Effect of Airports Elevation on the Jet Engine Thrust (Off – Design Operation)

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Abstract

It is well known that airport elevation with respect to sea level has a considerable effect on the jet engine thrust. In this study an airplane type (Viper jet, Learjet) with jet engine type (J85-CJ610) was selected and tested at different elevations to show the effect of elevation on the engine thrust . The study includes theoretical background about turbojet engines, thrust, atmosphere and the change of some parameters and the relation between the thrust and altitude. According to the values of engine thrust in this study at different airports in the world for the selected engine mathematical calculation shows that the thrust decreases as altitude increases during maintaining the same speed, and as result of that the fuel consumption decreases also. Mathematical calculations shows that at 11 km a jet engine develops 41% of the thrust at sea level .So the turbojet engine performance is more efficient at a higher altitude ،but that requires a longer runway to attain the take-off speed.

Keywords: Jet engine , Thrust , Altitude

تأثير ارتفاع المطارات على قوة دفع المحرك النفاث
(عمليات خارج التصميم)

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الخلاصة

من المعلوم أن ارتفاع المطارات عن مستوى سطح البحر له تأثير كبير على قوة الدفع للمحرك النفاث. تم في هذه الدراسة اختيار محرك نفاث نوع (J85-CJ610) مركب على بعض أنواع الطائرات مثل (فايبر جت و لاير جت) وحساب قيم قوة الدفع لهذا المحرك في مطارات مختلفة الارتفاع عن سطح البحر لإظهار تأثير الارتفاع على دفع المحرك. تشمل هذه الدراسة استعراض لبعض العناوين النظرية عن المحركات النفاثة ، قوة الدفع ،تغير خصائص الغلاف الجوي ،العلاقة بين زيادة الارتفاع وقوة دفع المحرك النفاث. من خلال النتائج التي تم الحصول عليها في هذه الدراسة لقوة دفع المحرك J85-CJ610) على مدارج مطارات بعض المدن في العالم بينت الحسابات الرياضية أن قوة الدفع تقل كلما ازداد الارتفاع مع ثبوت سرعة الطيران، وكنتيجة لذلك يقل استهلاك الوقود . كما بينت الحسابات أن قوة دفع المحرك المذكور على ارتفاع 11كم تبلغ 41% من قوة دفعه على مستوى سطح البحر ولنفس السرعة، وبذلك فان المحرك النفاث أكثر كفاءة في الارتفاعات الأعلى ولكن انخفاض قوة الدفع تتطلب زيادة مسافة الدرج لبلوغ سرعة الإقلاع.

الكلمات الدالة: المحرك النفاث، قوة الدفع، الارتفاع

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Symbols

A_5	Calculated nozzle effective throat area	m^2
C_5	Velocity of gas at the Nozzle	m/s
C_{PC}	specific heat at constant pressure for air	kJ/kg.K
C_{Pt}	specific heat at constant pressure for combustion products	kJ/kg.K
F_d	Ram drag	kN
F_g	Gross thrust	kN
F_n	Net thrust	kN
g	Acceleration of gravity	m/s^2
$\dot{m}_a$	Air Mass flow rate	kg/s
$\dot{m}_f$	Fuel mass flow rate	kg/s
P	Stagnation Pressure	kPa
r_{pc}	Compressor pressure ratio	
T	Stagnation Temperature	K
V_0	Velocity of airplane	m/s
η_c	Compressor efficiency	-----------
η_t	Turbine efficiency	-----------
ρ	Density	kg/m^3
${}_a\gamma$	Ratio of specific heat for air	-----------
${}_g\gamma$	Ratio of specific heat for combustion products	------------

Introduction

The performance requirements of an engine are dictated largely the type of operation for which the engine is designed .The jet engine uses one of many types as propulsion power plant for aircrafts. A reaction engine discharges a fast moving jet of fluid to generate thrust. Each engine type must satisfy the performance requirements and one of the most important requirements is operation at different altitudes according to the designed point of engine performance [1,2].

