter engine fuel systems. Jet transport fuel systems contain more redundancy as well as numerous options that crew can choose from when managing the aircraft’s fuel load. Of importance are the onboard APU systems, single point pressure refuelling and jettison systems which are not found in the other fuel systems. Jet transport fuel systems contain the following subsystems: storage, vent, distribution, feed and indicating (Langton et al., 2009).

Current transport fuel systems are generally similar and have three fuel tanks. There are tanks on either wings or one at the centre to carry the thousands of pounds of fuel that is needed on board. The figure below shows these fuel tanks.



Tank	Gallons	Pounds*
Left main tank	9,560	64,000
Right main tank	9,560	64,000
Center tank	26,100	174,900
Total	45,200	302,900

* Usable fuel at level attitude
Fuel density = 6.7 pounds per U.S. gallon.

Figure 3: Boeing 777 fuel tank locations and capacities

These fuel systems also require venting. These are a series of vent tubing and channels connecting all tanks. Venting ensures that the engine has adequate supply of fuel irrespective of the attitude of aircraft or the quantity of fuel that is carried on board. This often requires the installation of check valves, float valves, and multiple vent locations within tanks (Langton et al., 2009). The figure below shows venting.

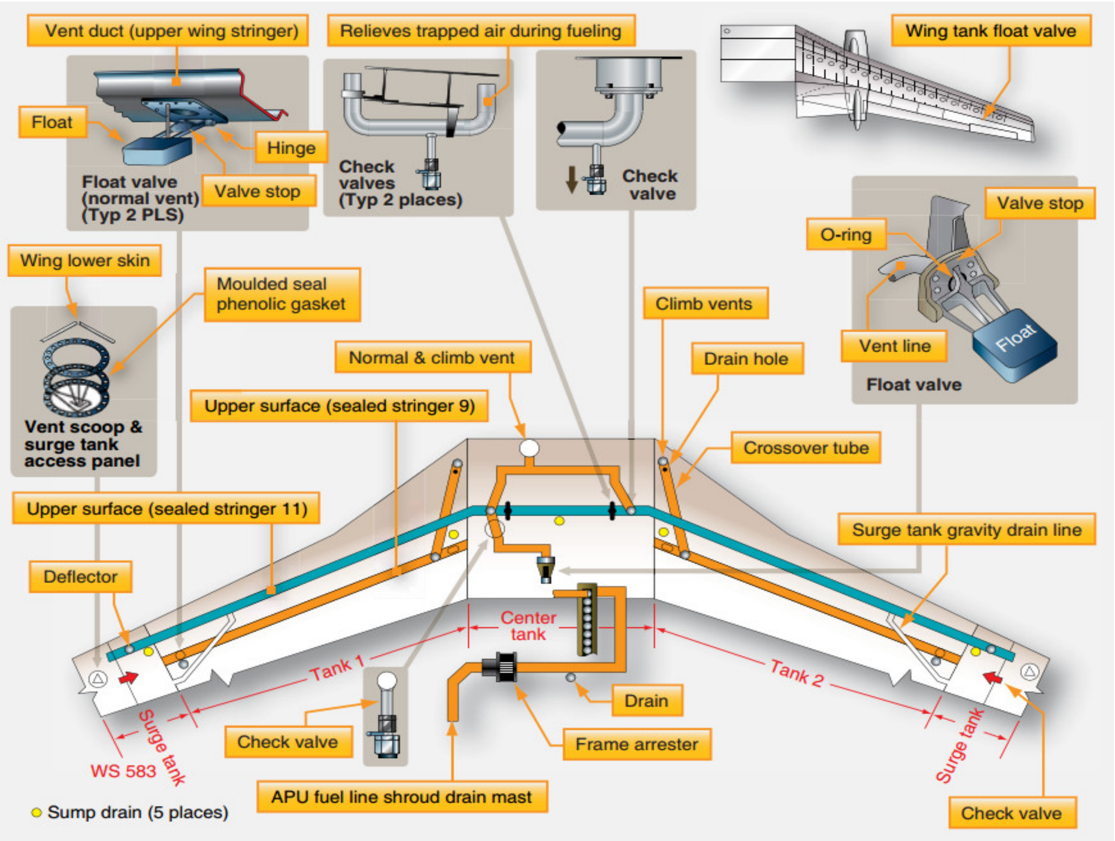


Figure 4: A fuel vent system with associated float and check valves that stop fuel and keep the tanks vented regardless of the aircraft attitude.

