Advances in Energy Research, *Vol. 3, No. 1 (2015) 31-43*
DOI: http://dx.doi.org/10.12989/eri.2015.3.1.031

The use of liquefied petroleum gas (lpg) and natural gas in gas turbine jet engines

Ibrahim Koc*

Aerospace Engineering Department, Turkish Air Force Academy, 34149 Yesilyurt, Istanbul, Turkey

(Received March 15, 2014, Revised November 22, 2014, Accepted February 24, 2015)

Abstract. This paper compares the performance of JP-8(Jet Propellant) fuel and liquefied petroleum gas (LPG) and natural gas in the F110 GE100 jet engine. The cost of natural gas usage in gas turbine engines is lower than JP-8 and LPG. LPG cost is more than JP-8. LPG volume is bigger than JP-8 in the same flight conditions. Fuel tank should be cryogenic for using natural gas in the aircraft. Cost and weight of the cryogenic tanks are bigger. Cryogenic tanks decrease the move capability of the aircraft. The use of jet propellant (JP) is the best in available application for F110 GE 100 jet engine.

Keywords: liquefied petroleum gas; natural gas; jet propellant; gas turbine jet engine

1. Introduction

Personal air transport has increased by 5.9% per year in the world for the last 27 years (Mazraati 2010). The fuel usage in aviation is about 5.8% of the world's total fuel usage (Mazraati 2010). NO_x and SO_x (Marquart *et al*. 2001) and CO_2 (Kivits *et al*. 2010) and unburned hydrocarbon gases are vented to the atmosphere by airplane engines.

Today, energy requirements have increased, especially in emerging countries. The fossil fuel resources needed for the production of energy is depleted continually. Environmental protection is very important in climate change in relation with carbon emissions to the atmosphere (Vine 2008). “To reduce dependence on fossil resources is required on reducing energy consumption by applying energy saving programs focused on energy requirement reduction and energy efficiency in industry (Lee and Chen 2009)”. It is estimated that the petroleum is depleted in the next 50 years. Therefore, energy manufacturers are turning to alternative energy sources.

An early study of natural gas as an airplane fuel (Weber 1970) covered a number of issues in addition to cost and tank requirements and actually showed that operating costs using natural gas could be substantially reduced at the prices then current. A similar result was found for the use of LH_2 as an airplane fuel (Baerst and Riple 1979).

A swirl-can modular combustor was tested as using natural gas fuel. The test results show that the modular combustor approach can be used effectively in designing a combustor for gaseous fuel (Marchionna and Trout 1970). Natural gas and biomass were used in micro gas turbine as fuel

∗Corresponding author, Assistant Professor, E-mail: i.koc@hho.edu.tr

http://www.techno-press.org/?journal=eri&subpage=7 ISSN: 2287-6316 (Print), 2287-6324 (Online)

(Riccio and Chiaramonti 2009). Combustion characteristics of gaseous hydrogen fuel in a can-type gas turbine combustor were presented (Desoky *et al*. 1990). Combustion performance of hydrogen was compared with that of ammonia and liquefied petroleum gaseous fuels using the same combustion hardware.

The gas turbine of the power plant was selected as the target of DME (dimethyl ether, CH_3OCH_3) application (Lee *et al*. 2009). Combustion performance tests were conducted by comparing DME with methane which is a major component of natural gas. The combustion performance tests show that DME is very clean and efficient fuel for gas turbines in power plant.

JP-8 fuel is currently used for F110-GE 100 engine which is used in F-16 aircraft. In this study, the usage of natural gas and LPG was investigated for F110-GE100 engine theoretically.

2. Performance analysis in turbofan engine with low bypass ratio

A schematic view of turbofan engine with low bypass ratio is presented in Fig. 1 (Ozturk 1997).

The properties for F110 GE-100 engine are given in Table 1 (Ozturk 1997).