Several parameters have been defined and used widely to characterize the quality and performance of jet engine. In many cases, these parameters also have the greatest effect on engine cost .The two useful performance parameters for jet engines in aircraft propulsion are the thrust of the engine and the specific fuel consumption. [3].

The aim of this study is to show the effect of altitude on the value of turbojet engine thrust, that dictates studying the relation between the troposphere layer characteristic and the change of main parameters which effect on the value of the thrust [2,4].

Turbojet engine type (J85-CJ610) is a small single-shaft turbojet engine , This engine , according to its specifications is the highest thrust –to-weight ratio of any production turbojet in the world. [5]. Its specifications are ($\dot{m}$ = 24 kg /s , r_p =7 , T_3 = 1000 k)
Mathematical calculation of thrust values for turbojet engine type (J85-CJ610) at sea level and at different altitude will be considered to support the theoretical side.

Jet engine must operate under many varying conditions and at varying airports elevations [14]. The change of altitude will affect the temperature and pressure of the air entering the engine, the density and the gas pressure at the engine jet nozzle. This means that, for any given throttle setting, different values must be entered in the thrust equations as the airspeed and altitude of the aircraft changes, many of the changes that will occur affect the thrust output of the engine directly interpreted into operating practice. The result is a characteristic of gas turbine type engine that must be understood by those who operate them. At any given throttle, setting engine thrust will vary as the temperature and pressure of the air entering the engine change. To illustrate how factors affecting, the thrust equations and how must the thrust be changed must be studied.[1, 8,18].

At the higher throttle setting and airspeeds encountered during normal aircraft operation ,the nozzle at the rear of the engine will probably "choked" most of the time ,which means that the gases passing through the convergent section of the nozzle will be at or near the speed of sound. The speed of sound varies with temperature, and, thus, as the exhaust gas temperature varies, so also will the speed of sound . This, in turn, will affect the exhaust gas velocity at which the nozzle becomes choked. When the nozzle is choked, the only variation in the ejection velocity of the gases will be due to changes in the engine exhaust gas temperature. Velocity change will be small under these conditions. Whenever the nozzle is not choked, varied atmospheric condition will cause some change in jet nozzle velocity. As can be seen by the thrust equations , change in the exhaust gas or nozzle velocity (v_j)will affect thrust[13].

In this study, the effect of airports location on thrust must be determined so we proposed that the aircraft is static, or the engine is being run up prior to take-off, therefore momentum drag is equal to zero, because V_0= 0.

However, as the aircraft commences to move, the velocity of the air entering the engine also beings to increase because of the speed of the aircraft .Therefore, the difference between V_j and V_0 will become less as airspeed increases.[13].

The mass airflow ($\dot{m}$) is the most significant variable in the thrust equations. Many factors affect the mass airflow, the most important being air temperature and pressure, because these, together, determine the density of the air entering the engine. [13, 14].

The density of the air going into the compressor determines the mass airflow into the engine at any given (rpm). When the air density decreases airflow decreases and the engine will produce less thrust. Thus, as the temperature increases, thrust decreases As the pressure increases, the air density also increases. As air density increases, airflow increases, and , consequently ,the thrust increases . From this, it can be seen that density affects airflow ($\dot{m}$) in the preceding equations, and that ($\dot{m}$) directly affects thrust. When pressure increase , as with increased airspeed or decreases altitude, density increases, and when temperature increases as on a hot day , density decreases. So **Density affects thrust proportionally [13,** 14].

Thrust – Main equations

Thrust is the force generated by the engine of the aircraft through some kind of propulsion system, which moves an aircraft through the air. It is a mechanical force used to overcome the drag of an airplane [2, 8]. The propulsion system must be in physical contact with a working fluid to produce thrust. The engine does work on the gas and accelerates the gas to the rear of the engine. To accelerate the gas, we have to expend energy. The energy is generated as heat generated by the combustion of fuel. The thrust equation describes how the acceleration of the gas produces a force. The equation for determining the thrust produced by a turbojet will only be used in actual practice by an engineer. The second and third Newton's laws of motion may explain the thrust produced by a turbojet engine. The basic equation which we may derived from Newton's second law F= ma, where F is force, m is mass, and a is acceleration. The law may be stated in words: A force is created by a change of momentum, and this force is equal to the time rate of change of momentum. [5, 17].