In addition to storage and venting, there is also a fuel distribution system that is comprised off the pressure the fuelling components, transfer system, defueling components and fuel jettison system. Jet transport fuel systems also have a feed system which provides the means of heating the fuel by mixing hot air and hot oil from the aircraft's engine. Finally, monitoring systems are used for assessing a variety of parameters such as fuel flow indicators for the engines and monitoring how fuel is being delivered to the engines. Different lighting systems are used to show fuel temperature, fuel pressure and even fuel quantity. The location of instrumentation depends on the type of jet aircraft. The figure 5 is a representation of the entire fuel system (Langton et al., 2009).

.

3.2. Components of the Fuel System

There are so many components of a jet aircraft fuel system. This analysis will only look at a few of them in summary. The discussion of the fuel system offers a better framework for analysing which components will need to be modified for the engine to become a dual fuel engine capable of operating on methane.

3.2.1. *Fuel Tanks*

The purpose of fuel tanks is to store fuel. These tanks are designed, located and installed to retain fuel when the fuels are subjected to inertia loads that result from static load factors and under conditions that occur when aircrafts land on runway at normal landing speed and the landing gear has been retracted. These tanks must also retain fuel when the gear collapses or even in situations when the engine mount is torn away. Many aircrafts have rigid removable fuel tanks strapped on the main frame. These tanks are riveted or welded together. They are also held in place by padded straps so that they don’t move when there are shifts in flight. There can also be bladder tanks or integral tanks (Langton et al., 2009).