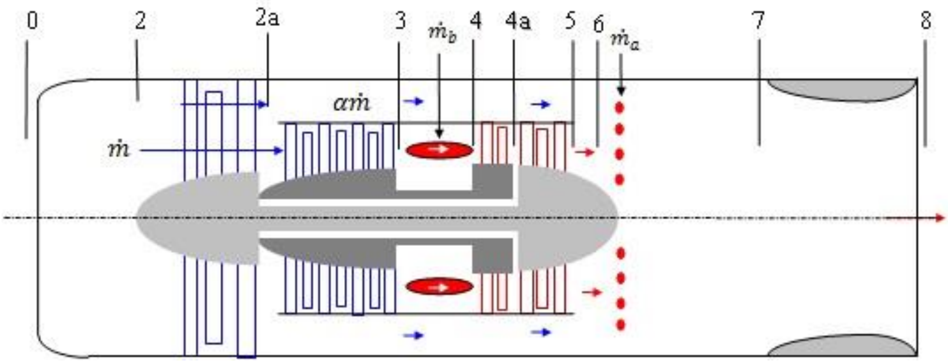

Fig. 1 Schematic view of turbofan engine with low bypass ratio; 0-2 intake, 2-2a; fan, 2a-3 high pressure compressor, 3-4 combustion chamber, 4-4a high pressure turbine, 4a-5 low pressure turbine, 5-6 mixer, 6-7 afterburner, 7-8 exhaust nozzle

Table 1 The properties of F110 GE-100 turbofan engine with low bypass ratio

Properties	**Values**
Maximum thrust (with after burner)	128.800 kN
Normal thrust (without afterburner)	63.9 kN
Total mass	1767 kg
Length	5.89 m
Maximum diameter	1.18 m
Bypass ratio	0.87
Fan pressure ratio	3:1
Total pressure/Fan pressure ratio	30.4:1
Air mass flow rate	115-122 kg/s
HPC-HPT (High Pressure Compressor- High Pressure Turbine) rotational velocity	14460 rpm

In this study, thrust and fuel mass flow rate values for JP-8 fuel have been calculated in different Mach numbers. The unit thrust is determined as follows (Kerrebrock 1992)

$$\frac{F}{\dot{m}a_0(1+\alpha)} = M_0\left\{\left[\frac{\theta_t - \left(\dfrac{\theta_t}{\theta_0\tau_c}\right) - \theta_0(\tau_c - 1) + \alpha(\theta_0 - 1)}{(\theta_0 - 1)(1+\alpha)}\right]^{0.5} - 1\right\} \tag{1}$$

where $\frac{F}{\dot{m}a_0(1+\alpha)}$ is the unit thrust and F is the thrust. The specific impulse is used as an index of the performance assessment of the propulsion system for aerospace. The specific impulse shows how much thrust is obtained for the fuel used (Yamada *et al*. 2010). The unit specific impulse is given in Eq. (2) (Kerrebrock 1992)

$$\frac{IgC_pT_0}{a_0h} = \frac{M_0\left\{\left[\dfrac{\theta_t - \left(\dfrac{\theta_t}{\theta_0\tau_c}\right) - \theta_0(\tau_c - 1) + \alpha(\theta_0 - 1)}{(\theta_0 - 1)(1+\alpha)}\right]^{0.5} - 1\right\}}{(\theta_t - \theta_0\tau_c)}(1+\alpha) \tag{2}$$

where I is specific impulse. θ_t, θ_0 and τ_c are given in the following Eqs. (3) and (4) and (5).

$$\theta_t = \frac{T_{t4}}{T_0} \tag{3}$$

$$\theta_0 = \frac{T_{t0}}{T_0} = 1 + 0.5(k-1)M_0^2 \tag{4}$$

$$\tau_c = \pi_c^{(k-1)/k} \tag{5}$$

The fuel mass flow rate is defined as the ratio of the thrust and the fuel weight consumption rate. The fuel mass flow rate is given in eq. (6).

$$\dot{m}_f = \frac{F}{gI} \tag{6}$$

where m_f is fuel mass flow rate and g is acceleration of gravity. The ideal cycle analysis was used in these equations. The data used for the turbofan engine performance are given in Table 2.

Stoichiometric or theoretical combustion is the ideal combustion process where fuel is burned completely. A complete combustion is a process burning all the carbon (C) to (CO_2), all the hydrogen (H) to (H_2O) and all the sulphur (S) to (SO_2). With unburned components in the exhaust gas, such as C, H_2, CO, the combustion process is uncompleted and not stoichiometric.