$$F = \frac{d(mv)}{dt}$$

where F is the force , mv **is the momentum, t** is the time , F_m is (momentum thrust)[1, 7] .
The equation for thrust may be written

$$F = \dot{m}(V_j - V_0)$$

V_j - Exhaust gas velocity (m/s)
V_0 - incoming air velocity (which is also the aircraft's true air speed) (m/s)

In actual practice – not all pressure of the gases flowing from the nozzle of a jet engine can be converted to velocity. In these cases, the static pressure of the gases at the jet nozzle is above the ambient air pressure .This difference in pressure creates additional thrust proportional to the area of the jet nozzle . The thrust generated at the jet nozzle is indicated by the equation

$$Fp = A_j(P_j - P_{amb})$$ Fp – Pressure thrust

In actual practice, fuel flow is usually neglected when net thrust is computed because the mass of air that leaks from various sections of the engine is assumed to be approximately equivalent to the mass of the fuel consumed.
When the jet nozzle thrust is added to the reaction thrust created by acceleration of gases in the engine ; the equation for the net thrust becomes

$$F_n = \dot{m}(V_j - V_0) + A_j(P_j - P_{amb})$$

There are two kinds of thrust, net thrust and gross thrust. Net thrust and gross thrust. Net thrust is the thrust that results from the change in momentum of the mass of air and fuel that passes through the engine .Net thrust includes the extra thrust at the jet nozzle when the static pressure at the nozzle exit exceeds the static pressure of the ambient (outside) air. Gross thrust does not take the incoming momentum of the air fuel into consideration. Zero coming momentum is assumed which is true only when the engine is static without considering fuel flow, the equation for gross thrust is:

$$F_g = \dot{m}(V_j) + A_j(P_j - P_{amb})$$ Where F_g –Gross thrust

When an aircraft and engine are static, as when the aircraft is parked , or when an engine is being run up prior to take off at the end of a runaway , net thrust and gross thrust are equal . The same is true when an engine is being operated in aground test stand. When the term, thrust , is used by itself in discussing a gas turbine engine , the reference is usually to net thrust unless otherwise stated.
Also the ram drag can be written by equation

$$F_d = \dot{m} V_0$$ where F_d is ram drag

So $F_n = F_g - F_d$ [9, 16].

Turbojet thermodynamic Cycle

A turbojet engine is a type of internal combustion engine often used to propel aircraft .It operates on what known as the Brayton cycle is shown schematically in Figure1. Temperature - Entropy diagram are usually used to illustrate the cycle of gas turbine engines[3]. The assumptions of ideal conditions will be taken to imply the following :

- The working fluid is air and considered as a perfect gas.
- The mass flow rate of the working fluid is constant throughout the cycle.
- The change of kinetic energy of the working fluid between inlet and outlet of each component is negligible.
- Compression and expansion processes are reversible and adiabatic (isentropic).
- The combustion process is modeled as a constant-pressure heat addition.
- There are no pressure losses in the inlet ducting, combustion chamber.
- The specific heat C_p , C_v are constant at different altitude so the value of (γ) is constant too .
- Cp_{air} =Constant = 1.005 kJ/kg.k , , Cp_{gas} = 1.1462 kJ/kg.k , γ_a = 1.4 , γ_g =1.333
  ρ_o = 1.226 kg/m^3 , T=15 ^{0}C = 288 K , $\eta_{compressor}$ =0.88 , η_{nozzle} = 0.95

  Turbojet engine mainly consist of Diffuser , Compressor , Combustion Chamber , Turbine and finally a nozzle to obtain a required thrust as show in Figure (1).