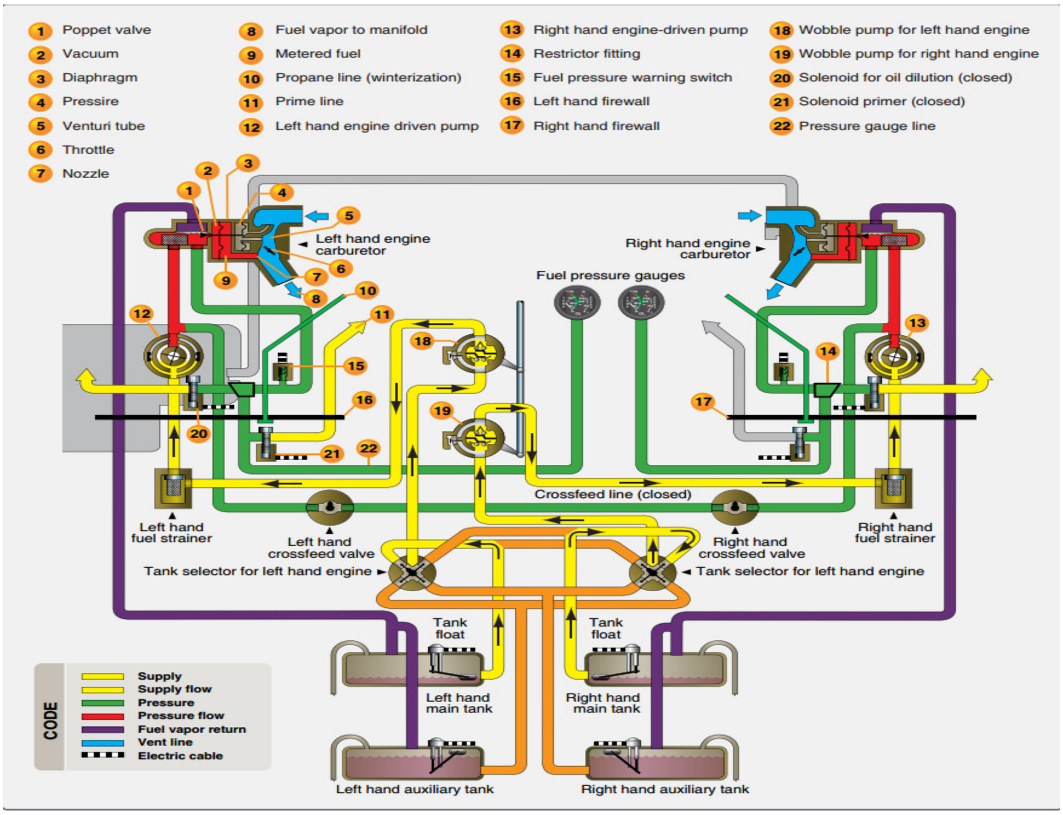


Figure 5: Jet aircraft fuel system

3.2.2. *Fuel Valves*

There are many fuel valves uses in aircraft fuel systems. These valves shut off fuel flow or route the fuel to a desired location. Apart from the sump drain valves, light aircraft fuel systems may include only one valve, the selector valve which incorporates the shutoff and selection features into a single valve. However, large aircraft fuel systems have numerous valves. These are mostly open and usually go by different names depending on the location and function, thus: shutoff valve, transfer valve, cross feed valve, and many others. Fuel valves can either be manually operated, solenoid operated, or in some cases electric motor operated (Langton et al., 2009).

3.2.3. *Fuel Pumps*

Apart from aircrafts that use gravity-feed fuel systems, all jet aircrafts have at least one fuel pump which serves the function of delivering clean fuel under pressure to the fuel metering device for each engine. While these engine-driven pumps are the primary delivery devices, aircrafts can also have auxiliary tanks that are used for providing fuel under pressure to the engine driven pumps to speed up sufficient fuel delivery. These pumps also serve as back-up pumps to the engine-driven pumps when the aircraft is taking off or when the plane is at high altitude to guard against vapour lock. Large aircrafts have boost pumps to move fuel from one tank to the other. Pumps can be hand-operated, but most are electrically operated (Langton et al., 2009).

3.2.4. Fuel Filters

Fuel filters serve the function of fuel cleaning. They are usually constructed with relatively coarse wire mesh. These filters are designed to trap large pieces of debris and prevent their passage through the fuel system. They are usually fine mesh and have the ability of trapping fine sediments as well as water. Turbine-powered aircrafts use micronic filters that have the ability to capture extremely fine particles in the range of 10–25 microns. A micron is 1/1,000 of a millimetre. All aircraft fuel systems have filters and strainers that ensure that the fuel delivered for combustion is contaminant free. Sumps are always used to encourage the collection of debris in the lowest part of the tank. Once collected, they can be drained off before flight. The actual tank outlet for the fuel is positioned above this sump.

3.2.5. Fuel System Indicators

As the name suggests, these are indicators for showing the integrity of various aspects in the fuel system. The Fuel system indicators also measure the fuel flow, temperature, and pressure, Fuel system indicators have valve position indicators and various warning lights that convey the necessary information needed for making a decision.

3.2.6. Fuel Quantity Indicating Systems

Again, as the name suggests, these systems are used for indicating the quantity of fuel. These indicators may vary depending on the aircrafts fuel system complexity. There are indicators which are simple and require no electrical power to operate. These types of indicators are commonly used in light aircrafts where the fuel tanks are closer to the cockpit. However, for larger aircrafts, electric indicators are necessary. Some aircrafts use electronic capacitance-type of indicators.

3.2.7. Fuel Flowmeters

A fuel flowmeter is a device indicating an engine’s fuel use in real time. These meters make it possible for the pilot to ascertain engine performance and carry out flight planning calculations. There are different types of fuel flow meters. However, there are various challenges that fuel flow meters face. For instance, it is difficult to accurately measure fuel flow because fuel mass changes with changes in fuel mass or with the type of fuel used in turbine engines. Nonetheless, there are systems that have been developed to measure fuel volume (Selim, 2005). The actual mass is assumed to be the average weight of the fuel per unit fuel volume.

Large reciprocating engines utilize a vane-type of fuel flow that measures the volume of the fuel that has been consumed by the engine. This meter is usually located between the engine-driven fuel pump and the carburettor. This means that the entire volume of fuel delivered to the engine must pass through the fuel flowmeter. As the fuel pushes through the vane so is the fuel volume measured. In other words, the fuel flowing to the engine pushes the vane and triggers movement of a calibrated spring. As the vane shaft rotates, the varying degrees match the fuel flow rate through the unit. An autosyn transmitter deflects the pointer on the cockpit fuel flow gauge the same amount as the vane deflects. The dial face of the indicator can be calibrated in gallons per hour or pounds per hour based on an average weight of fuel. There are important considerations that are taken into account in such a system. For example, since the fuel must pass through the meter unit, it means that any malfunctioning of the unit will prevent fuel flow. As such a relief valve is included to permit greater flow in response to pressure or build-up.