The most common oxidizer is air. Therefore, air is used as an oxidizer in the aircraft. The chemical equation for stoichiometric combustion of JP-8 can be expressed as

$$C_{12}H_{24} + 18(O_2 + 3.76N_2) \longrightarrow 12CO_2 + 12H_2O + 67.68N_2 \tag{7}$$

Table 2 The data used for the turbofan engine

Properties	Values
Air mass ratio (m)	120 kg/s
Bypass ratio (α)	0.87
Turbine inlet temperature (T_{t4})	1580 K
Compressor pressure ratio (π_c=P_{t3}/P_{t2})	30.4
Atmosphere temperature (T_0)	280 K
Specific heat ratio (k)	1.4
Gas constant (R)	0.287 kJ/kgK
Specific heat capacity - constant pressure (c_p)	1.005 kJ/kgK
Mach number	0.6, 0.8, 1.0, 1.2
Enthalpy ($h_{JP\text{-}8}$)	43150 kJ/kg
Enthalpy ($h_{\text{Natural gas}}$)	55684 kJ/kg
Enthalpy (h_{LPG})	46473.48 kJ/kg
Density ($\rho_{JP\text{-}8}$)	804 kg/m^3
Density ($\rho_{\text{Natural gas}}$)(in liquid phase)	430 kg/m^3
Density (ρ_{LPG})	509 kg/m^3

The chemical equation for stoichiometric combustion of LPG can be expressed as

$$0.7C_4H_{10} + 0.3C_3H_8 + 6.05(O_2 + 3.76N_2) \longrightarrow 3.7CO_2 + 4.7H_2O + 22.748N_2 \tag{8}$$

The chemical equation for stoichiometric combustion of natural gas can be expressed as

$$CH_4 + 2(O_2 + 3.76N_2) \longrightarrow CO_2 + 2H_2O + 7.52N_2 \tag{9}$$

If more air is supplied some of the air will not be involved in the reaction. The additional air is termed as excess air. The excess air is usually sent to the aircraft engine with the afterburner to be full burning. Aircraft are used their afterburners for take-off and sudden manoeuvres.

High turbine inlet temperatures are required to obtain high cycle efficiency in gas turbines. However, high temperatures also damage the blade and vane materials. Therefore, it is necessary to either use blade materials that can work at the high temperatures or to apply efficient cooling schemes to the turbine vanes and blades. The latter solution is usually a cheaper alternative (Koc and Parmaksızoglu 2006).

The adiabatic flame temperature values are important for turbine and combustion chamber cooling. If natural gas adiabatic flame temperature is lower than JP-8, there is no need for an additional cooling system.

Adiabatic flame temperature of the combustion chamber can be found by applying the first law of thermodynamics (Fig. 12). (Ozturk 1997)

$$Q\text{-}W = \Sigma H_{exit} - \Sigma H_{inlet} \tag{12}$$

There is no heat exchange and work in an adiabatic combustion chamber. Kinetic and potential energy changes are zero.

$$\Sigma H_{inlet} = \Sigma H_{exit} \tag{13}$$

$$\Sigma H_{reactant} = \Sigma H_{product} \tag{14a}$$

$$\sum_R n_i \bar{h}_i = \sum_P n_e \bar{h}_e \tag{14b}$$

$$\sum_R n_i \left(\bar{h}_f^0 + \Delta\bar{h} \right)_i = \sum_P n_e \left(\bar{h}_f^0 + \Delta\bar{h} \right)_e \tag{14c}$$

where n is mol number and $\bar{h}_f^0$ is formation enthalpy and $\Delta\bar{h}$ is difference enthalpy. Subscript i indicates the entrants to reaction and subscript e indicates the products.

Formation and difference enthalpies can be found by using JANAF thermochemical tables. Formation and difference enthalpy values were taken from the following tables (Ozturk 1997).

3. Results and discussion

The change of the thrust with the variation of the JP-8 fuel mass flow rate is given in Fig. 2. According to the Fig. 2, the high thrust can get in low Mach number. For example, the thrust is 126.682 kN and the mass flow rate is 2.191 kg/s at M=0.6.