  The thermodynamic processes can be divided according to the turbojet engine components and as follows:

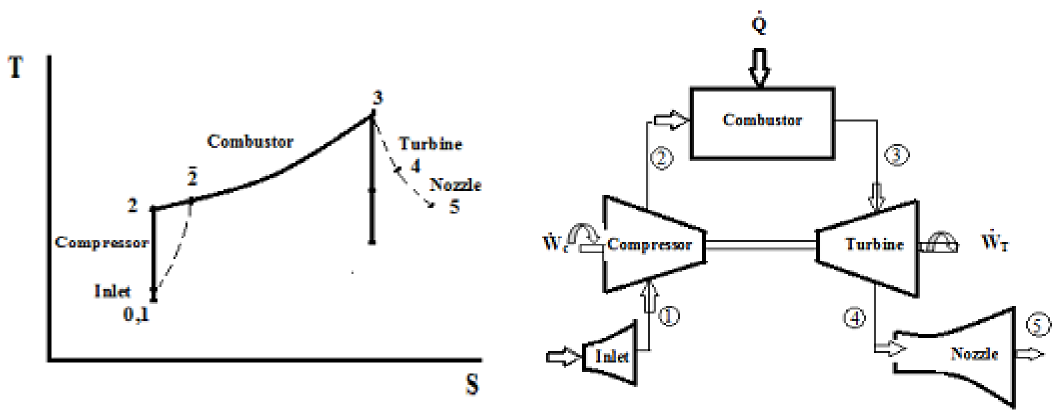

Figure (1) Brayton Cycle for Jet propulsion [7]

Diffuser: The engine inlet and the inlet ducting direct the required supply of air to the face of the compressor under all flight conditions with a little turbulence .The incoming air velocity decrease and the pressure increase. Since the aircraft engine in this study on the airport , the diffuser affect will be ignored .

The process depicted is: **(0 to 1)** 100 % inlet pressure recovery is assumed , the aircraft is stationary, so that state 0 and 1 are coincident

Compressor: It usually used to raise the pressure of air .This results in an increase in the energy of the air. The squashed air is forced into the combustion chamber. In the compressor the ideal process **(1 to $\bar{2}$)** would appear vertical on a T-S diagram(the process is isentropic compression). In the real process there is friction, turbulence and, possibly, shock losses, making the exit temperature, for a given pressure ratio, higher than ideal.

$$\frac{T_{\bar{2}}}{T_1} = \left[\frac{P_{\bar{2}}}{P_1}\right]^{\frac{\gamma-1}{\gamma}}$$

$$T_{\bar{2}} = T_1 \left|\frac{P_{\bar{2}}}{P_1}\right|^{\frac{\gamma-1}{\gamma}}$$

$$\eta c = \frac{T_{\bar{2}} - T_1}{T_2 - T_1}$$

$$w_c = C_P\,(T_{\bar{2}} - T_1) \quad kJ/kg$$

Combustor ($\bar{2}$ to 3) Heat (usually by burning fuel) is added, raising the temperature of the fluid. There is an associated pressure loss, some of which is unavoidable, but the process at constant pressure is assumed in the combustion chamber.

$$q_{add} = C_{pt}\,(T_{\bar{2}} - T_3) \quad kJ/kg$$

Turbine (3 to $\bar{4}$) : The high-energy airflow coming out of the combustor goes into the turbine causing the turbine to rotate so the compressor linked with it by shaft will rotate too. Ideally the process would be vertical on a T-S diagram (isentropic expansion). However, in the real process, friction and turbulence cause the pressure drop to be greater than ideal.

$$w_T = C_{pt}\,(T_{\bar{3}} - T_{\bar{4}}) \quad kJ/kg$$

However , the turbine work usually is assumed to be equal to compressor work, hence

$$w_c = w_T$$

$$\dot{m}_a\, Cp_{air}\,(T_2 - T_1) = (\dot{m}_a + \dot{m}_{fuel})\, Cp_{gas}\,(T_3 - T_4)$$

Fuel flow is usually neglected when net thrust is computed because the mass of air leaks from various sections of the engine is assumed approximately equivalent to the mass of the fuel consumed.