4. Modification of Dual Fuel Engines

The researcher's initial interest in modifying diesel engine to dual fuel engine was inspired by the development of the Husky CNG 200P Dual Fuel which is touted as the "world's first dual fuel, CNG piston powered aircraft" which will be unveiled this year and was on display from July 29 to August 4 at AirVenture 2013. This aircraft operated on compressed natural gas and aviation gasoline. These data are important to the study because preliminary examination of gaseous fuel has rightly showed that compressed natural gas (CNG), preferably of high purity methane is the most preferable. This study primarily focused on the design of dual fuel engines in a bid to understand which modifications, and at what costs to performance, can be made on a Jet A fuel airline.

4.1. Duel Fuel Engines

All over the world, there has been an increase in the number of dual fuels, natural gas/diesel engines. The degree of sophistication of these engines varies depending upon fuel control strategies, however, they have proven reliable in many parts of the world and continue to expand their market share, particularly in regions where diesel pollution and climate change has become a major issue. However, for aircraft pollution, the concern is worldwide hence the movement by international regulatory agencies to impose environment performance standards on airlines.

4.1.1. Operating Characteristics and Advantages of Dual Engines

Natural gas engines can either be bi-fuel engines or dedicated engines. Bi-fuel engines are spark ignited and can either run on natural gas or gasoline/diesel alone. The bi-fuel natural gas maintains a two-fuelling system; in this case methane and diesel. These dual-fuel engines tend to be more environmentally friendly when compared with petrol engines. They can also run on natural gas alone in the absence of gasoline and easily fuel on gas fuelling stations.

On the contrary, dedicated natural gas engines can only operate on natural gas. These engines tend to be more optimized that the dual engines since they have a compression ratio that has been designed to take full advantage of the 130 octane of natural gas. Further, these engines are also designed to consider the combustion characteristics of the fuel leading to very low pollution (Ross, 2009).

Dual fuel engines are based upon diesel technology. The fundamental concept of diesel engine is not a new idea. The concept was first developed by Rudolf Diesel in the 1980s. Diesel experimented with the approach when he was researching and developing the diesel engine. He was the first to introduce what is commonly referred to as pipeline natural gas into the air intake and observed improvements in engine performance. Since this initial understanding, dual engines have been in the market (Dallara, 2009).

These engines are used in stationary applications in the gas compression industry. In industrial applications, dual engine applications are often separated into low speed and high speed engines. Low speed is defined as 1000 rpm or lower while high-speed engines generally run between 1200 and 1800 rpm.

A diesel engine is a compression ignition engine, and therefore it does not have spark plugs or any ignition system. The primary fuel; diesel serves as the ignition source or the mixture of diesel and air cab be ignited in a combustion chamber. At the basic level, dual-fuel engines retain these fundamental principles of diesel engine efficiency while allowing the engine to operate on cheaper and cleaner fuel.

In a dual fuel engine, methane is the primary fuel, and it is designed to operate interchangeably with diesel as a 'pilot ignition source. The diesel functions on heat compression and not a spark plug. When the engine is idle, it operates on 100% diesel. However, when the engine begins to move to full load performance, an increasing amount of natural gas replaces the diesel fuel to 80% or more. This replacement of diesel with natural gas is valuable if the environmental and economic objectives are to be achieved. Another way of replacing diesel with natural gas is through a fumigation system where natural gas is added to the engine when higher speeds are required (OECD, 2012).

In more complex systems, the mixing of natural gas and diesel is computer controlled to ensure that the optimal ratio of natural gas and diesel fuel is delivered to the engine depending upon load and performance requirements. The performance and the level of emission of dual fuel engines depend on various factors such as operating conditions and the complexity of the control system. Nonetheless, dual engines achieve better environmental and economic performance compared to conventional diesel engines.