Table 3 Formation enthalpy ($\bar{h}_f^0$)

	Chemical Formulas	Formation Enthalpy $\bar{h}_f^0$ (kJ/kg)
JP-8	$C_{12}H_{24}$	-385400
Natural gas	CH_4	-74837
LPG(butane)	C_4H_{10}	-126142
LPG(propane)	C_3H_8	-103847
Carbon dioxide	CO_2	-393522
Water	H_2O	-241827
Nitrogen	N_2	0
Oxygen	O_2	0

Table 4 Difference enthalpy ($\Delta\bar{h}$)

T (K)	Carbon dioxide, CO_2 $\Delta\bar{h}$ (kJ/kmol)	Water, H_2O $\Delta\bar{h}$ (kJ/kmol)	Nitrogen, N_2 $\Delta\bar{h}$ (kJ/kmol)	Oxygen, O_2 $\Delta\bar{h}$ (kJ/kmol)
1400	55907	43447	34936	36966
1500	61714	48095	38405	40610
1600	67580	52844	41903	44279
1700	73492	51685	45430	47970
1800	79442	62609	48982	51689
1900	85429	67613	52551	55434
2000	91450	72689	56141	59199
2100	97500	77831	59748	62986
2200	103575	83036	63371	66802
2300	109671	88295	67007	70634
2400	115788	93604	70651	74492

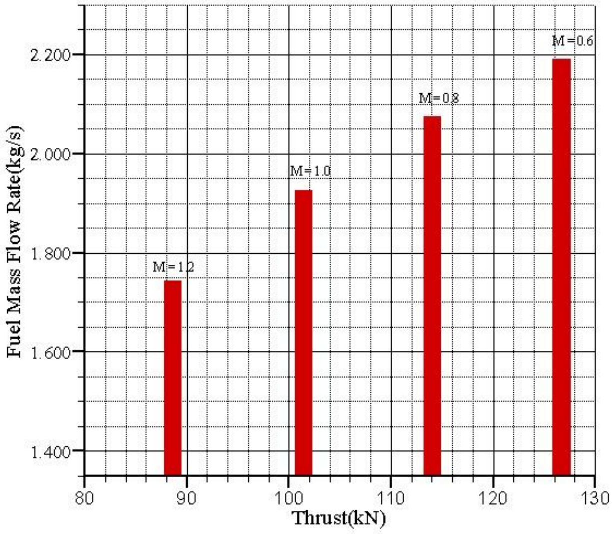

Fig. 2 The change of the thrust with the variation of the fuel mass flow rate

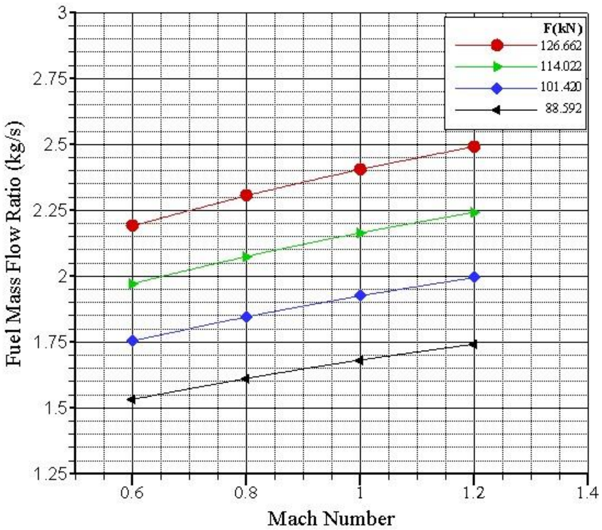

Fig. 3 The change of the fuel mass flow rate in different Mach numbers

The change of the thrust with the variation of the fuel mass flow rate

If the flight Mach number is increased for the same thrust value, the fuel mass flow rate increases. For example, in Fig. 3, the fuel mass flow rate is 2.191 kg/s at the 0.6 Mach number, the fuel mass flow rate is 2.491 kg/s by increasing the differences between Mach numbers for the thrust which is 126.682 kN.