$$Cp_{air}\,(T_2 - T_1) = Cp_{gas}\,(T_3 - T_4)$$

$$\eta_T = \frac{T_3 - T_4}{T_3 - T_{\bar{4}}}$$

$$\frac{T_3}{T_{\bar{4}}} = \left(\frac{P_3}{P_{\bar{4}}}\right)^{\frac{\gamma_{t-1}}{\gamma_t}}$$

$$\frac{P_3}{P_{\bar{4}}} = \left|\frac{T_3}{T_{\bar{4}}}\right|^{\frac{\gamma_t}{\gamma_{t-1}}}$$

$$P_3 = P_2 = P_{\bar{2}}$$

$$\frac{P2}{P_1} = \frac{P_3}{P_1}$$

$$P_4 = P_{\bar{4}}$$

Nozzle ($\bar{4}$ —to $\bar{5}$) The nozzle is placed at the end of turbine to accelerate the hot gases leaving the turbine to velocity C_5 to produce thrust. The process is isentropic expansion process in Nozzle.

$$\frac{T_4}{T_{\bar{5}}} = \left(\frac{p_4}{p_5}\right)^{\frac{\gamma_t - 1}{\gamma_t}}$$

$$C_5 = \sqrt{2\, C_{pt}\, (T_{\bar{4}} - T_{\bar{5}})}$$ [3, 5]

$$\eta_{Nozzle} = \frac{T_4 - T_5}{T_4 - T_{\bar{5}}}$$

$\dot{m}_a = \rho * C_5 * A_5$

Thrust = $\dot{m}_a (C_5 - v_0)$

Effect of altitude on Turbojet Engine Thrust

The troposphere is the lowest layer of the atmosphere; it begins at the earth surface and extends to 8 km at the poles and 15 km at the equator, with some variation due to weather factors. Average depth of the troposphere is approximately 11 km[4, 11]

About 80% of the total mass of the atmosphere is contained in troposphere . Maximum air temperature occurs near the earth's surface in this layer. With height increasing , air temperature drops uniformly with altitude at a rate of approximately 6.5 °C per 1000 meters. At an average temperature of -56.5° C , the top of the troposphere is reached [12] .The troposphere has the following characteristics:

- It extends from the earth's surface to an average of 11 km .
- The pressure ranges from 1 to 0.2 bar .
- The temperature generally decreases with increasing height up to the top of the troposphere
- The temperature averages 15°C near the surface and -57° C at top of this layer
- The layer ends at the point where temperature no longer varies with height.
- Winds increases with height in this layer.
- The moisture concentration decreases with height up to the top of this layer .
- The air is much drier above the troposphere layer .[11, 12].

According to the change of elevation the pressure , temperature , and density of the atmosphere change . In the troposphere , the temperature decreases linearly and the pressure decreases exponentially .The following empirical relations for height (h) < 11000 m (Troposphere) are[4 , 11]

$T=15.04 - 0.00649 * h$

$P = 101.29*((T+273.1)/288.08)^{5.256}$

$\rho = P/(0.2869*(T+273.1))$

Results and Discussions

The performance of turbojet engine were studied at different altitude . The results involves the relationship between pressure, temperature , and density of air at different altitude , as shown in table (1) moreover the relationship between altitude and thrust is given in table (2)

Figure (2) shows the relationship between altitude and pressure. It can be seen that the atmospheric pressure decreases as the altitude increases. Figure (3) indicates the relationship between the ambient temperature and the altitude ,obviously the ambient temperature decreases as altitude increase.

Figure (4) represents the relationship between the altitude and density, It can be noted that the density decreases as the altitude increases.

Figure (5) indicates the relationship between altitude and thrust of the selected turbojet engine. It can be seen that the thrust force decreases as altitude increase because the mass of working fluid decreases.

Figure (6) shows the relationship between thrust force and altitude for selective airports throughout the world .Clearly ,the thrust of selective jet engine at the highest airport (Daocheng Yading) in chine nearly 4411m over the sea level (opened on September 2013) is 10.23 kN while the thrust of the same engine 13.83 Kn at Basra airport at sea level.