The modification can either be through single-point fuel admission or multiple point fuel admission. In single-point fuel admission, methane admission is achieved by admitting methane through the engines gaseous intake through mixers installed upstream of the turbocharger. The incoming supply of methane is filtered prior to the pressure regulator through shutoff valves while the flow is regulated using a butterfly throttle valve governed by the main control system before the gas is admitted through the mixer (s). The control system will rely on a series of sensors and transducers including fuel pressure, manifold air pressure and temperature to compute the optimal diesel-to-gas ratio. The fuel valve can be optimally positioned to admit the proper amount of methane for the engine. In a single-point fuel admission, between 50% and 70% substitution rates and higher can be achieved. This technique is usually used in high speed engines (Papagiannakis & Hountalas, 2003).

In low speed engines, multi-point fuel admission is the preferred technique. Here, fuel is injected to the engine through individual valves on each cylinder in a concept referred to as multi-point injection. Through thus technique, between 60% and 80% gas substitution rates and higher can be achieved.

4.2. Modified Fuel Injection System

During the past few decades, jet engines have achieved significant improvements in terms of performance, efficiency, emissions and acoustics. Modification is based on changing the fuel admission system of the jet aircraft fuel system. In general, the technical solution to the problem is the design and development of fuel injection valves for internal combustion engines. Such a design should be configured in such a way that it can be used for both a diesel engine and a dual-fuel engine, in that it can alternate between these two fuel operations. The fuel injection valves should also be able to inject high pressure diesel fuel in the combustion chamber in such a way that main injection and pilot injection are simultaneously conducted, or only a small amount of fuel oil is injected into the combustion chamber in a pilot injection manner.

4.2.1. Technical solution

Generally, conventional fuel injection valves in the market consist of a needle and a spring operated in such a way that application of pressure to the valve leads to the opening of the valve flow passage which only closes when the pressure is withdrawn. In the absence of pressure, the valve flow passage remains closed. Therefore, when high pressure fuel is supplied from a fuel pump to the injection valve and the pressure is higher than the opening pressure formed in the fuel injection valve, then the needle will be pushed upwards which leads to the opening of the flow passage. The fuel is then injected into a cylinder through several nozzle holes formed in one end of the nozzle. It is important to note that in this injection method, all the nozzle holes are opened or closed according to a single injection mechanism with a single present opening pressure. Therefore, in a scenario where there is a low-load operation, the injection pressure of fuel is comparatively low. As such, conditions of fuel spray deteriorate and the efficiency of combustion is reduced (Ross, 2009).

In the case of a dual-fuel engine, the injection valve system can alternate between gas fuel operation and diesel fuel operation. This means that when the engine is in diesel mode (when it is operating primarily on diesel fuel); the diesel is injected into the combustion chamber through a conventional fuel camp and a fuel injection valve. On the contrary, in a case where the engine is operating primarily on gas, there is need for a separate electronic control fuel injection system to inject a small amount of fuel that is adequate in functioning as an ignition source as a gas mixer that is subsequently injected alongside compressed air supplied into the combustion chamber. The solution for the dual fuel engine therefore revolves around the diesel injection through a mechanical fuel pump and pilot injection operation through an electronic control fuel injection system.

Dual fuel operation will require the injection of pilot fuel and gas fuel into the combustion chamber. Modification involved changing different types of valves. Ideally, the new fuel injection system will have four injection valves: two for methane injection and two for diesel injection. The valves responsible for high-pressure supply, diesel supply, controlling diesel supply for actualization of the gas injection valves, and sealing diesel supply. This gas injection valve design can be represented as:

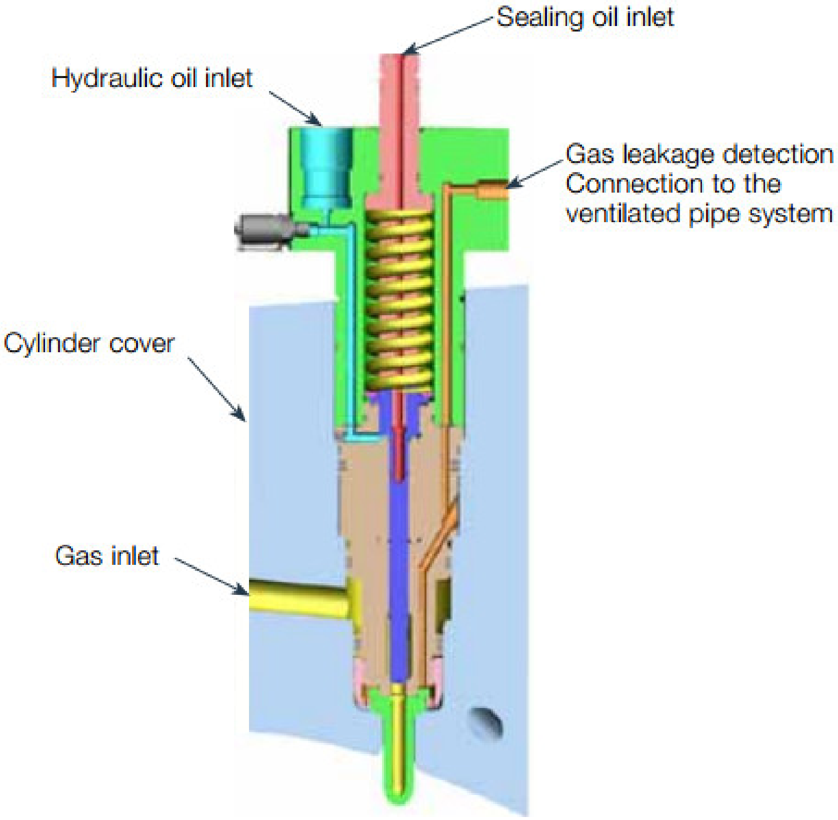


Figure 6: Gas injection valve

The design of the gas injection valve aligns with traditional design principles for a compact design. The gas is admitted through bores in the cylinder cover. There are sealing rings made of temperature and gas resistant materials have been installed to prevent gas leak between the cylinder cover/gas injection valve and the valve housing/spindle guide. From the design, it can also be seen that any gas leakage will be directed through the gas sealing rings and led through bores in the gas injection valve to the space between the outer and inner shield pipe of the double-wall gas piping system. It is in this space that gas sensors are installed and can detect any leakage (Martz, 2012).

Further the gas acts continuously on the valve spindle at the optimal pressure. Further, to prevent gas from entering the diesel actuation system through the clearance around the spindle, the spindle is sealed by sealing oil at a pressure higher than that of the incoming gas.

The diesel/oil valve is a standard fuel oil valve and it has not been modified. This valve constantly monitors the fuel oil pressures. The diesel valve design should allow operation solely on diesel fuel at 100% load anytime without stopping the engine. For durability of the operation on diesel, it is recommended that the nozzles be changed frequently to increase efficiency when the aircraft is running at full engine load (Martz, 2012).

It should be noted that natural gas is buoyant at temperatures above -160°F (-106°C) and does not pool on the ground but rather rapidly dissipates in the environment. It is nontoxic and is environmentally safe. The gas also has a high auto ignition temperature. The minimum temperature needed for methane to ignite without a spark is 1076°F (580°C). This range of flammability is an important safety feature of methane as the primary fuel. Again, natural gas only burns when the concentrations range from 5% and 15% hence making it highly unlikely that accident ignition can occur. Other safety features are the double-walled or single walled gaseous fuel piping. For instance, the space between the double wall piping can be continuously ventilated, or installed with gas detection sensors to continuously monitor the environment for any presence of gas. These sensors are connected to an alarm system that can switch off the gas fuel supply and ether return the engine to operation on 100% diesel fuel or shut it down completely (Martz, 2012).

5. Conclusion

Increasing concerns over energy security and the emissions of pollutant gases represents a survival challenge for the global transport industry. This has prompted new studies on the development of technologies that can be used to improve specific fuel consumption and air pollutant emissions. These studies concentrate on essentials of specific fuel consumption, aircraft efficiency, emissions technologies, and the possibility of potential alternative fuels. With respect to alternative fuels, there has been an increase in dual fuel, gas/diesel engines worldwide. This thesis investigated the viability of introducing dual fuel operations to facilitate the introduction of non-kerosene base aviation fuel, with specific focus on the modification of a jet A fuel aircraft to operate on methane as a dual fuel.