The natural gas and LPG were used instead of JP-8 fuel in F110-GE-100 turbofan engine. In addition, as shown in Table 2, the natural gas enthalpy value is higher than the enthalpy values of LPG and JP-8. Due to the large enthalpy value of the natural gas, the same thrust is produced with less fuel when the natural gas compare with the other fuels. For example, the fuel mass flow rate

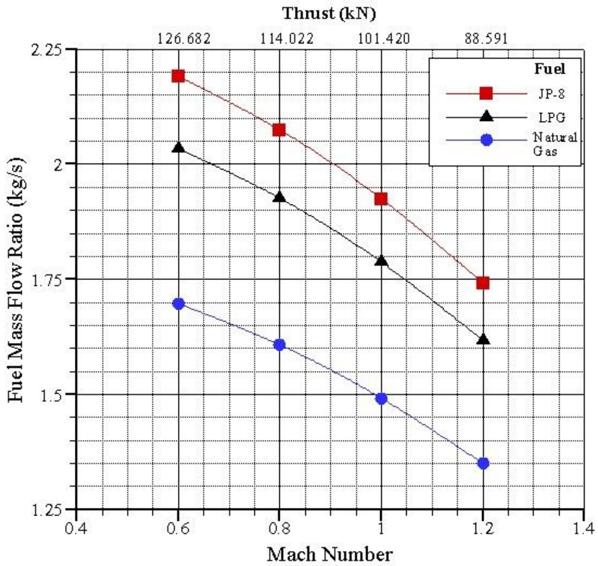

Fig. 4 The change of the fuel mass flow rate in different Mach numbers and thrust values

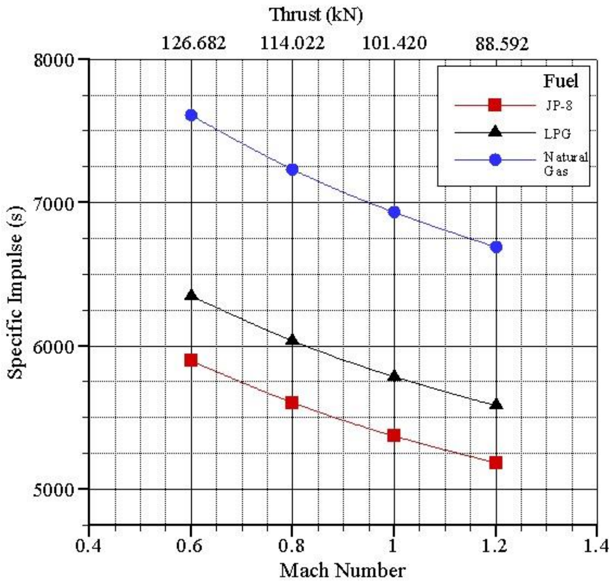

Fig. 5 The change of the specific impulse in different Mach numbers and thrust values

for 126.682 kN thrust at 0.6 Mach is 1.698 kg/s natural gas, 2.034 kg/s LPG and 2.191 kg/s JP-8 (see Fig. 4). The change of the fuel mass flow rate in different Mach numbers and thrust values are given in Fig. 4.

Natural gas has a value of high specific impulse. For example, the specific impulse for 126.682 kN thrust at 0.6 Mach is 7607.344 s natural gas, 6349.036 s LPG and 5894.995 s JP-8 (Fig. 5). The change of the specific impulse at different Mach numbers and thrust values are given in Fig. 5.

Another advantage of the natural gas is lighter than other fuels. Weight is one of the most

Table 5 Average fuel prices for Turkey

JP-8 unit price ($/lt)	0.914
Natural gas unit price ($/lt)	0.218
LPG unit price ($/lt)	1.386

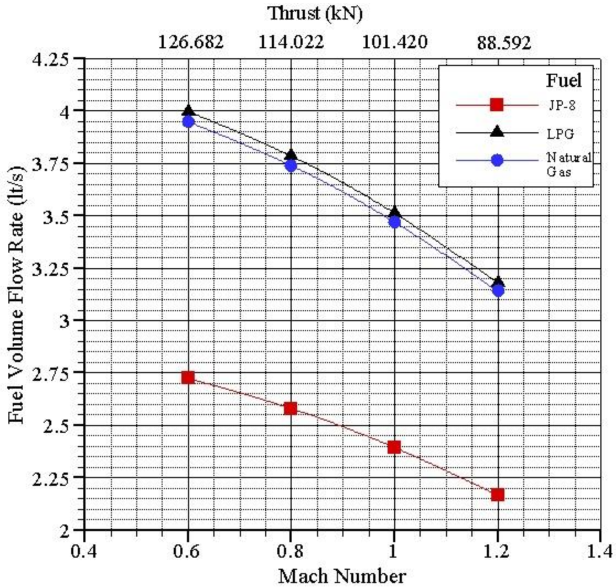

Fig. 6 The change of the fuel volume flow rate in different Mach numbers and thrust values