Table (1) : Variation of parameters with respect to altitude

Altitude h (m)	Density(kg/m^3)	pressure(kPa.)	Temp(C)
0	1.2266	101.400	15.04
1000	1.1132	89.958	8.55
2000	1.00811	79.584	2.06
3000	0.9107	70.201	-4.43
4000	0.8207	61.734	-10.92
5000	0.7376	54.114	-17.41
6000	0.6612	47.274	-23.9
7000	0.5909	41.151	-30.39
8000	0.5266	35.687	-36.88
9000	0.4677	30.826	-43.37
10000	0.4140	26.516	-49.86
11000	0.3651	22.707	-56.35

Table-2 The Relation between altitude and thrust

Altitude h (m)	$\dot{m}$(Kg/s)	C_5	Thrust (kN)
0	24	576.037	13.824
1000	22.162	586. 099	12.989
2000	20.407	595.977	12.162
3000	18.736	605.681	11.348
4000	17.150	615.218	10.551
5000	15.650	624.597	9.775
6000	14.235	633.825	9.022
7000	12.905	642.909	8.296
8000	11.659	651.855	7.601
9000	10.495	660.668	6.934
10000	9.412	669.355	6.301
11000	8.408	677.921	5.701

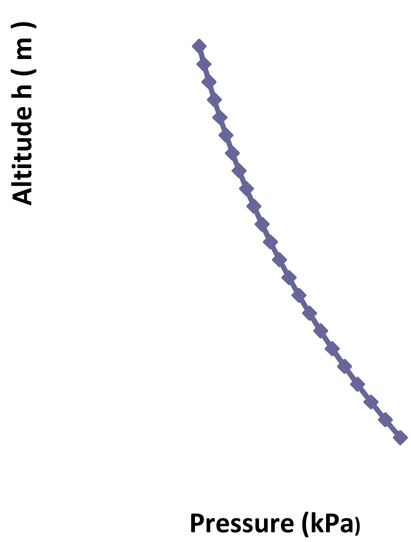

Fig. (2) The relation between altitude and pressure

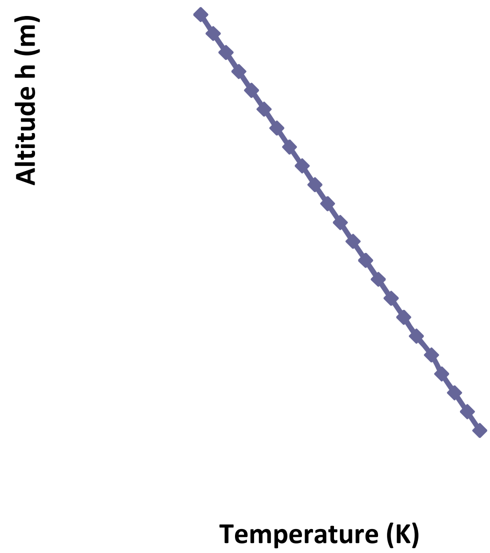

Fig (3) The Relation between altitude and Temperature

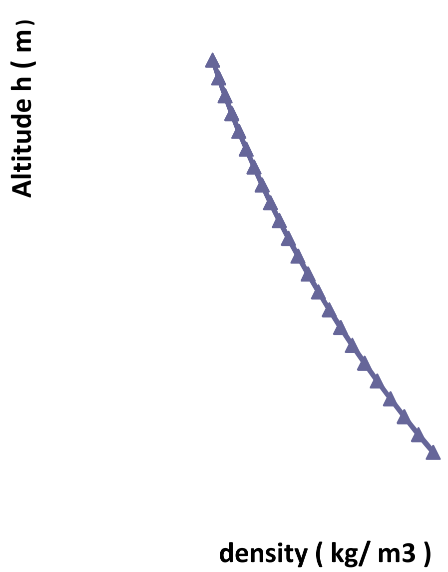

Fig (4) The relation between Altitude and density

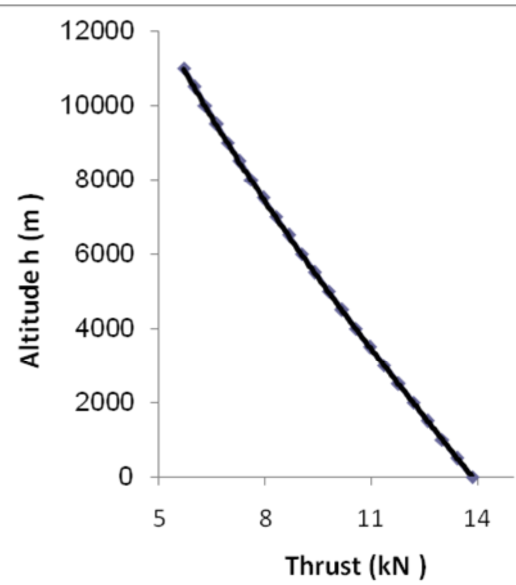

Fig. (5) The Relation between Altitude and Thrust

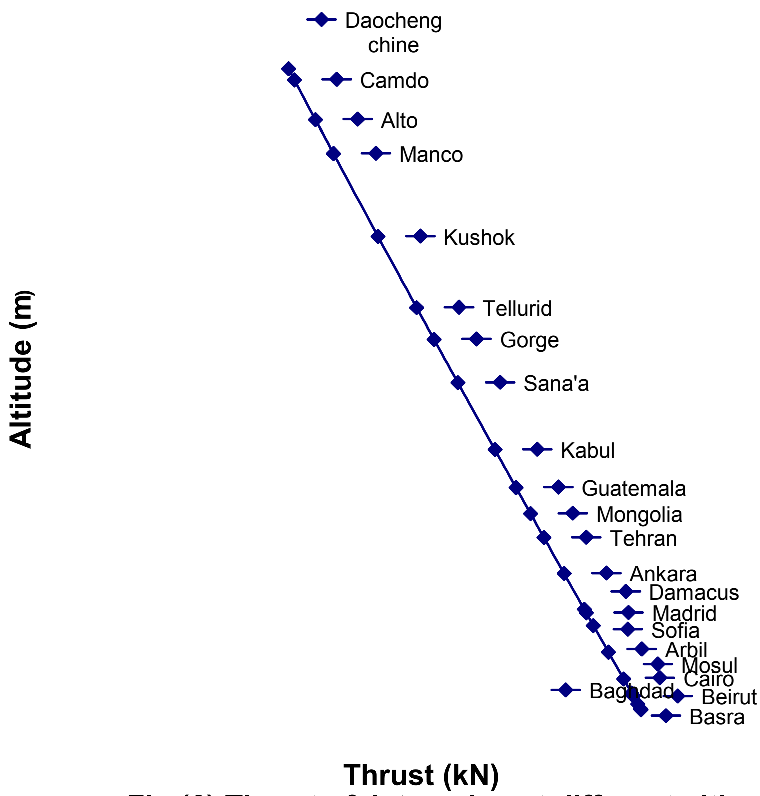

Fig.(6) Thrust of Jet engine at different cities

Conclusion

The following conclusions can be drawn from this study :

- For a given throttle\thrust lever setting the amount of thrust developed by a jet engine is directly proportional to the air density
- As altitude increase the thrust will be decrease while maintaining the same speed.
- There will be a decrease in fuel consumption since it is proportional to the thrust force.
- A low air density decreases the thrust and this increases the length of the ground roll to attain the lift-off speed , this fact is particularly important for take-off from a high elevation aairport , (for example the airports at 4000 m elevation required more than 5000 m runway long, almost twice the length of typical runway at sea level.
- As altitude increases the thrust reduction caused by reduced air density becomes more significant.
- At 11 km a jet engine only develops 41% of the thrust at sea level with the same thrust lever setting at the same gross mass
- For the same throttle-thrust lever setting Jet engine (J85-CJ610) at (Daocheng Yading) airport develops 74% comparing with the thrust at Basra airport.
- Turbojet engine performance is more efficient at higher altitude.

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