The paper also analysed the aviation industry and its impact on climate. Aviation emissions continue to be of specific concern because aircrafts flying at cruising altitudes exert a significantly higher climate impact compared with emissions at ground level. Therefore, one of the ways of reducing greenhouse gas emissions is the pursuit of alternative fuels, as a core component of sustainable transport. Using methane as the preferred alternative fuel, the paper has analysed dual fuel (natural gas/diesel) engines, particularly their operation, applications, and contribution. The investigation also covered aircraft fuel systems, the components; including, storage tanks, pumps, filters, valves, fuel lines, metering devices, and motoring devices and how the system can be modified to ensure uninterrupted flow of contaminant-free fuel to the jet A engine.

Apart from engine modification, it is also important to reiterate that aircrafts are essentially fuel efficient due to high-tech engines and propeller efficiency. Therefore, other factors can directly be controlled by the airline's employees (such as flight crews, operations/despatch crews, or maintenance staff) during flight preparation and flight management should also receive attention. In this regard, there is need for accurate data in aircraft planning, correct aircraft loading, keeping an aerodynamically clean aircraft, aircraft speeds with relevance to altitudes, and overall flight planning and management to ensure high levels of performance. Finally, even though the engine has been modified to dual fuel, the engine maintenance requirements that ensure durability, performance, and safety must be complied.

References

Intergovernmental Panel on Climate Change (IPCC). Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, 2007.

David S. Lee, David W. Fahey, Piers M. Forster, Peter J. Newton, Ron C.N. Wit, Ling L. Lim, Bethan Owan, and Robert Sausen. Aviation and global climate change in the 21st century. Atmospheric Environment, 43:3520{3537, 2009.

Radiative Forcing Index- Aviation and the Global Atmosphere http://www.grida.no/climate/ipcc/aviation/064.htm

Commission for Integrated Transport (CfIT), United Kingdom http://www.cfit.gov.uk/docs/2003/aec/aec/index.htm

Forster P., Shine K., Stuber N. (2006). Atmospheric Environment, 40:1117-11121

Dallara, E. S. (2011). Aircraft design for reduced climate impact. A Dissertation. Department of Aeronautics and Astronautics: Stanford University

Duc, P. M. & Wattanavichien, K. (2007). Study of biogas premised charge diesel dual fuelled engine. *Energy Conversion and Management* 48: 2286-2308

Langton, R., Clark, C., Hewitt, M., & Richards, L. (2009). *Aircraft Fuel Systems*. John Wiley & Sons, Ltd: United Kingdom

Papagiannakis, R. G. & Hountalas, D. T. (2003). Experimental investigation concerning the effect of natural gas percentage on performance and emissions of a DI dual fuel diesel engine. *Applied Thermal Engineering* 23: 353-365

Santoni, G. W., Lee, B. L., Wood, E. C., Herndon, S. C., Miake-Lye, R. C., Wofsy, S. C., McManus, J. B., Nelson, D. D., & Zahniser, M. S. (2011). Aircraft Emissions of Methane and Nitrous Oxide during the Alternative Aviation Fuel Experiment. *Enviro. Sci. Technol.* 45: 7075-7082

Selim, M. Y,E. (2001). Pressure-time characteristics in diesel engine fuelled with natural gas. *Renewable Energy* 22: 473-489

Selim, M. Y. E. (2003). Effect of exhaust gas recirculation on some combustion characteristics of dual fuel engine. *Energy Conversion and Management* 44: 707-721

Selim, M. Y. E. (2005). Effect of engine parameters and gaseous fuel type on cyclic variability of dual fuel engines. *Fuel* 84: 961-971

Wu, X., Daniel, R., Tian, G., Xu, H., Huang, Z., & Richardson, D. (2011). Dual-injection, bi-fuel concept for spark-ignition engines fuelled with various gasoline and biofuel blends. *Applied Energy* 88: 2305-2314

Ross, D. (2009). GHG Emissions Resulting from Aircraft Travel, Flight Calculator 9.2 5/6/2009

OECD (2012), Green Growth and the Future of Aviation, Paper prepared for the 27th Round Table on Sustainable Development to be held at OECD Headquarters, 23-24 January 2012

Martz, J. (July 2012). The Basics of converting Diesels to Dual-fuel operation: Advanced electronic controls invigorate an established technology. Reprinted from July 2012 CompressorTech Two. Diesel & Gas Turbine Publications Printed in U.S.A