important parameters in aviation. The use of natural gas reduces the weight of aircraft engines. Thus, the aircraft can carry more ammunition. In addition, lightweight aircraft have more advantage in a dogfight because they can maneuver easier than weighty aircraft.

The biggest advantage of natural gas is that much more economical than other fuels. Average fuel prices for Turkey are given in Table 5.

Besides these advantages, there are also disadvantages of natural gas. The liquid natural gas has a value approximately 650 times greater than the gaseous natural gas. That is, 1 m^3 liquid natural gas equals 650 m^3gaseous natural gas. Therefore, the use of natural gas as a fuel in aircraft required to have a very large volume of the fuel tank. To use a very large volume of the fuel tank is impossible for breaking the structure of the aircraft aerodynamics. In this case, natural gas must be stored as a liquid. However, storage of natural gas in liquid form is not very easy. For storage of natural gas in liquid form, over 250 bar pressure values are needed. The natural gas can be stored in the cryogenic tanks as a liquid. Cryogenic tanks are manufactured to transport and store the liquefied natural gas (LNG). The fluid which is in the cryogenic tank is maintained at lower temperatures than -196^{o}C MERKBLATT CODE 2000 AD, EN 13458, EN 13530, and ASME ADR 2009 the standards are used for the design of cryogenic tanks. Each tanks are consists of two nested the tank. 304L stainless steel materials are used for interior tanks. S355J2G3 material is used for the external tank. Double wall is called the internal and external tank. Using vacuum perlite between the inner and outer tank is provided insulation. Owing to vacuum insulation the external containers of the cryogenic tanks are very sensitive. The welding process is not used on

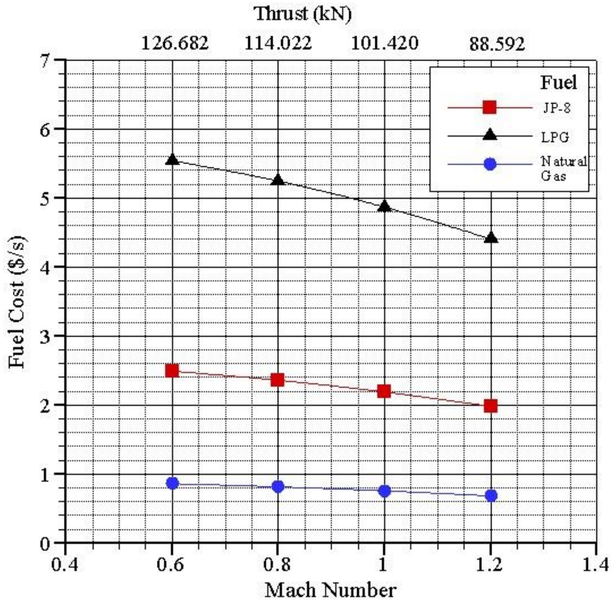

Fig. 7 The change of the fuel cost in different Mach numbers and thrust values

cryogenic tanks after manufacturing. When natural gas is used as fuel in aircraft, these tanks are used. These tanks are very heavy and their costs are high. The natural gas which is stored in liquid form is sent to the combustion chamber in the gaseous state. Evaporator is used for the gasification of the liquid which is taken from LNG tank. Evaporator converts from LNG to gas with using heat which is taken from the environment. Because of the evaporator, the extra weight and drag occur on the aircraft. This is a disadvantage encountered in when using natural gas.

For F110 GE 100 engine being used in F-16 Block 30 and Block 40 aircraft, it was calculated the fuel consumption values of the natural gas and JP-8 at M=1 for a one-hour flight. The values in Table 2 and Fig. 6 were used in these calculations. When the necessary calculations have for natural gas, natural gas is consumed 12487.68 liters. When the similar calculations have for JP-8, JP-8 is consumed 8618.89 liters.

When the natural gas and JP-8 were compared each other according to their cost, the natural gas is more economic more than JP-8. For example, the fuel cost for natural gas is 0.7562 $ in a one second at M=1 and it is 2.1882 $ in the same time for JP-8 (Fig. 7). The cost for a one-hour flight is $2722.32 in the natural gas. The cost of JP-8 is $7877.52 in the same conditions.

The cost of natural gas as shown in the calculations is about 1/3 times the JP8 fuel cost (Fig. 7). Natural gas will provide a huge advantage in aircraft engine when it is used. This is an important reason for the use of natural gas. However, a major disadvantage of natural gas is storage problem and it needs a large fuel tank. It is need high pressures for the storage of natural gas as a liquid. These tanks are much heavier and greater than normal aircraft fuel tanks. These tanks are cryogenic. Due to the structure of these, they should be either cylinder or sphere. The aircraft fuels are generally stored in the wings. However, this is not appropriate because of the structure of the cryogenic tanks. These cryogenic tanks can be placed as external fuel tank to the bottom of the wing. The placement of the cryogenic tank to the bottom of wing forms extra weight. Besides, it will lead to increases in the drag force.

LPG which is used quite extensively in the automotive industry may also be used in aircraft engines. However, the use of LPG in the aircraft engines has its own advantages and disadvantages. The biggest advantage of LPG is much easier than the storage of the natural gas. LPG can be kept in liquid form under 3 bar pressure. There is no obligation to use the cryogenic tank such as natural gas. Therefore, the LPG is stored in easily. It does not require to store additional cost. Another advantage of LPG is lighter compared with the jet fuels in the same volume. The advantage obtained from its weight provides the possibility of using more aircraft ammunition as natural gas. Since the use of LPG reduces the overall weight of the aircraft, the fuel consumption becomes less.

LPG fuel volume flow rate for the same thrust is much more than JP-8 fuel volume flow rate as shown in Fig. 6. For F110 GE 100 engine being used in F-16 Block 30 and Block 40 aircraft, it was calculated the fuel consumption values of the LPG and JP-8 at M=1 for a one-hour flight. The values in Table 2 and Fig. 6 were used in the above equations. When the necessary calculations have for LPG, LPG is consumed 12640.32 liters. When the similar calculations have for JP-8, JP-8 is consumed 8618.89 liters.

When the LPG and JP-8 were compared each other according to their cost, LPG is not economic more than JP-8. For example, the fuel cost for LPG is 4.8666 $ at M=1 and it is 2.1882 $ in the same time for JP-8 (Fig. 7). Fig. 7 shows that the cost per unit time of LPG is more than twice that of JP-8 and this criterion is used to conclude that LPG is not a viable competitor to JP-8. The cost for a one-hour flight is $17519.76 in LPG. The cost of JP-8 is $7200.05 in the same conditions.

When using LPG fuel instead of JP-8 fuel, the fuel tank which covers more volume is needed. Thus, the drag is increased. In addition, LPG tanks take up more space under the wing.

It appears from Fig. 8 that the adiabatic flame temperature of LPG is greater than the adiabatic flame temperature of JP-8. Therefore, it is need better cooling of the combustion chamber and turbine blades. LPG adiabatic flame temperature is approximately 0.764% higher than JP-8 adiabatic flame temperature. For example, the adiabatic flame temperature at the excess air coefficient of 1.2 is 2126.2 K for LPG and it is 2112.23 K for JP-8.

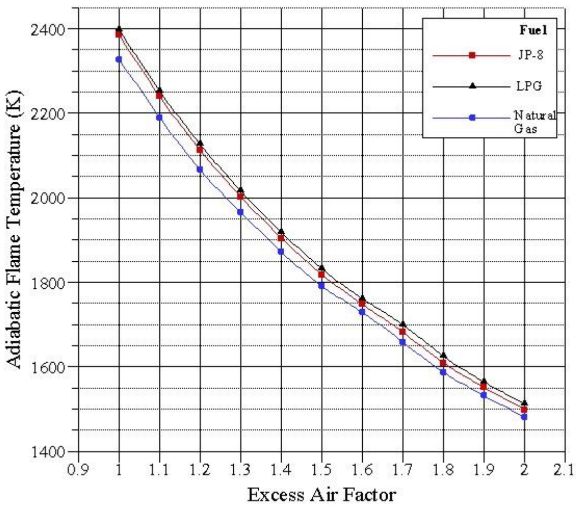

Fig. 8 The change of the adiabatic flame temperature in different excess air factor values

It appears from Fig. 8 that the adiabatic flame temperature of natural gas is lower than the adiabatic flame temperature of JP-8. Natural gas adiabatic flame temperature is approximately 1.662% lower than JP-8 adiabatic flame temperature. For example, the adiabatic flame temperature at the excess air coefficient of 1.2 is 2065.8 K for natural gas and it is 2112.23 K for JP-8. In this case, it is not happen cooling problems for natural gas in the combustion chamber and turbine inlet. Too much excess air is not desirable for reducing the thermal efficiency. For high efficiency, high adiabatic flame temperature is required. Natural gas in this regard is more advantageous than other fuels. For example, when the combustion chamber is run in an adiabatic temperature of about 2000 K, the excess air coefficient is 1.3 for JP-8 but, it is less for natural gas (Fig. 8).

The current industrial approach in finding a substitute for JP-8 concentrates on the economic formulation of synthetic hydrocarbon fuels which would treat the problem of both supply and distribution without any substantial change in engine design and performance.

It seems that a more comprehensive analysis of the use of these alternative fuels is needed to fairly determine their current and future feasibility as an airplane fuel.

4. Conclusions

In this study, the usage of JP-8 fuel and liquefied petroleum gas and natural gas in the F110 GE100 jet engine was investigated. The following conclusions were drawn from this investigation:

• The cost of natural gas is lower than LPG and JP-8.

• Aircraft fuel tanks should be cryogenic tanks for natural gas.

• Cryogenic tanks cost, weight and volume are high. In addition, cryogenic tanks are difficult to mount into the aircraft wing. Additionally, cryogenic tanks make it difficult to the operational capabilities of aircraft due to the structure of aerodynamics.

• The cost of LPG use in aircraft is higher than JP-8.

• LPG under the same conditions occupies more volume than JP-8.

• The adiabatic flame temperature of natural gas is lower. It can provide energy for aircraft engine by using less excess air.

According to these results, it is best to use existing application JP fuel. In addition, natural gas as fuel in aircraft for use with today's technology does not seem possible. However, the use of natural gas may be applied to the aircraft engines with the growing technology and improvements in cryogenic tanks. It is possible to generate electricity by using natural gas in the aircraft engines that are inactive. The natural gas can be stored in liquid form in an electrical generation facility because there is no shortage of space. Due to the low cost of natural gas, it can be obtained by low cost energy.

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NB

Nomenclature

a	Sound velocity, m s^{-1}
c_p	Specific heat capacity in constant pressure, kJ kg^{-1} K^{-1}
F	Thrust, kN
g	Acceleration of gravity, m s^{-2}
h	Enthalpy, fuel enthalpy, kJ kg^{-1}
H	Enthalpy, kJ
$\bar{h}_f^0$	Formation enthalpy, kJ kmol^{-1}
I	Specific impulse, s
k	Specific heat ratio
M	Mach number
$\overline{m}$	Air mass flow rate, kg s^{-1}
$\overline{m}_a$	Fuel mass flow rate for afterburner, kg s^{-1}
n	Mol number
Q	Heat, kJ
T	Temperature, K
W	Work, kJ

$\Delta\bar{h}$ Difference enthalpy, kJ $kmol^{-1}$

Greek symbols

α Bypass ratio
π Exit total pressure/inlet total pressure
θ Total temperature/atmosphere temperature
ρ Density, kg m^{-3}
τ Exit total temperature/inlet total temperature
Σ Total

Subscripts

c Compressor
e exit
f Fuel
i inlet
P Product
R Reactant
t Total, turbine
0 Surrounding